Possible KAGRA upgrade plan and strategy

KIW4
Jun 2018

Tokyo Institute of Technology

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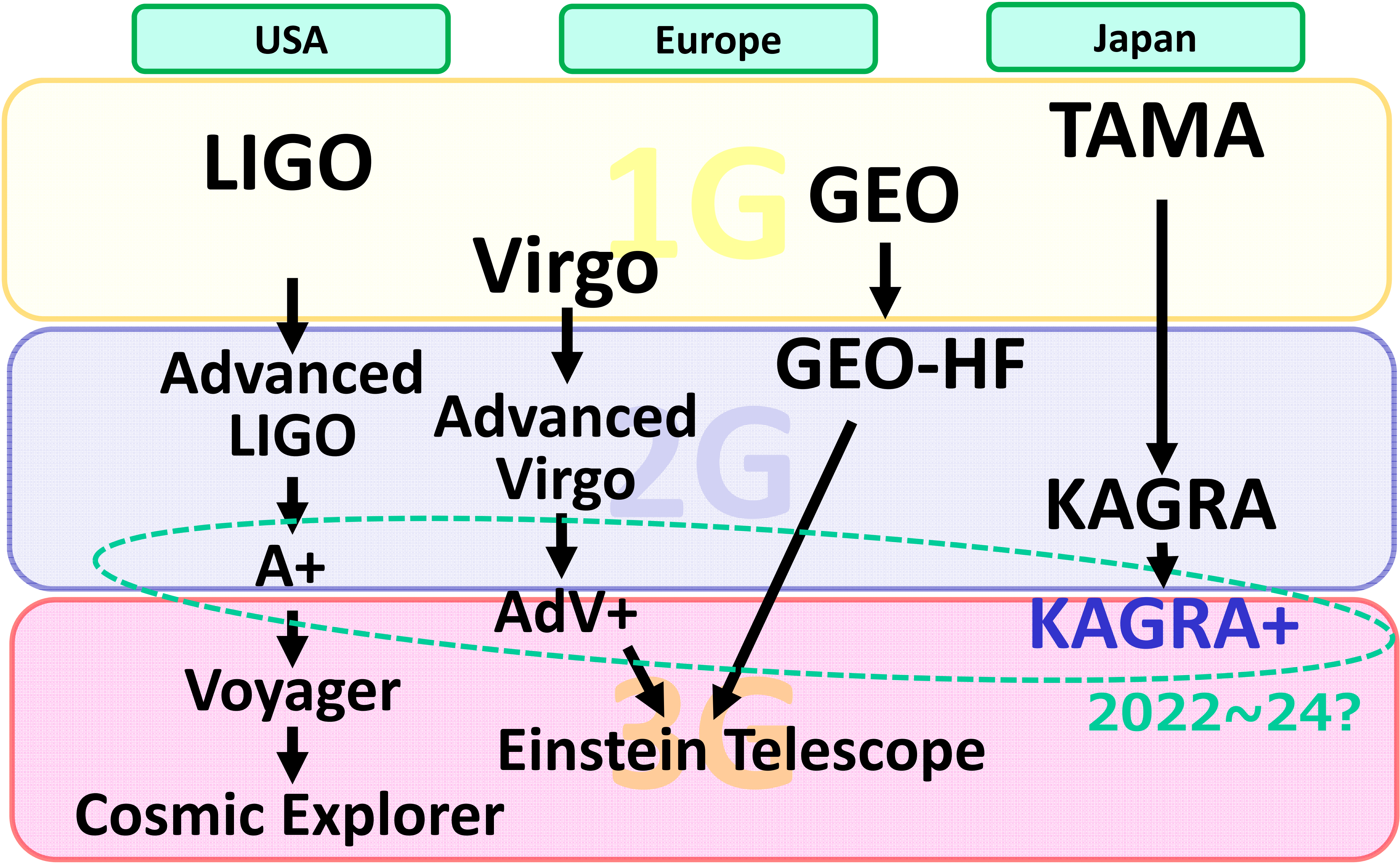
K.Somiya

Background


USA
Europe
Japan
1G
LIGO
Virgo
GEO
TAMA
2G
Advanced LIGO
Advanced Virgo
GEO-HF
KAGRA
A+
AdV+
KAGRA+
3G
Voyager
Cosmic Explorer
Einstein Telescope
2022~24?

History of discussions

2017.3 F2F@Niigata
First proposal to start discussing upgrade plans

2017.5 KIW3@Taipei
Three talks on future discussions

2017.8 F2F@Toyama
Scientific targets for “KAGRA+”
Three possible configurations: HF, LF, Heavy

2017.12 F2F@TITech, satellite session
Technical challenges for “KAGRA+”

2018.5 GWADW@Alaska
Session for 2.5G (A+, AdV+, “KAGRA+”)

Upgrade or No upgrade

Have all the bKAGRA items successfully installed? → No upgrade (installation)

↓

Are there reasonable plans for the upgrade? → No upgrade (the end)

↓

Do we all agree to schedule an upgrade in near future? → No upgrade (astrowatch)

↓

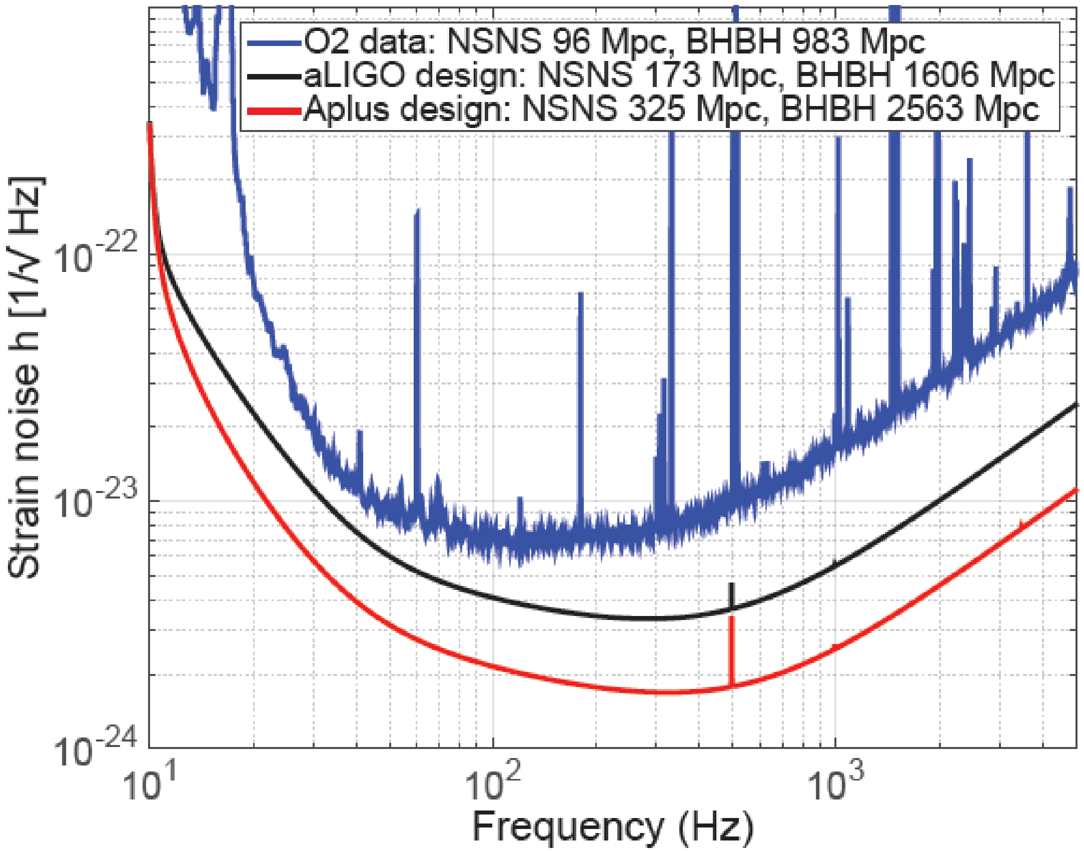
Can we find sufficient grant for the upgrade? → Upgrade! (KAGRA+)

Contents of my presentation

- Overview of other 2.5G: A+ and AdV+
- Downselection of the KAGRA+ configuration
- Required tasks to be shared
- How can we make it “official” in the project
- Strategy to realize KAGRA+ by 2024

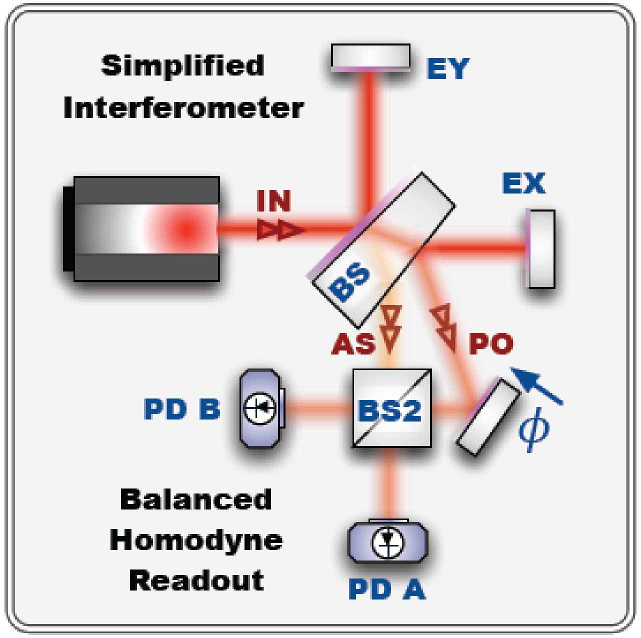
A+

[Barsotti, LIGO-T1800042-v5]
[Evans, GWADW2018]



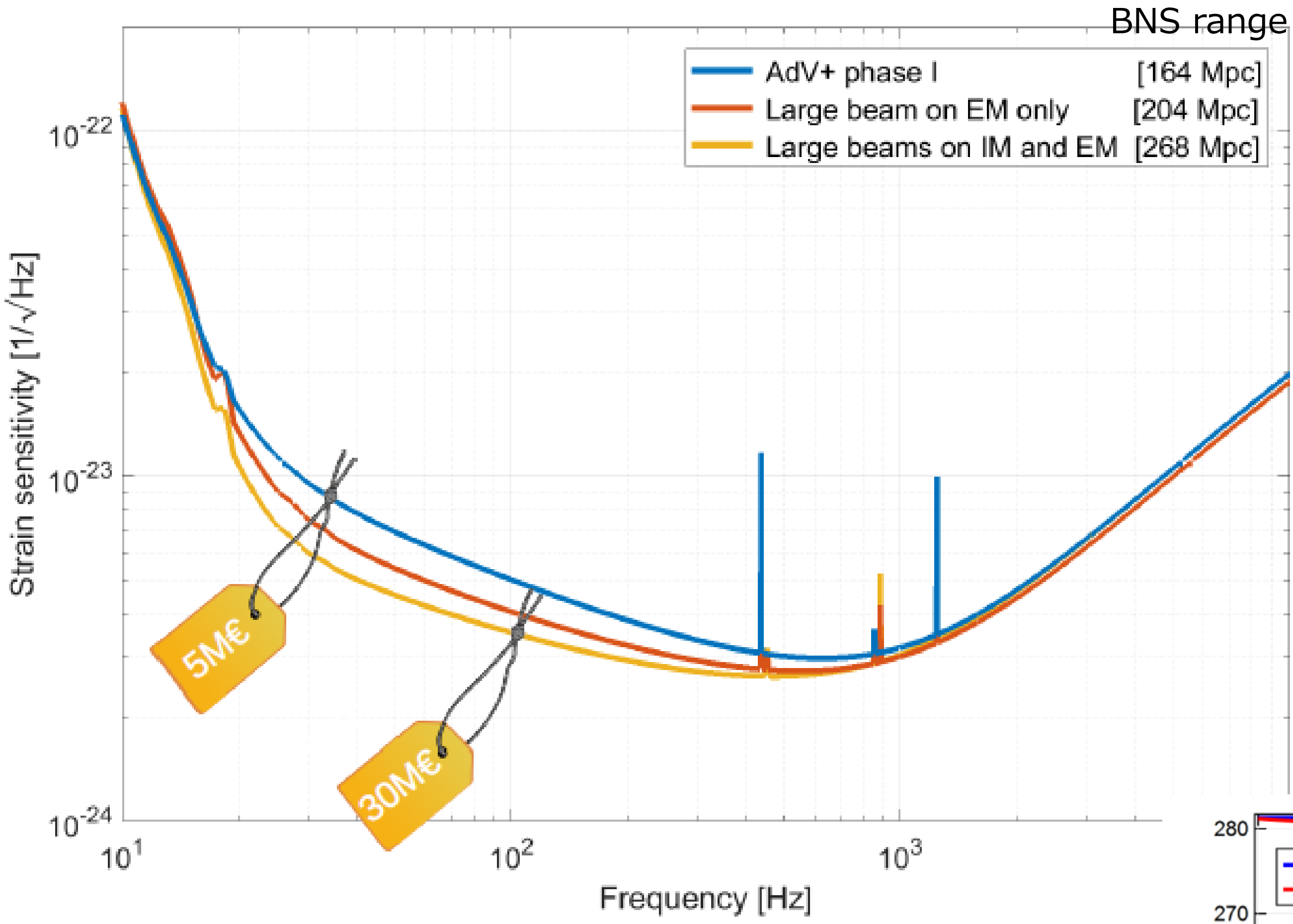
- 12dB squeezing injection (6dB observed w/15% readout loss)
- 300m filter cavity (20ppm RT loss)
- x2 better coating thermal noise
- Balanced homodyne detection

Joint proposal for 3-yr project.
Likelihood of funding:
- 2018 Oct (US)
- 2019 Jan (UK)
- Approved (AUS)



AdV+

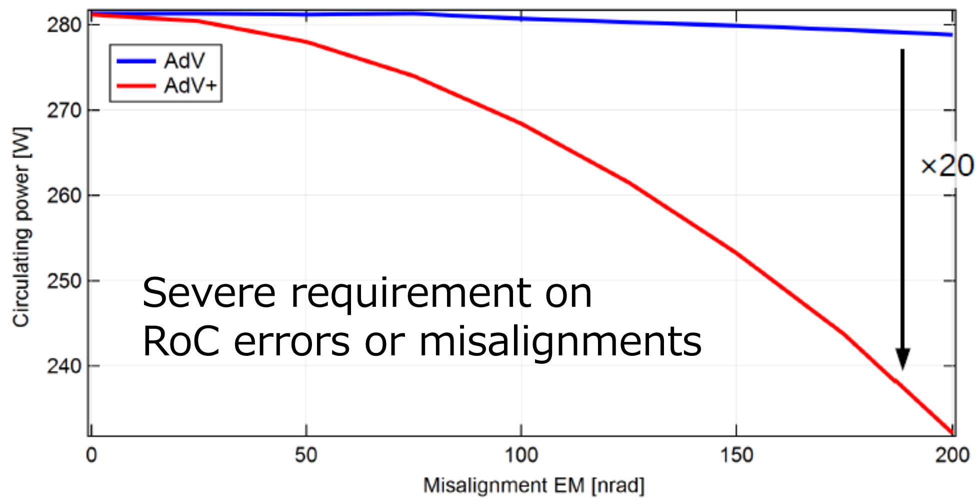
[Degallaix, GWADW2018]



Phase I
- 8dB squeezing
- 300m filter cavity
- Newtonian noise reduction

Phase II
- ϕ550x200 mirror (105kg)
- w=81mm/96mm
- g=0.98

BNS range would be 303Mpc if coating thermal noise could be reduced by x3.

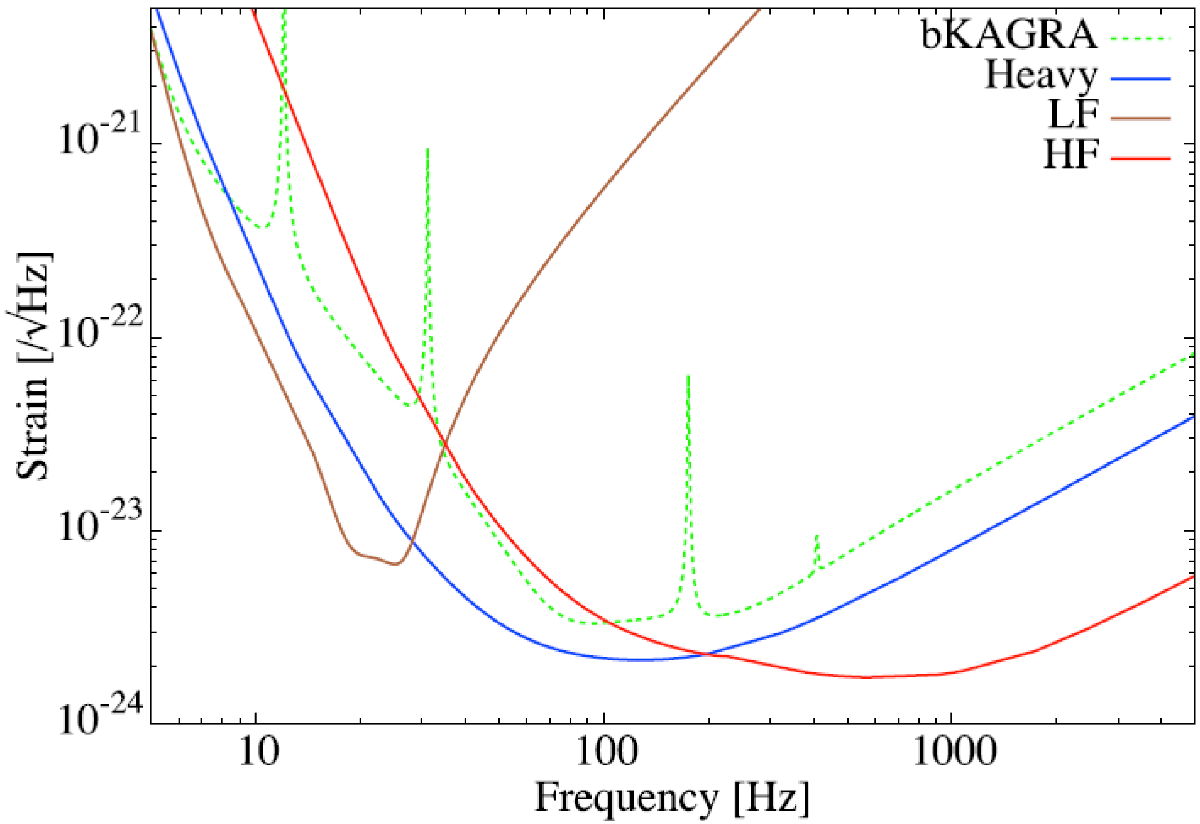


Both A+ and AdV+ are quite realistic while KAGRA+ is still like a dream...

3 important items missing in KAGRA+

- **Serious R&Ds**
- **Agreement in the collaboration**
- **Strategy**

KAGRA+ candidates



[Michimura, Nagano, Komori, Enomoto, Haino, Somiya, et al.]

Heavy (Blue)
m=73kg, 10dB FDSQ

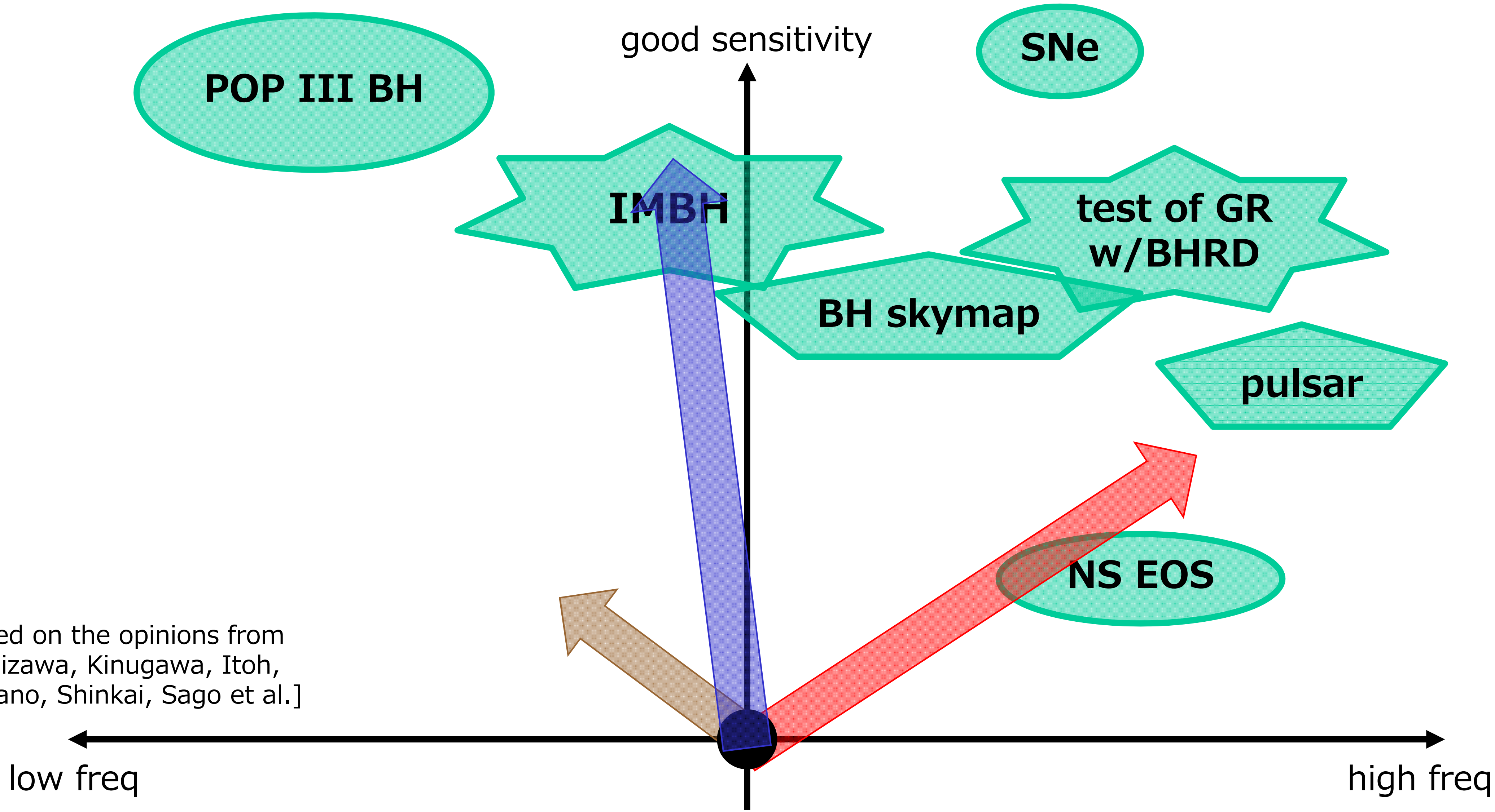
LF (Brown)
I_{BS}=6W, l_{sus}=88cm, d_{sus}=320um

HF (Red)
I_{BS}=5.2kW, l_{sus}=20cm, d_{sus}=2.4mm
10dB SQ

We prepared three possible sensitivity curves and asked some theorests about **scientific impacts**.

We then discussed **technological challenges** in each plan.

KAGRA+ scientific impacts



[Based on the opinions from Nishizawa, Kinugawa, Itoh, Nakano, Shinkai, Sago et al.]

Turned out eithr Heavy or HF would be favorable.

KAGRA+ technological challenges

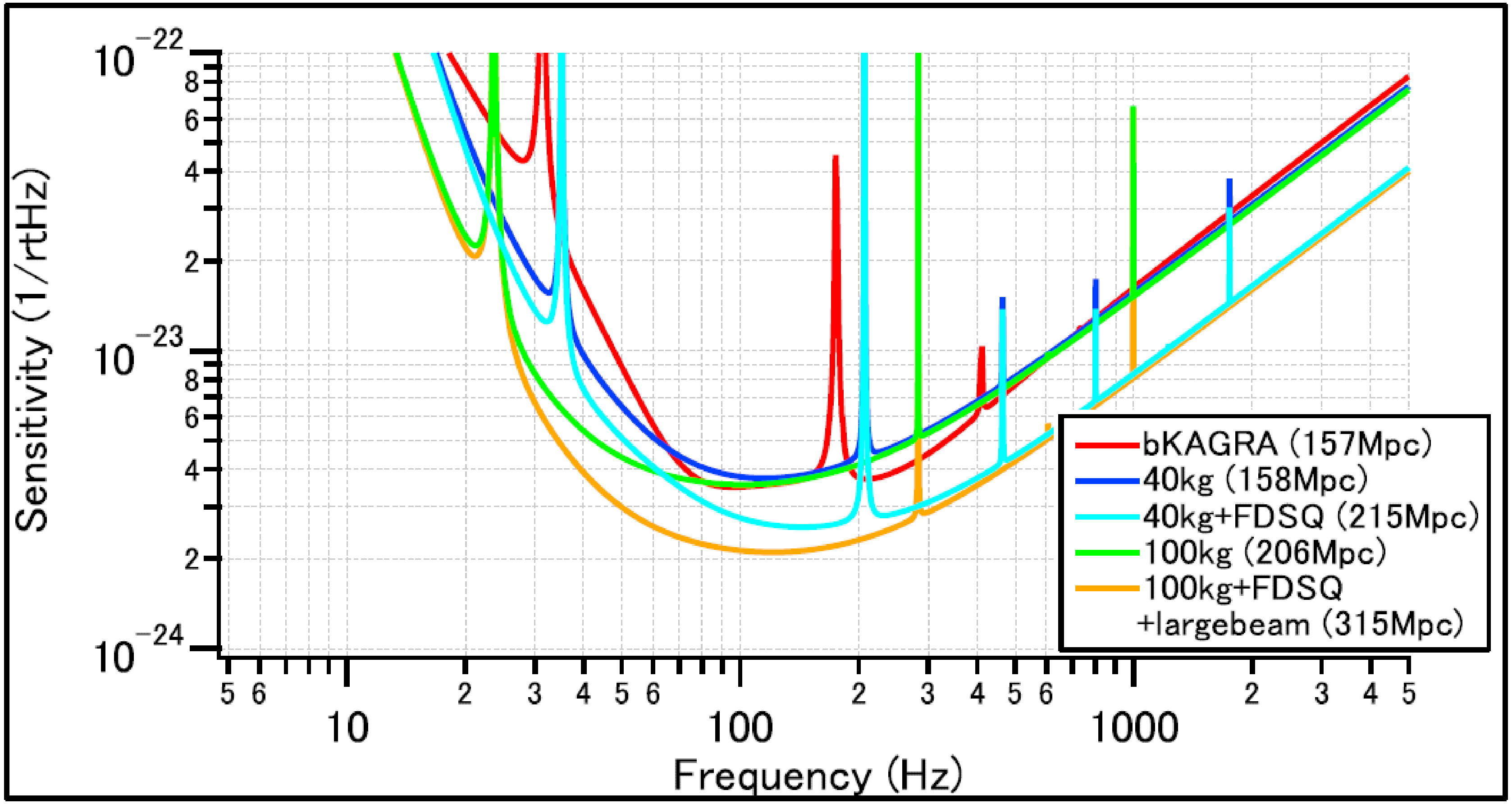
Heavy

- Production of big good sapphire bulk
- High cost of polishing
- Modification of cryo-payload/baffle
- Modification of Type-A suspension

HF (Red)

- Procurement of high power laser
- Modification of input optics
- Thermal lensing
- Parametric instabilities
- Implementation of squeezing

Sensitivity curves with heavier masses



Required items

$3M

$6M

$8M

$12M

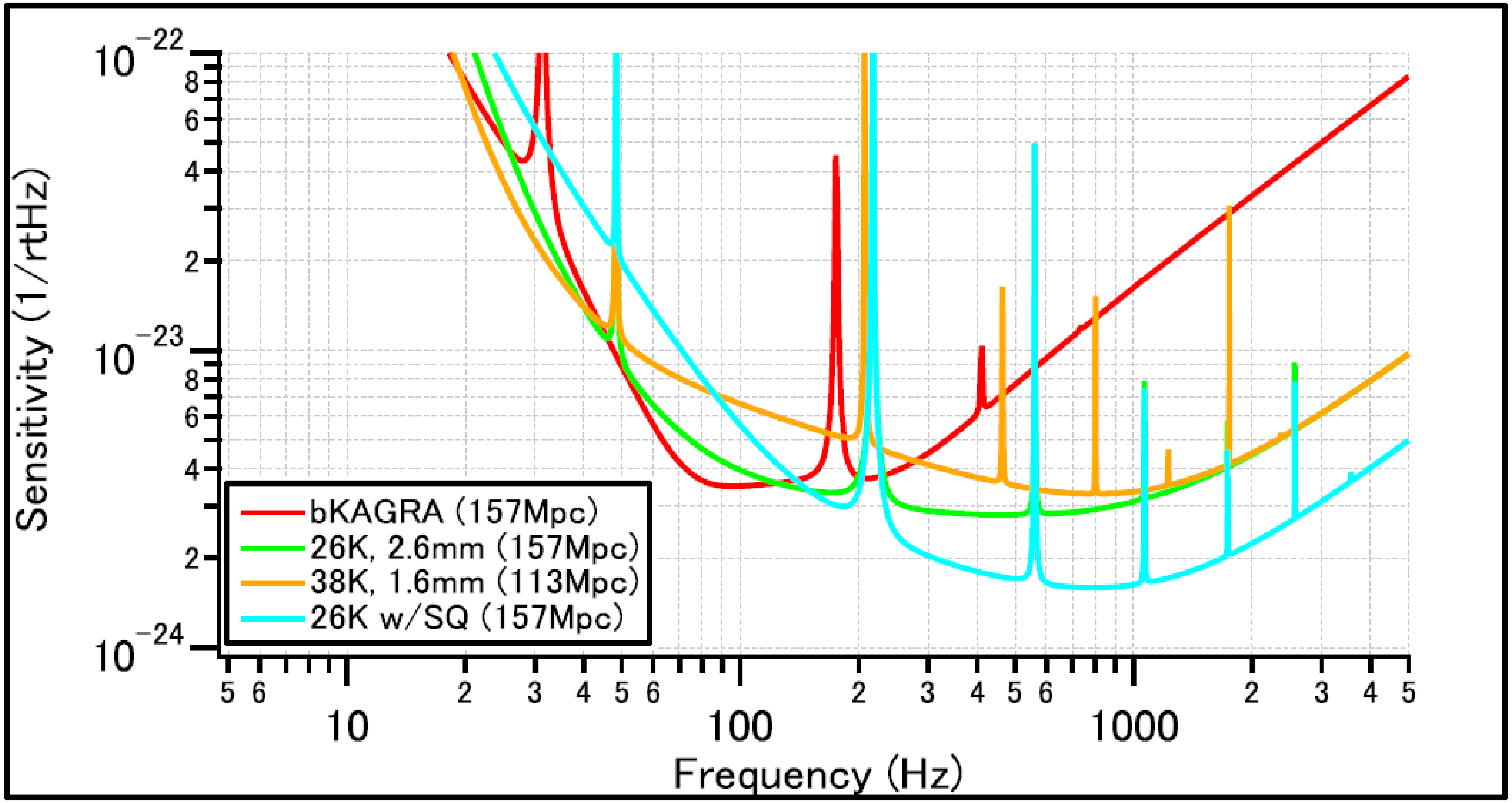
158Mpc: Mirror

215Mpc: Mirror + FDSQ

206Mpc: Mirror + Cryostat/payload + Type-A

315Mpc: Mirror + Cryostat/payload + Type-A + FDSQ + RMs

Sensitivity curves with high power



Required items

38K: 400W laser + IO (+ TCS) — $3M

26K: 400W laser + IO + Fiber (+ TCS) — $4M

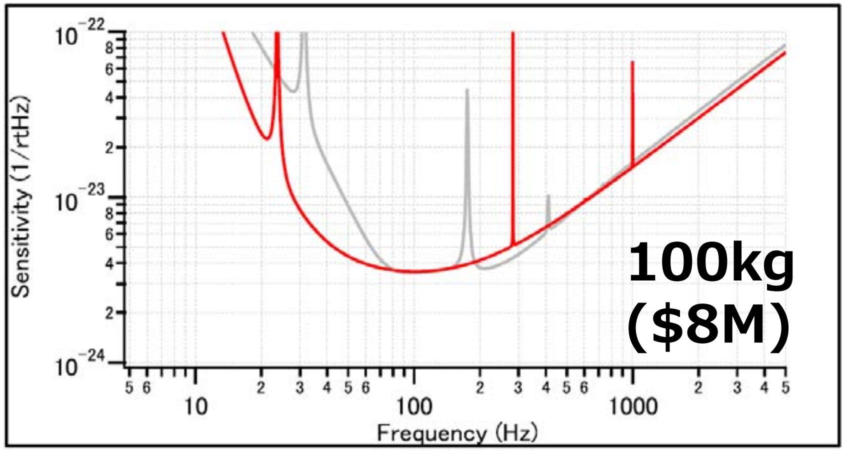
26K+SQ: 400W laser + IO + Fiber + SQ (+ TCS) — $5M

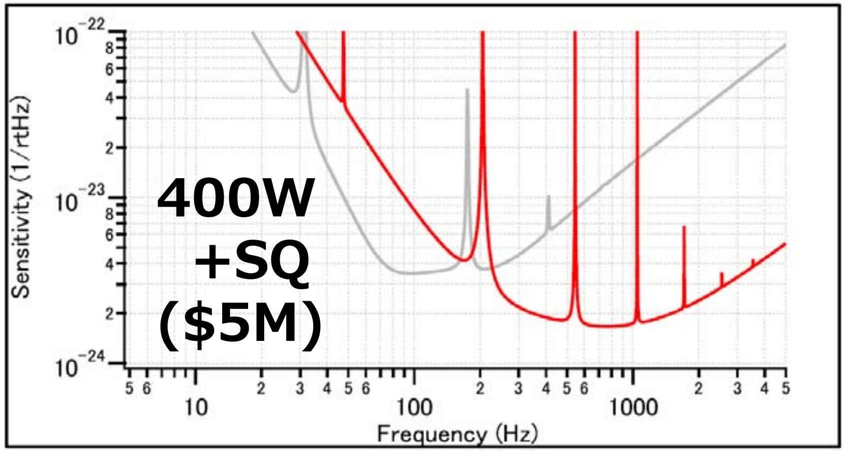
KAGRA+ possible chart

bKAGRA commissioning done

either or in 2022~24

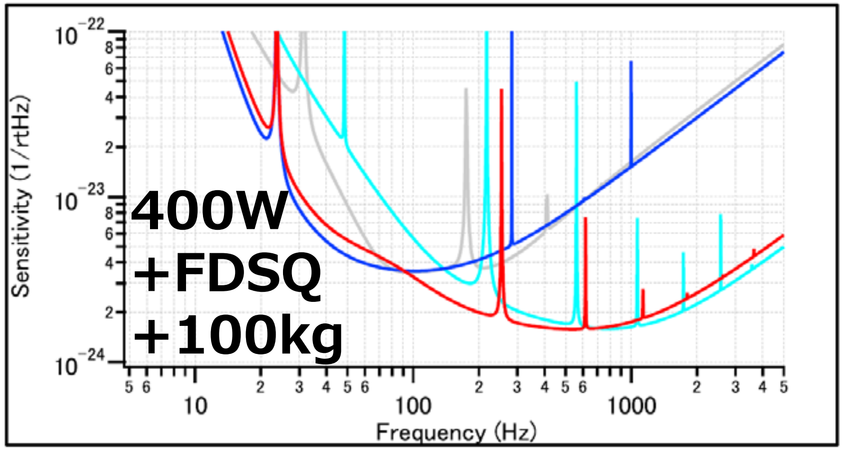
KAGRA+





KAGRA++?

combine them in ~2028? (293Mpc)



Additive vs Interruptive

item	Possible interruption	Misc.
New mirror	installation: 2 months commissioning: 3 months	4 mirrors
New suspension	installation: 6 months commissioning: 3 months	Type-A + CRYp
Squeezing	installation: 1 month commissioning: 2 months	Can be turned on/off
Filter cavity	installation: 2 months commissioning: 0 month	A 25m vacuum duct & 2 small chambers
High power laser	installation: 0~1 month commissioning: 2 months	Gradual increase

If we are to upgrade our detector,

Which one would you like for KAGRA+?

Heavy? or HF?

Required tasks of Heavy

1. Development of a big and good sapphire substrate
2. Accommodation of the big mirror in the cryostat
3. Durability of sapphire blades and suspensions
4. Accommodation of the heavy payload in Type-A
5. Cavity stability and LSC/ASC with a large beam
6. Development of squeeze injection
7. A proper design and robust control of a filter cavity
8. Output optics for squeezing

Required tasks of HF

1. Development of a 400W laser system
2. Thermal lensing calculation with 400W laser
   and development of thermal compensation system
3. Development of a damper for parametric instability
4. Development of squeezing injection
5. Balanced homodyne detection
6. Durability of the current input optics for high power
7. Output optics (OFI/OMC) for squeezing

High-power laser and PRG

Currently we have two 40W fiber lasers. Our solid-state amp turns out to be not easy to handle.

( + ) **x4**

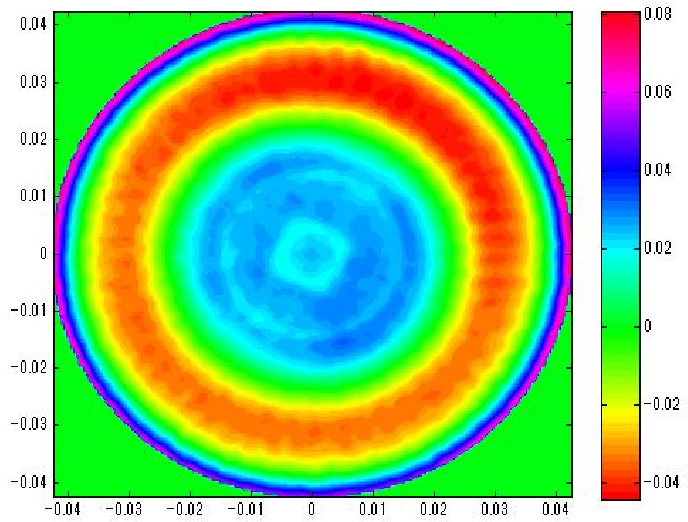
20W -> 100W

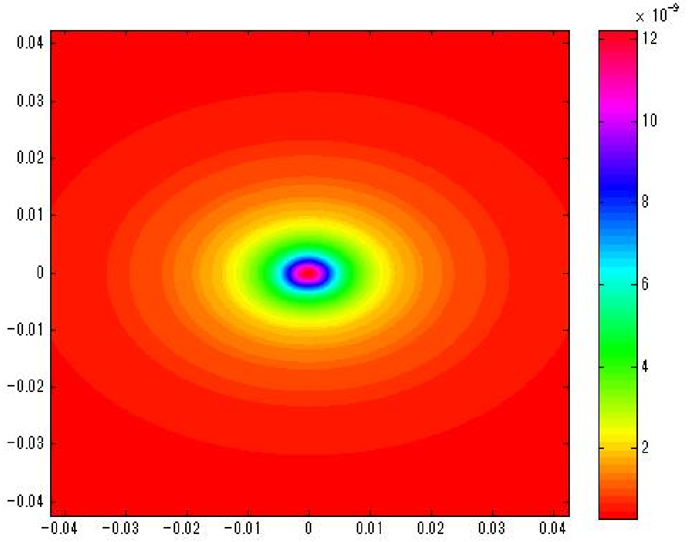
arm loss	contrast	PRM	PRG
45ppm	99.9%	90%	10
30ppm	99.9%	93%	15
25ppm	99.9%	94%	17

PRG could be as high as 17 if the arm loss turns out to be small.

400W LASER → **300W after MC** → **5kW at BS**

Thermal lensing calculation






```
l i1 83.74 0  nL                #I0=780W
const fmod 16.880962M       #f1
mod eo1 $fmod 0.0 2 pm 0 nL neo2
s eo1refl 0 neo2 neo22
bs refl 0.0001 0.9999 0 45 neo22 dump npr nREFL   #REFL
s bsm 0 npr nprb
m prm 0.90 0.10 0 nprb nf0
s Lp1 14.7615 nf0 nf1
bs PR2 1 0 0 0 nf1 nf2 dump dump # not tilted
s Lp2 11.0661 nf2 nf3
bs PR3 1 0 0 0 nf3 nf4 dump dump # not tilted
s Lp3 15.7638 nf4 n1

bs bs1 0.5 0.5 0 45 n1 n2 n3hr n4hr   #BS
s bs1bsAR1 0 n3hr n3hr2
m bsAR1 0 1 0 n3hr2 n3ar
s subBS1 0.0 1.754 n3ar n3ar2
m bsAR3 0 1 0 n3ar2 n3
s bs1bsAR2 0 n4hr n4hr2
m bsAR2 0 1 0 n4hr2 n4ar
s subBS2 0.0 1.754 n4ar n4ar2
m bsAR4 0 1 0 n4ar2 n4
```

Beam distortion due to thermal lensing can be calculated with modal model simulation software: *FINESSE.*

http://www.gwoptics.org/finesse/

A KAGRA code can be found here:

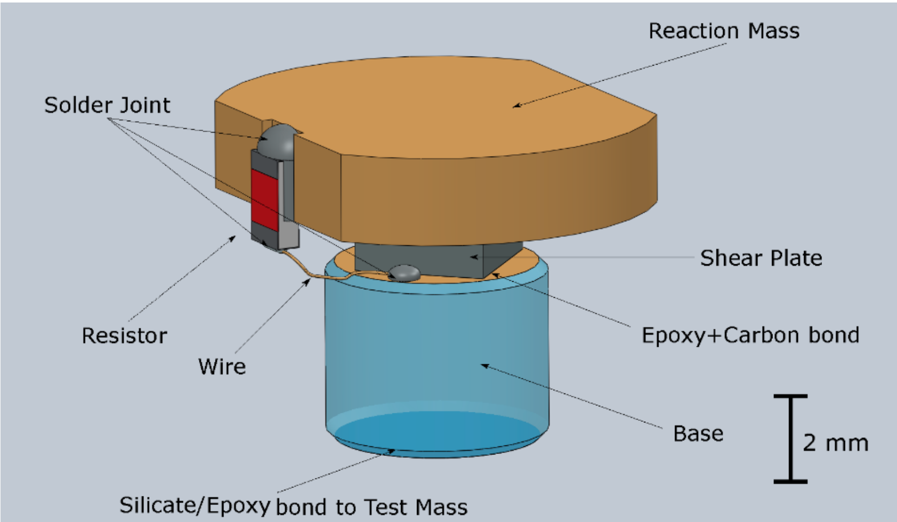
https://granite.phys.s.u-tokyo.ac.jp/svn/LCGT/trunk/mif/

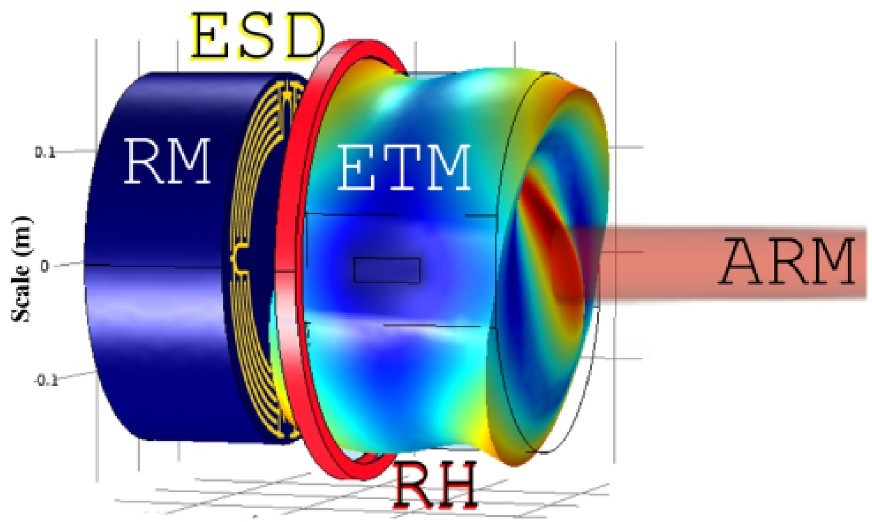
Parametric instability

[C.Blair, GWADW2018]

Detector	# instabilities	Rmax	Prefactor	Notes		
ALIGO	32	50	5.4	Mixture of simulation ℨ and measurement ϟ		
COSMIC Explorer	5	100	0.3	ℵ		
Voyager	70	~1000	6.4			
China/Aust 8km	0	<1	3	Possible to design in a parametric instability free window		
LCGT	2-4**	?		Number of unstable modes and max parametric gain significantly reduced by smaller beams and low mode density in sapphire **		
ET HF	?	?	3	Estimate 1.4 x R_{ALIGO} Based on use of LG33 beam ***		

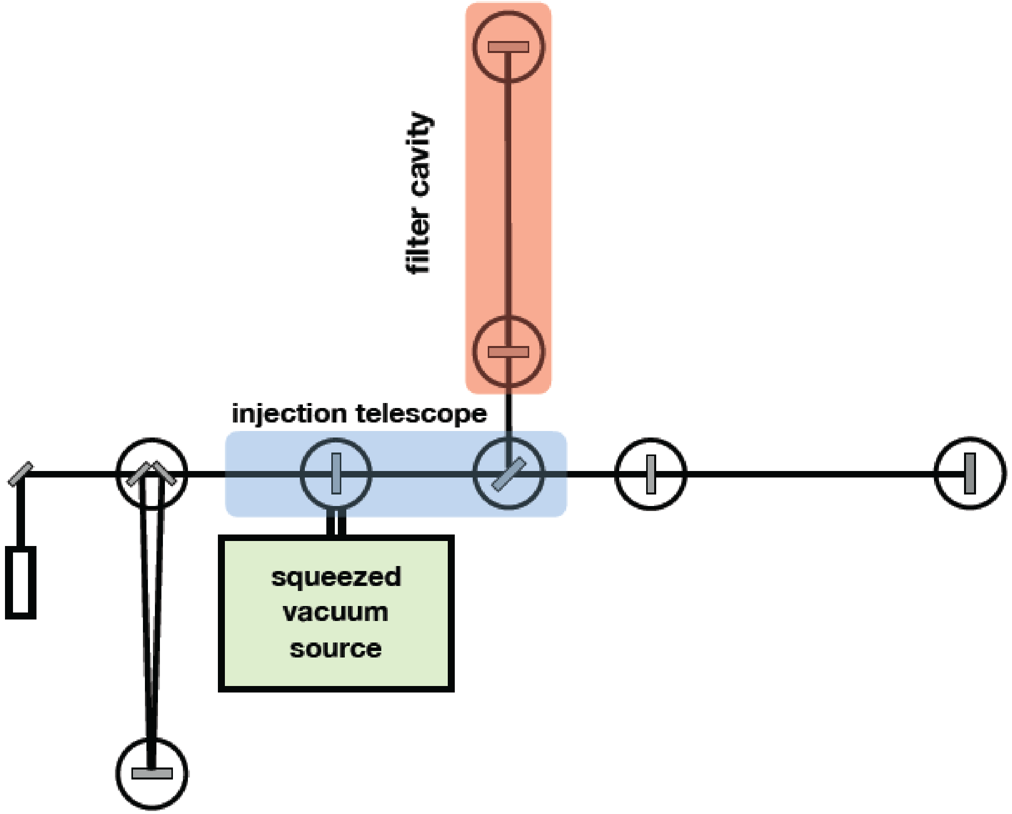
* Dwyer G1700843, ** Yamamoto, *** ET Design Study, ℵ Zhang G1800509 ℨ Evans PLA ϟ Blair PRL





Filter cavity

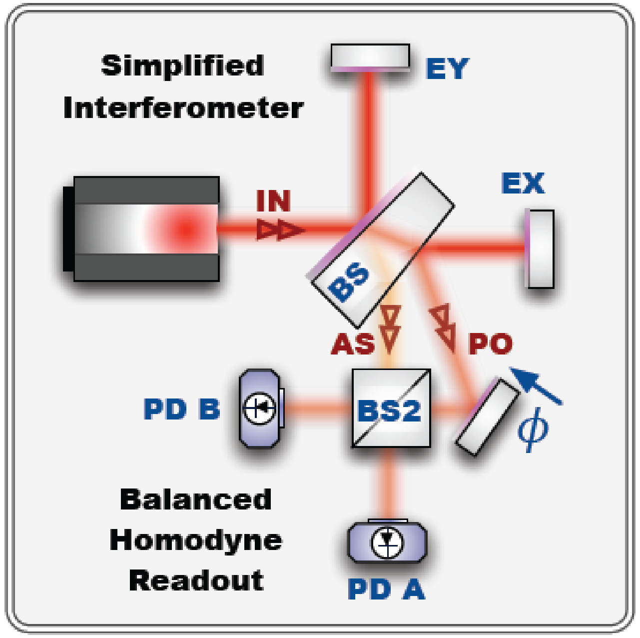
[Capocasa et al., GWADW2018]



- A 300-m Filter cavity experiment has been performed in TAMA 300
- Successful control of the cavity using 532nm beam
- Roundtrip loss was measured to be 45~85ppm, which is good for 4dB squeezing at LF

SQ and BHD

[R-K.Lee, F2F May 2018]



LIGO BHD

- R-K Lee just reported 10dB SQ in Taiwan
- BHD is said to be better than DC readout to remove offsets

Discussion points

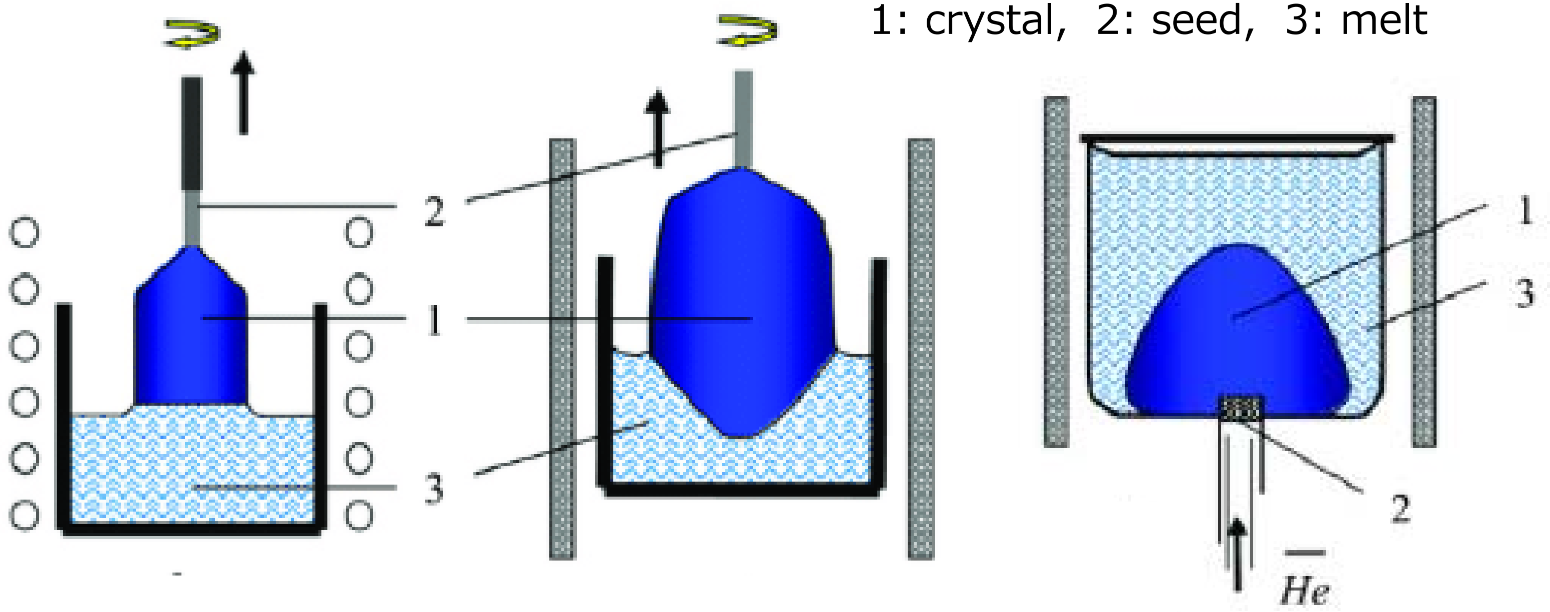
1. How can we reach an agreement to start KAGRA+ study in the August F2F meeting?

2. How many of you would be interested in working on one of the important tasks for KAGRA+?

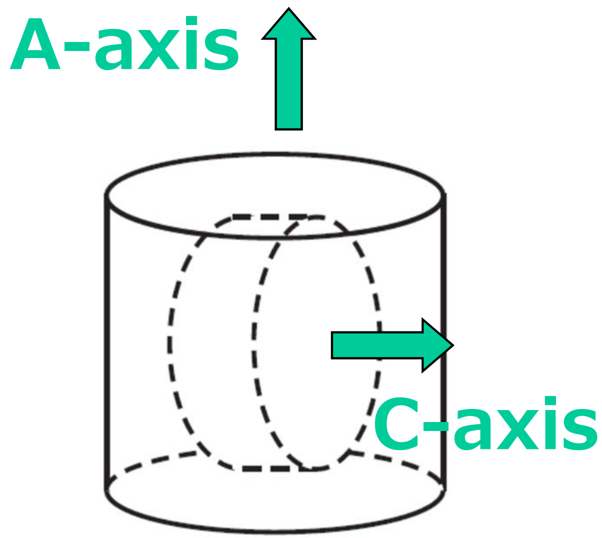
3. Any other crazy ideas for 2.5G?

Supplementary slides

Heavier Sapphire for KAGRA+?

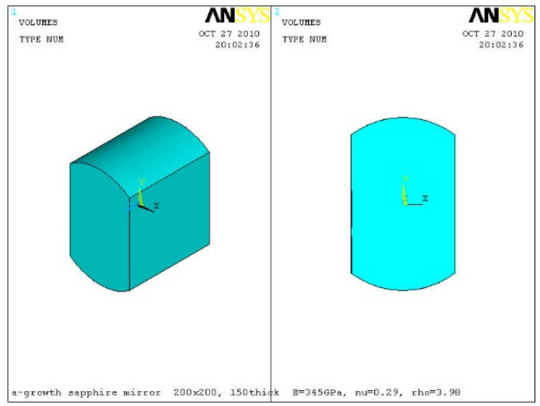


Czochralski Kyropoulous HEM



	crystal size	crystal axis	quality
Czochralski	medium	can be c-axis	bad
Kyropoulous	big	usually a-axis	good
HEM	very big	usually a-axis	bubbles

Reference: Kawaminami et al., J. of the Cer. Soc. of Japan 122, 695 (2014)



Kamaboko mirror
(40kg)

Heavier Sapphire for KAGRA+?

[Kawaminami et al., J. of the Cer. Soc. of Japan 122, 695 (2014)]

- A Japanese company has developed TSMG (Top Seeded Melt Growth) method which can produce big, c-axis, good sapphire crystals.
- KAGRA's ITMs were produced with this TSMG method.
- Eiichi is to establish a new collaborative project to produce high quality larger crystals with this company, aiming at 100kg crystal(ϕ400mm x t200mm).

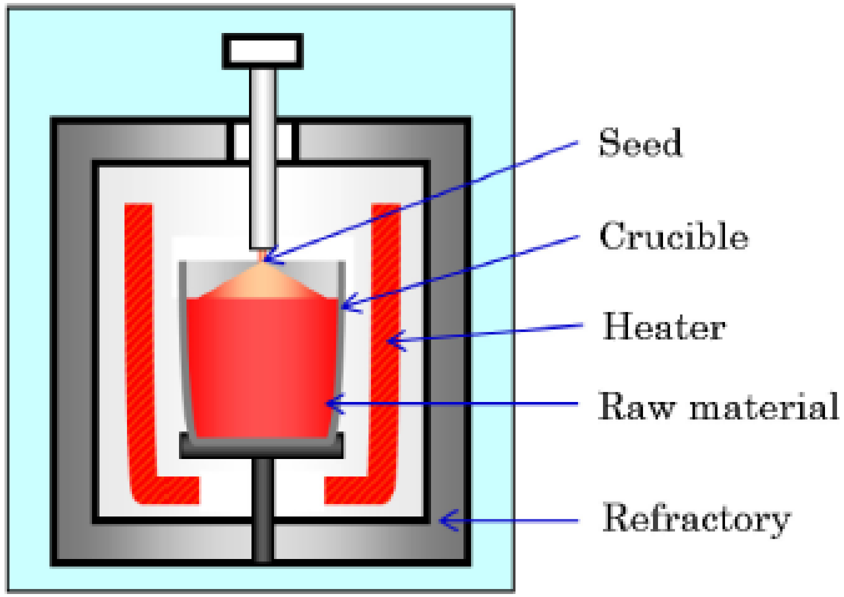
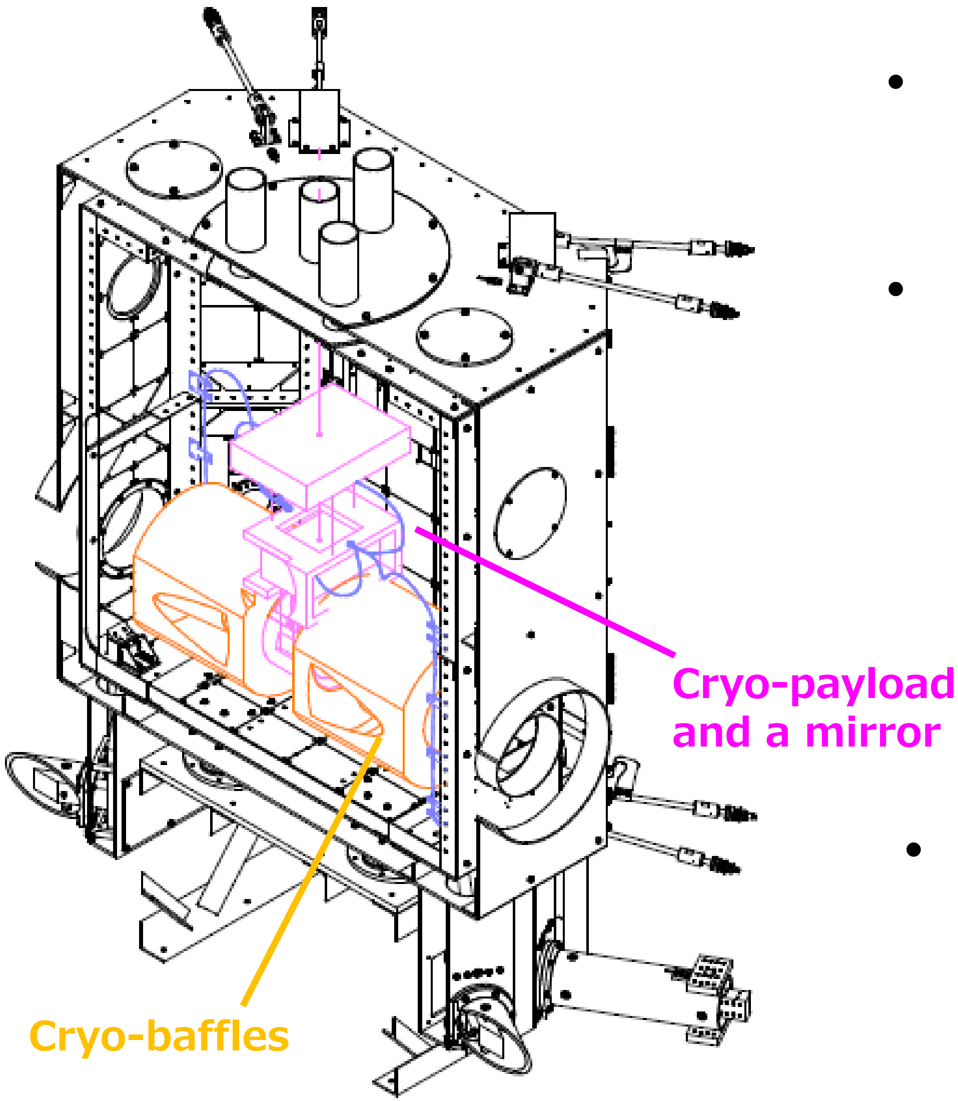


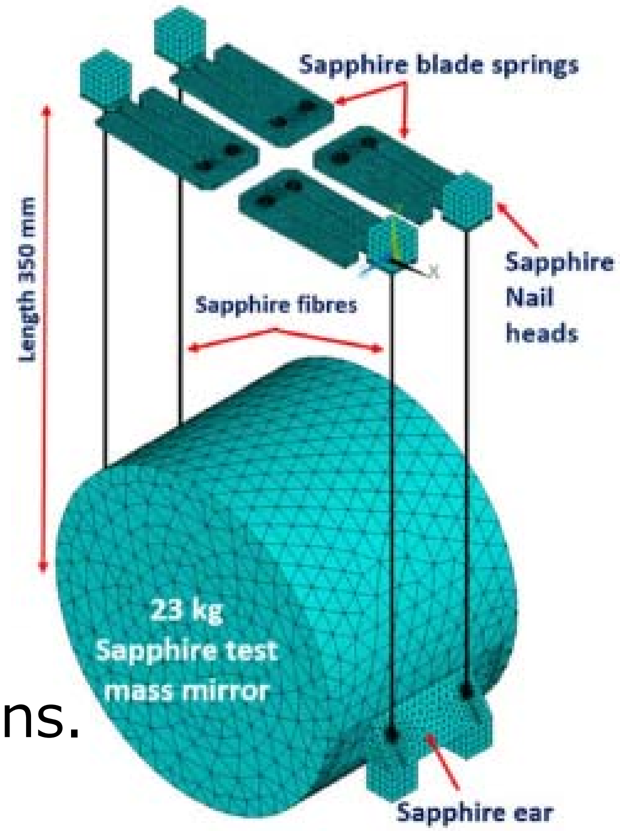
Fig. 1. Schematic illustration of the TSMG method.

- **Having both advantages of CZ and KY**
- **Small rotation over short pulling distance**
- **Arbitrarty direction of growth**
- **Oxygen vacancies (UV absorption)**

Additional issues to be solved

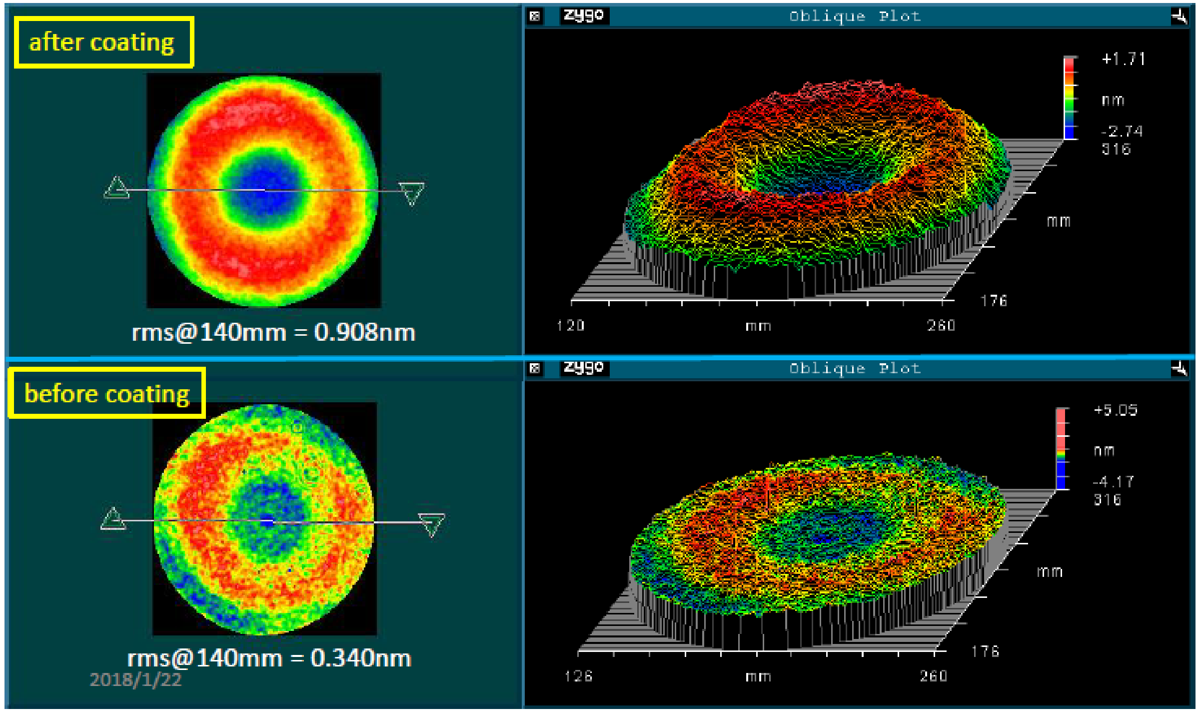


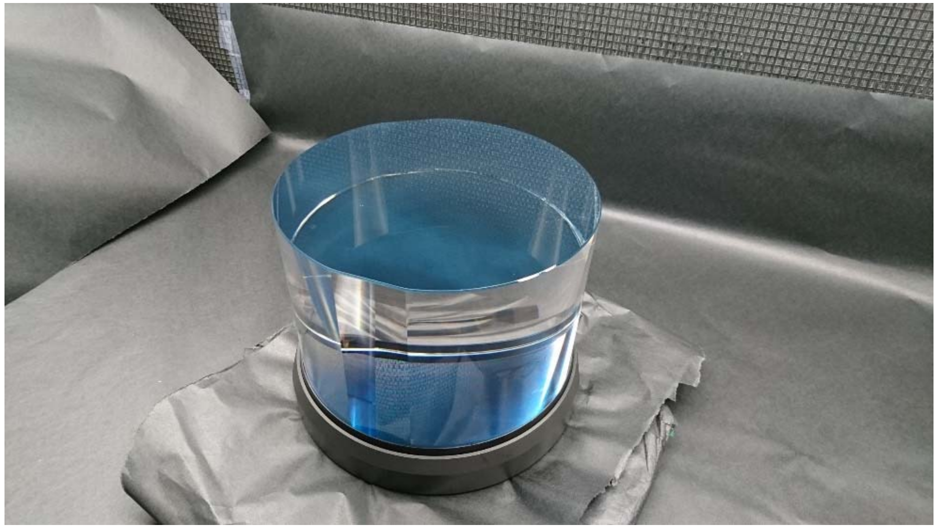
- A cryostat is quite full with the current ϕ220 x t150 crystal and cryo-baffles.
- Kazuhiro Yamamoto says x1.2 may be ok but x1.5 larger mass would be hard. (23kg x 1.2^3 = 40kg)



- Load capacity of the blade and bondings are also an issue.
- Type-A suspension may need modifications.

Cost of sapphire mirrors





- crystal: ~$100k per piece
- polish: ~$400k per piece
- coating: ~$100k per piece

Most of the budget for the upgrade would be spent for the mirrors.

Heat extraction with thick fibers

Removable heat is given as

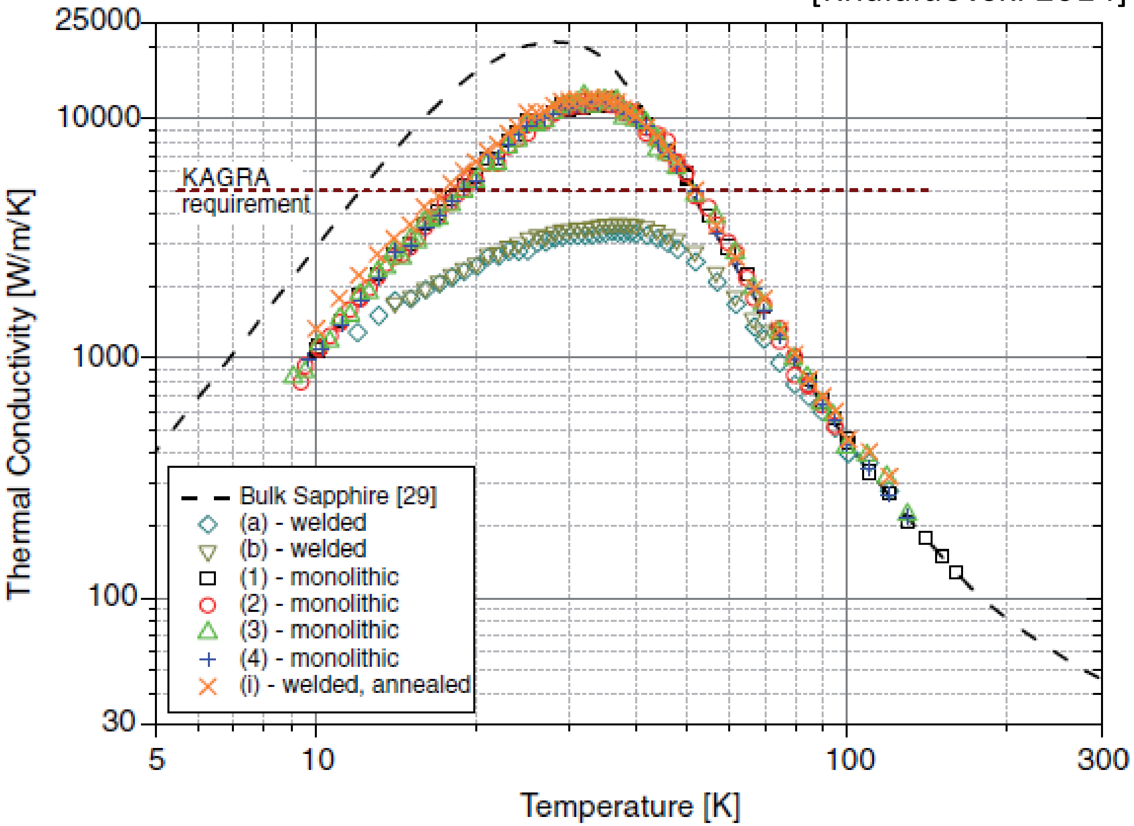
$$K_{abs} = \int_{T_1}^{T_2} \frac{\pi d^2 \kappa(T)}{l_{sus}} dT$$

where T_1 (IM) is 16K.

Sapphire thermal conductivity is approximated to be

$$\kappa = 5270\, d \times T^{2.24}$$ **(W/m/K)**

[Khalaidovski 2014]



T=22K	d=1.6mm	d=2.4mm
l=35cm	0.86W	2.9W
l=20cm	1.5W	5.1W

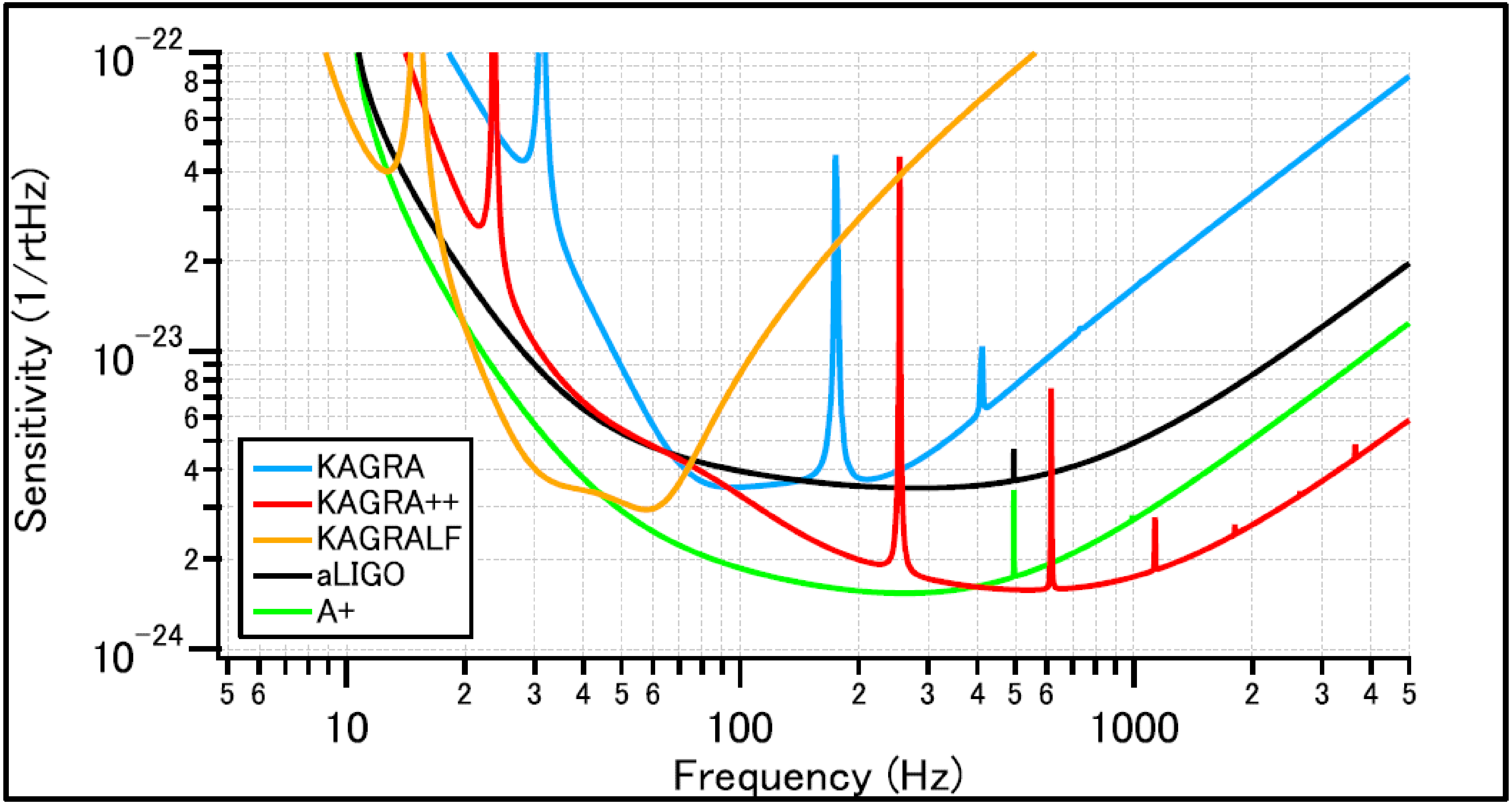
T=24K	d=1.6mm	d=2.4mm
l=35cm	1.3W	4.4W
l=20cm	2.3W	7.7W

T=25.9K	d=2.6mm
l=35cm	7.7W

T=38.5K	d=1.6mm
l=35cm	7.7W

x10 power is capable.

KAGRA-LF with 100kg mirrors



The 4th KAGRA International Workshop @ Ewha Women's University June 30, 2018

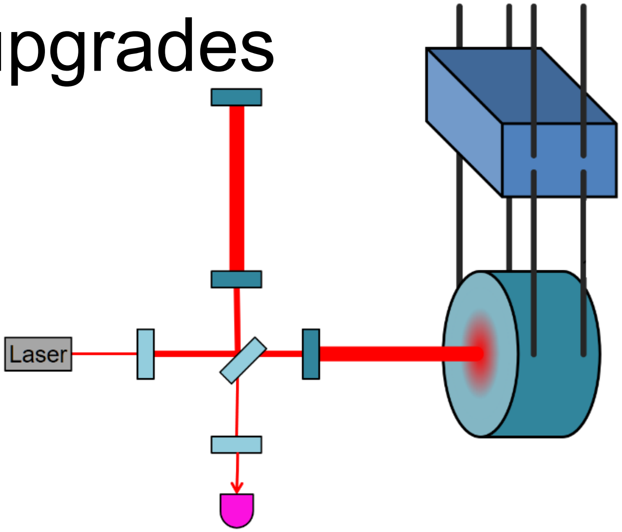
Optimization of the KAGRA sensitivity

Yuta Michimura
Department of Physics, University of Tokyo

Kentaro Komori, Atsushi Nishizawa, Hiroki Takeda,
Koji Nagano, Yutaro Enomoto, Kazuhiro Hayama,
Kentaro Somiya, Masaki Ando, Sadakazu Haino

KAGRA+ with Budget Constraints

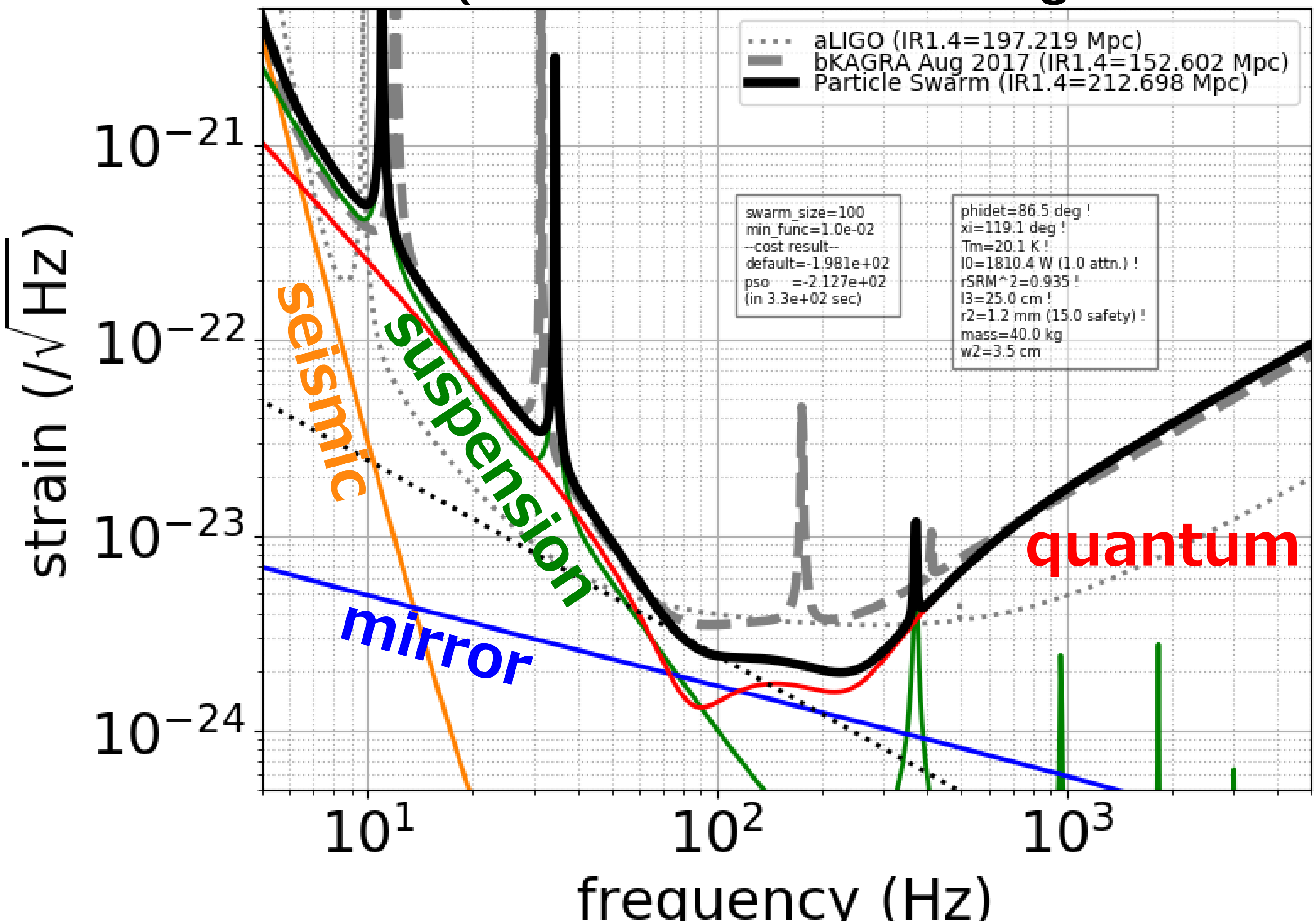
- Let's consider a bit more drastic upgrades
- Suppose you have
  $5M for KAGRA+



- 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?)

Plan A: 40 kg Mirror

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

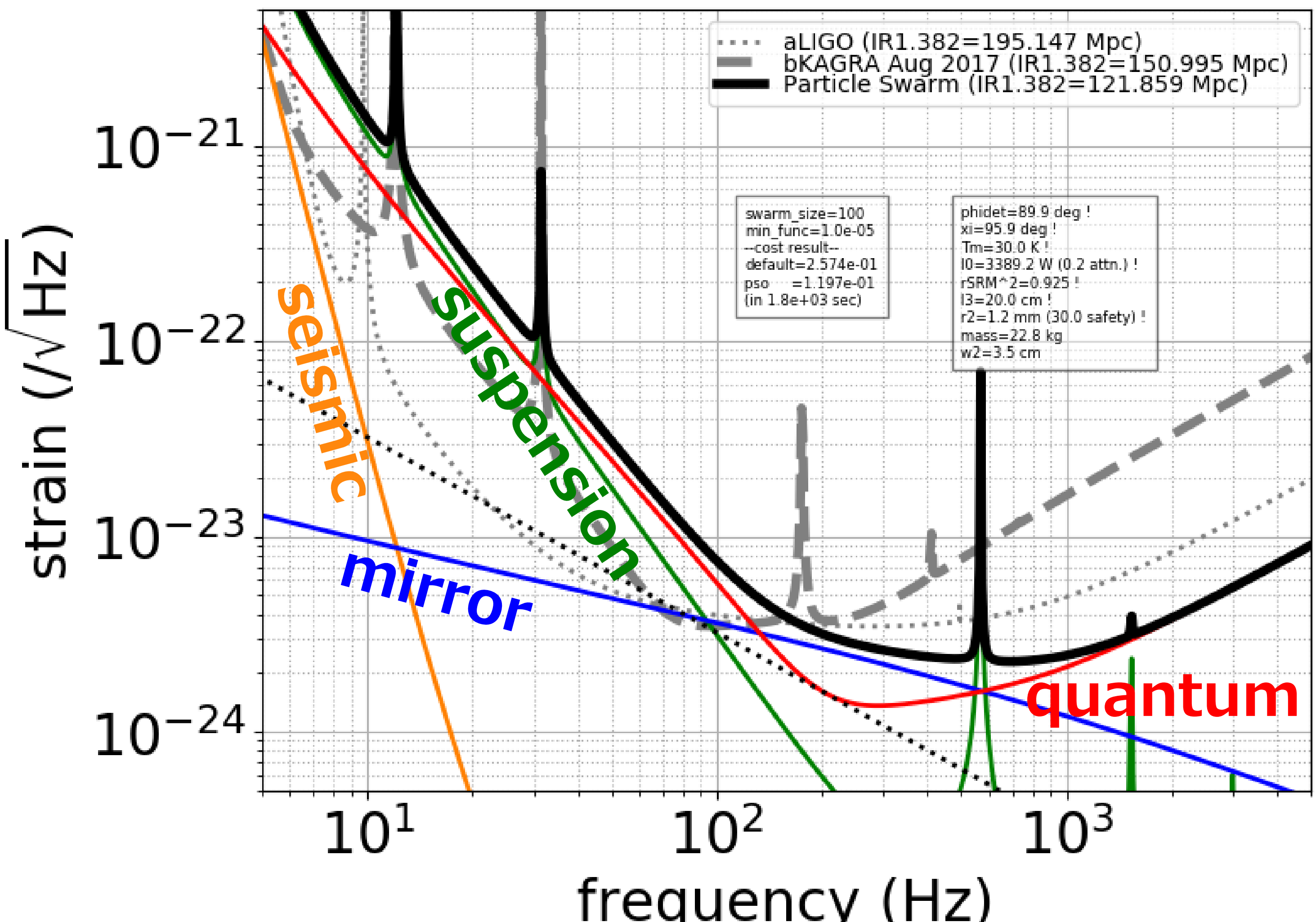


Good for mid frequency improvement → BNS range optimized

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

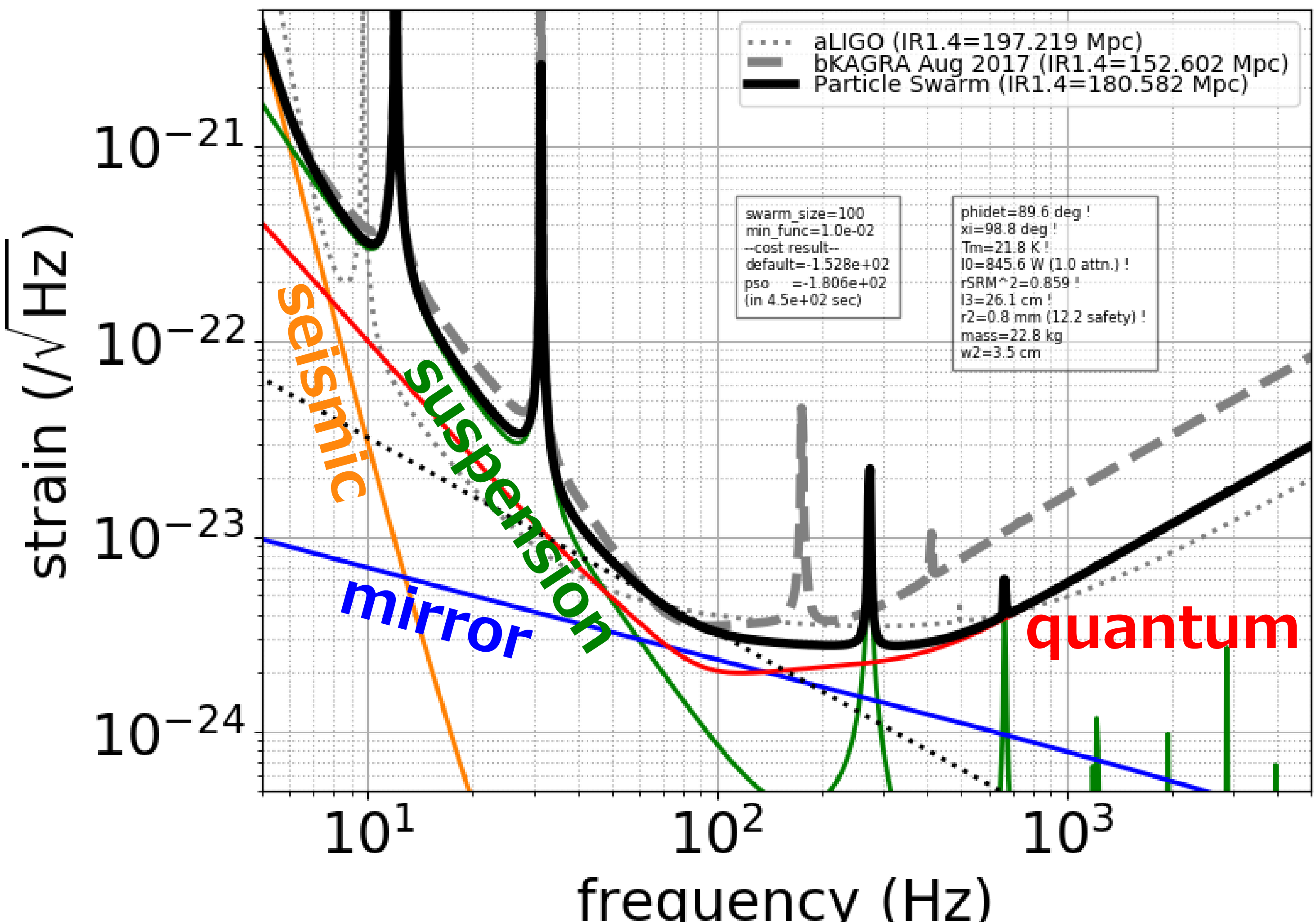


Good for high frequency improvement → BNS range optimized

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)

Summary of $5M Plans

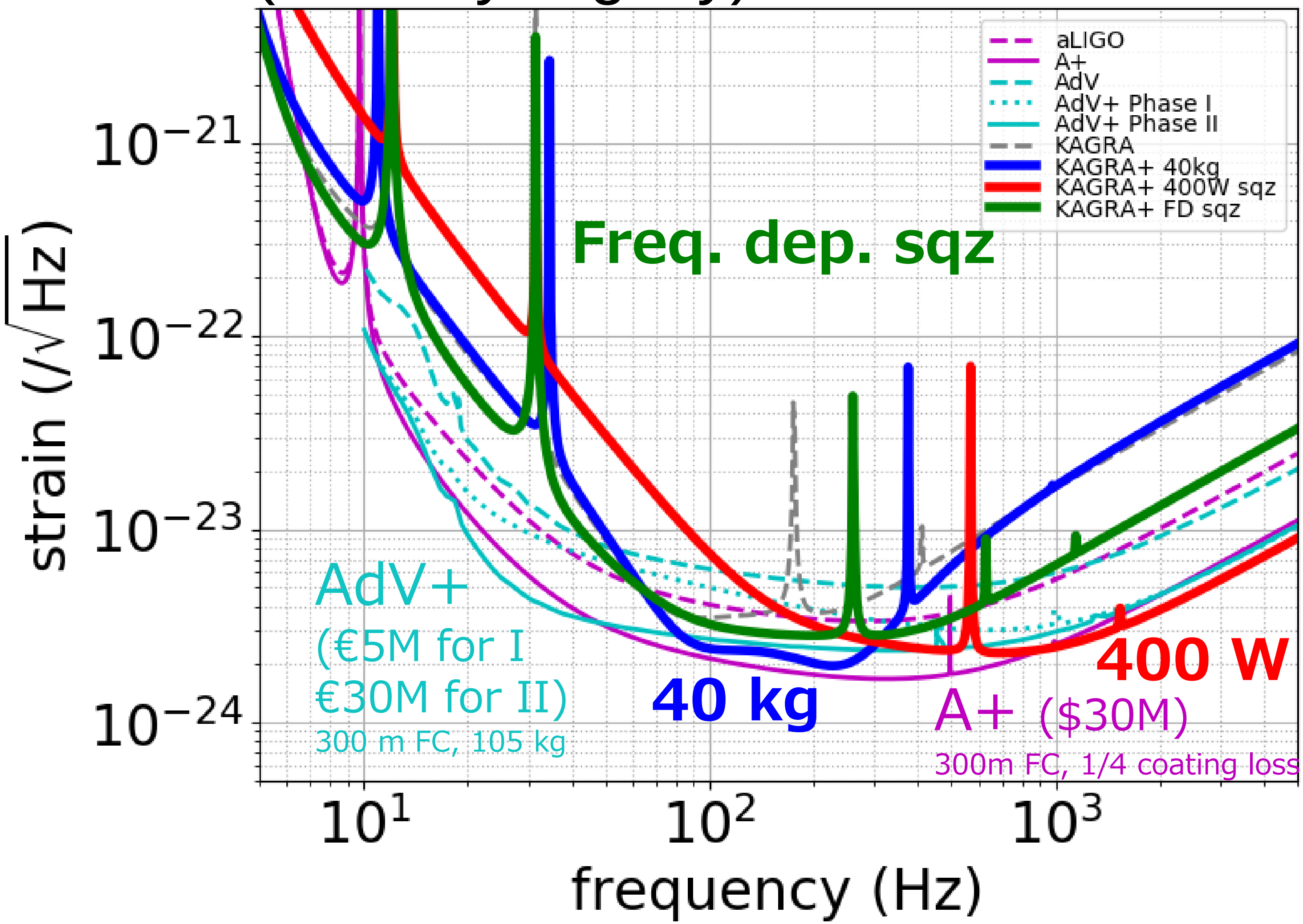
- A. New mirror takes time to fabricate
- B. High power operation is tough
- C. Does it fit in the facility?

	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

- I like A because of simplicity, but if fabrication of heavier mirrors cannot be done on time, go for C?

Comparison Between 2G and 2G+

- Only Plan B (400W laser with squeezing) can beat A+ (but only slightly)



aLIGO curve from LIGO-T1800044 (updated ver)

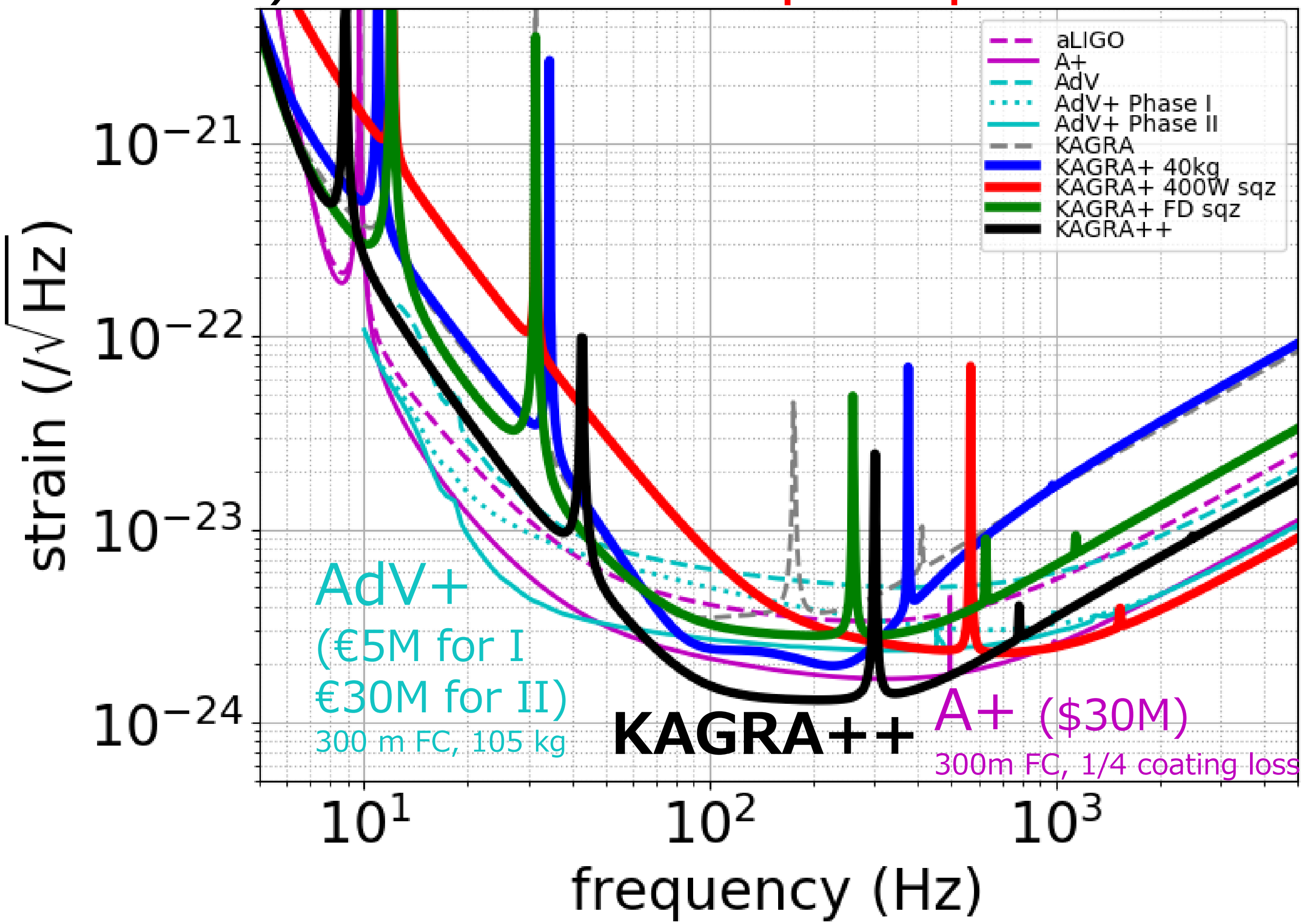
A+ curve from LIGO-T1800042

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

KAGRA curve from JGW-T1707038

Be Optimistic, Combine Them!

- 100 kg mirror with1/4 coating loss (and larger beam size), 320 W, 10dB input sqz with 100 m filter cavity



355 Mpc

~ 10 yrs ?

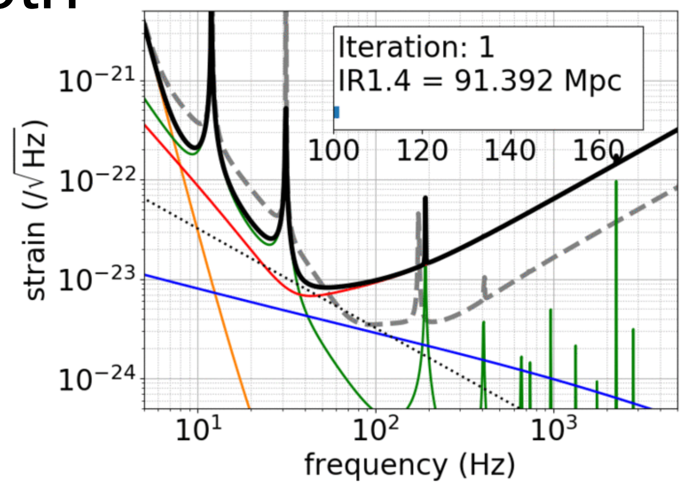
~$20M ?

Summary

- Demonstrated sensitivity design with PSO
- Application to KAGRA shows both
  - BNS inspiral range
  - BNS sky localization

  can be improved by retuning 7 parameters of existing components

  YM+, Phys. Rev. D 97, 122003 (2018)



- Also applied to KAGRA+ study and showed optimized sensitivity for 3 candidates

  Sensitivity data available at JGW-G1808426