4M-COCOS @ Fukuoka University
October 23, 2019

Present status and future prospects of KAGRA gravitational wave telescope

Yuta Michimura
Department of Physics, University of Tokyo

for the KAGRA Collaboration

Plan of This Talk

- Status of gravitational wave observations
  - Global network of detectors
  - Interferometric detectors
  - Noise sources and inspiral range
  - Observing scenario of LIGO, Virgo and KAGRA

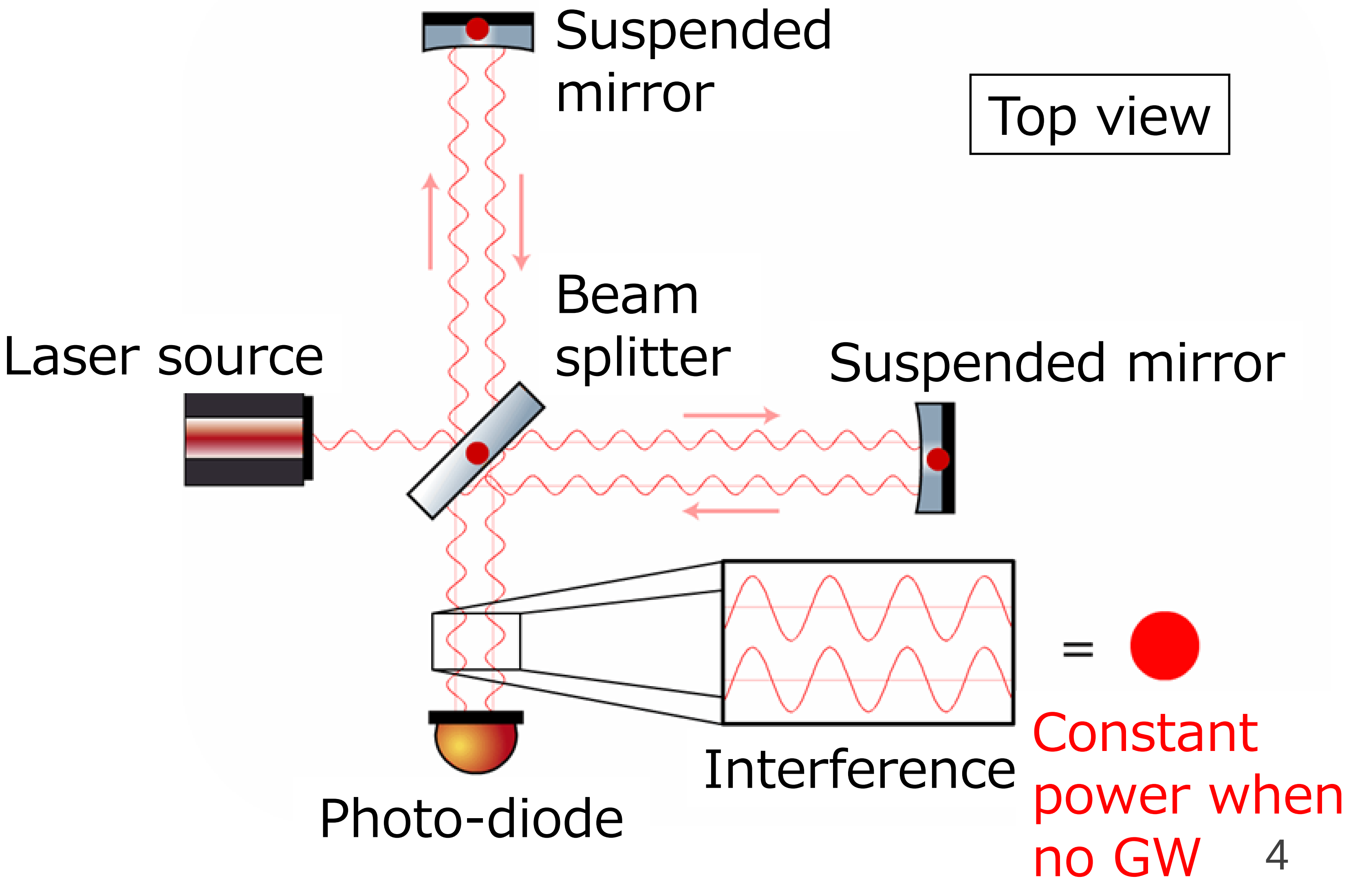
- Status and future of KAGRA
  - Introduction to KAGRA project
  - Impact of KAGRA joining observing runs
  - Status of KAGRA commissioning
  - Upgrade plans for KAGRA

Global Network of GW Detectors

- Network of ground-based Advanced interferometric gravitational wave detectors

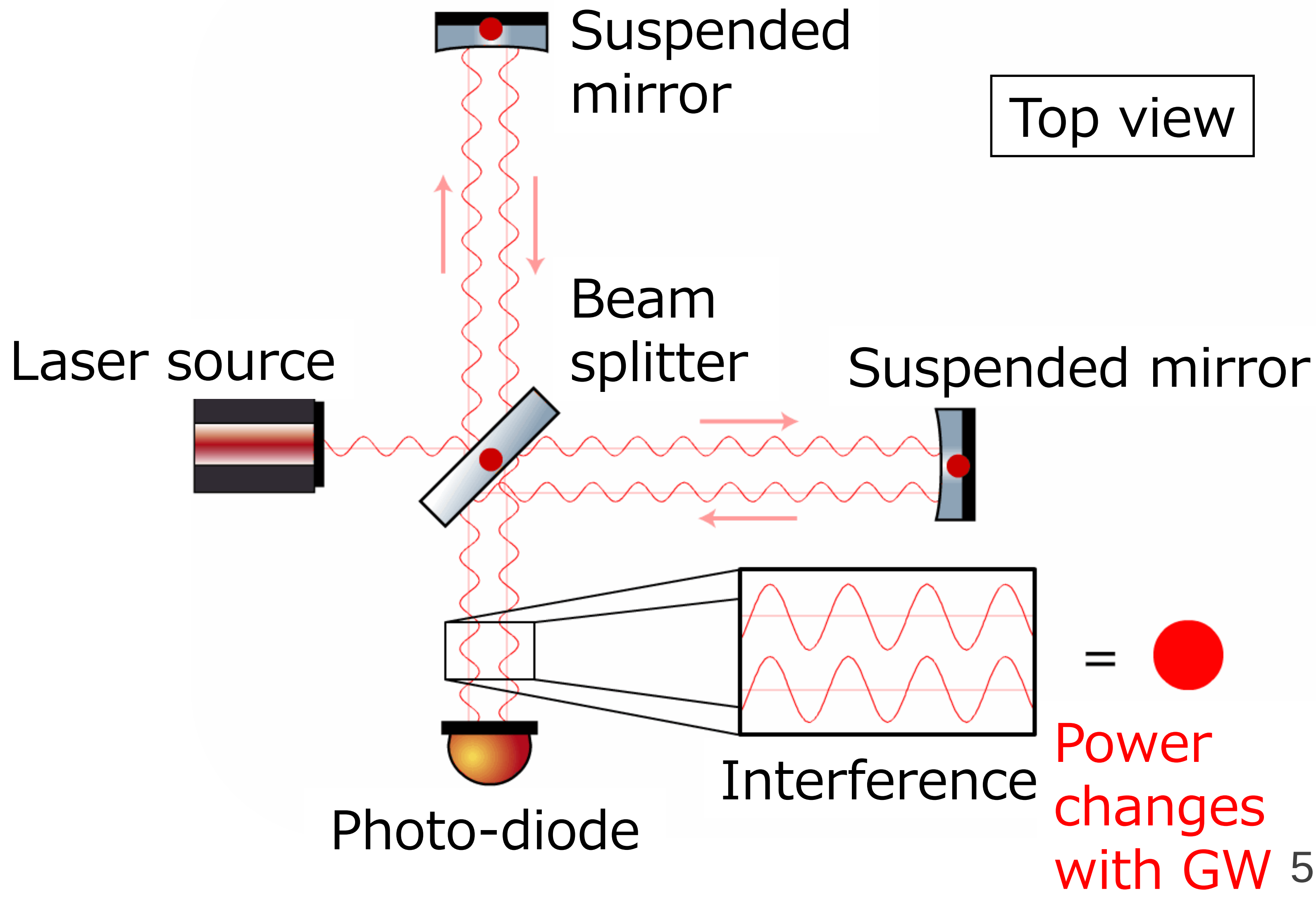
Laser Interferometric GW Detector

- measure differential arm length change



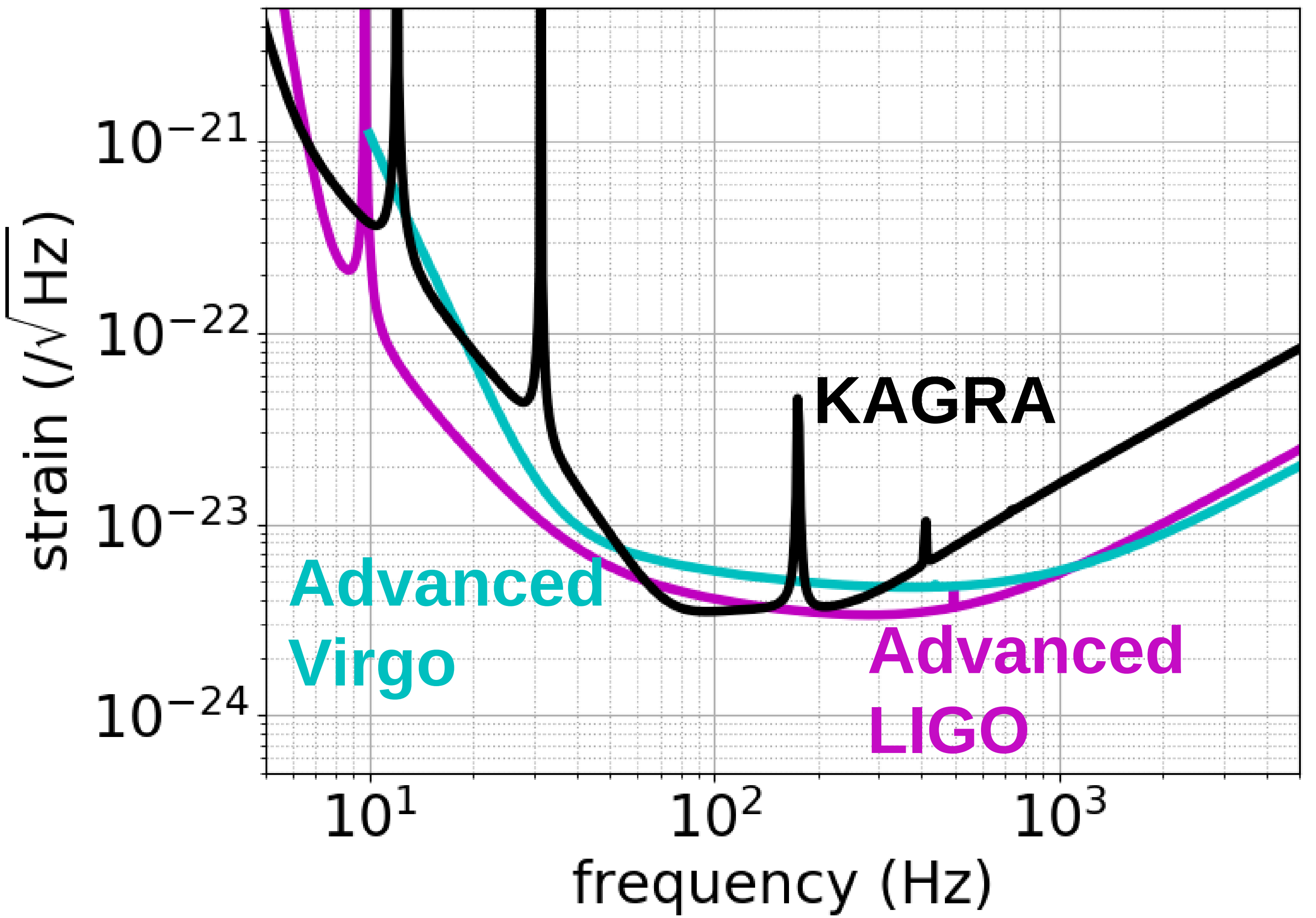
Laser Interferometric GW Detector

- measure differential arm length change



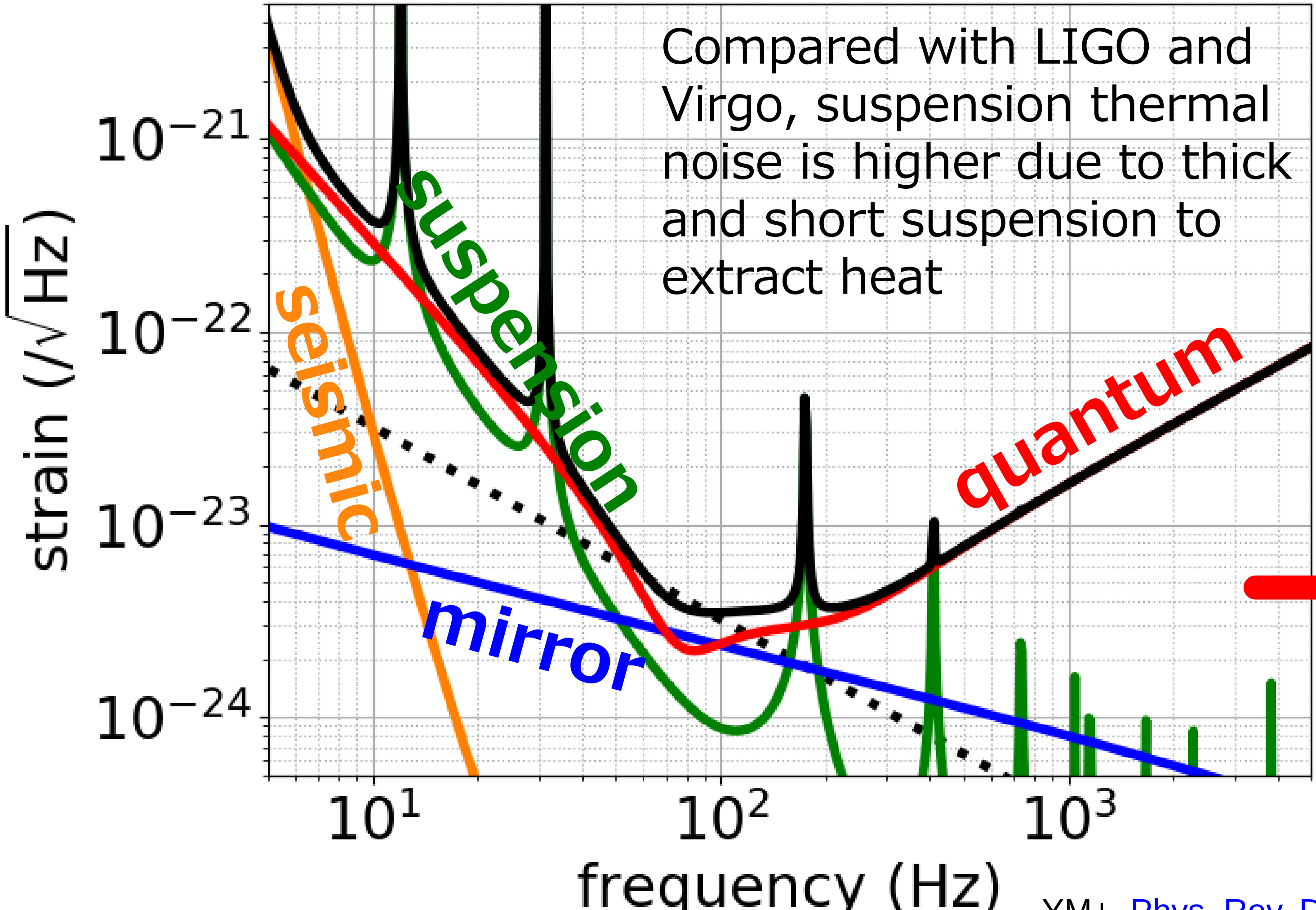
Designed Sensitivity

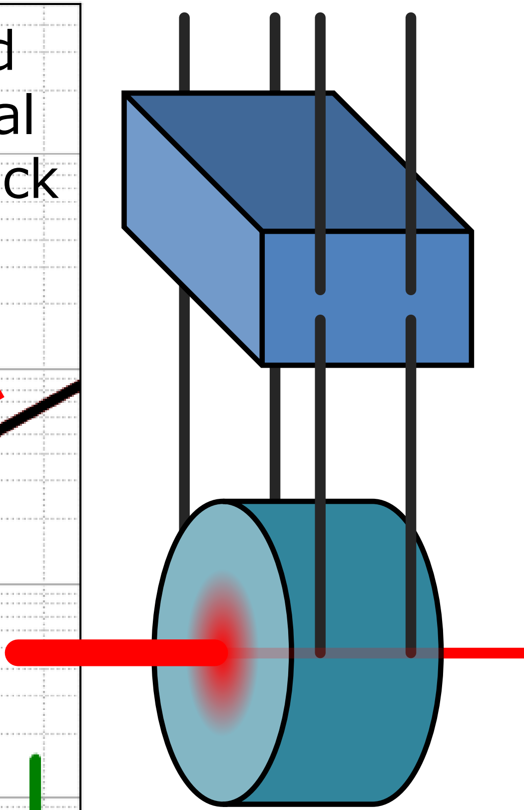
- aLIGO, AdV and KAGRA has similar designed sensitivity



Noise Sources

- Sensitivity is limited by seismic noise, suspension and mirror thermal noise, and quantum noise

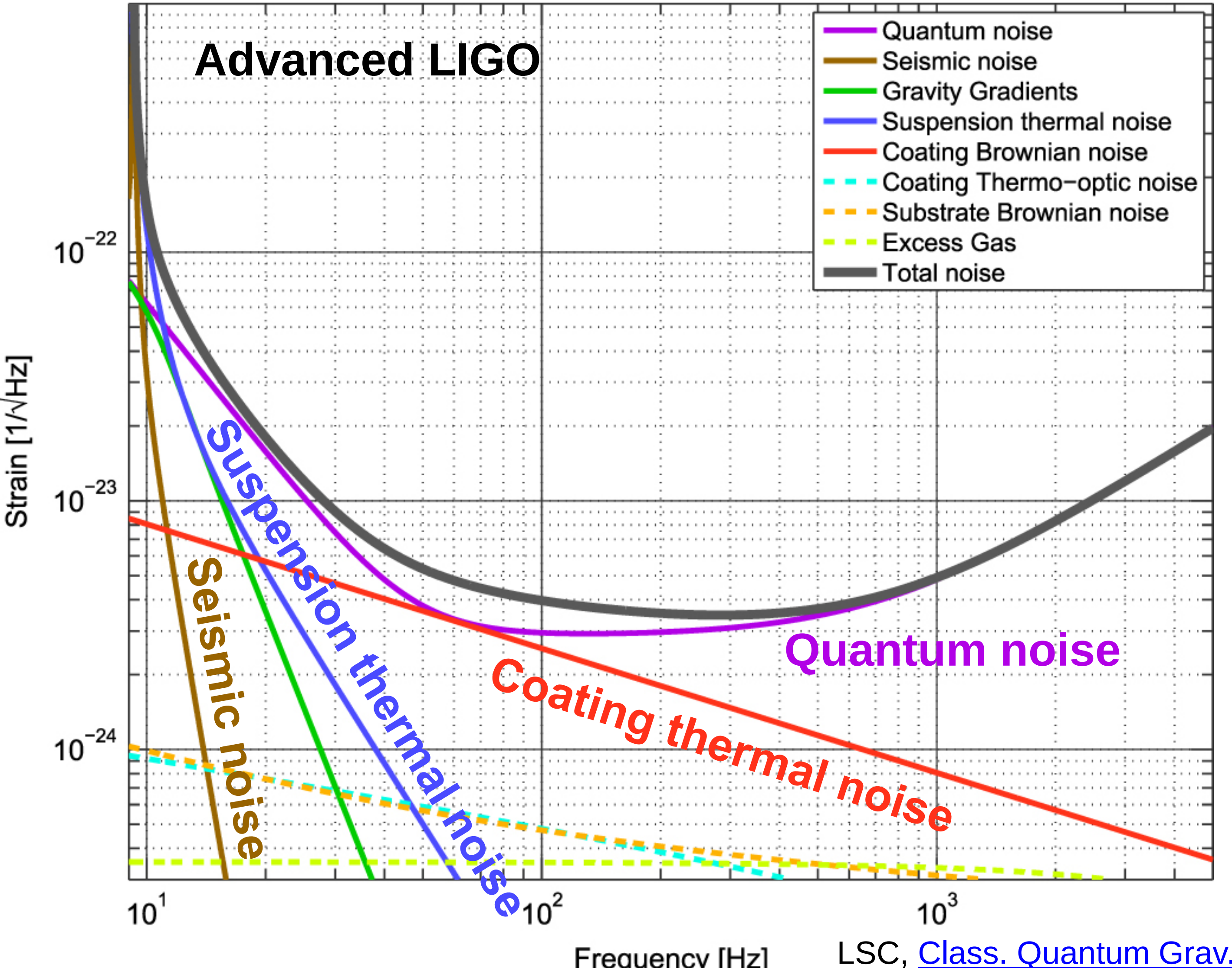




YM+, Phys. Rev. D 97, 122003 (2018)

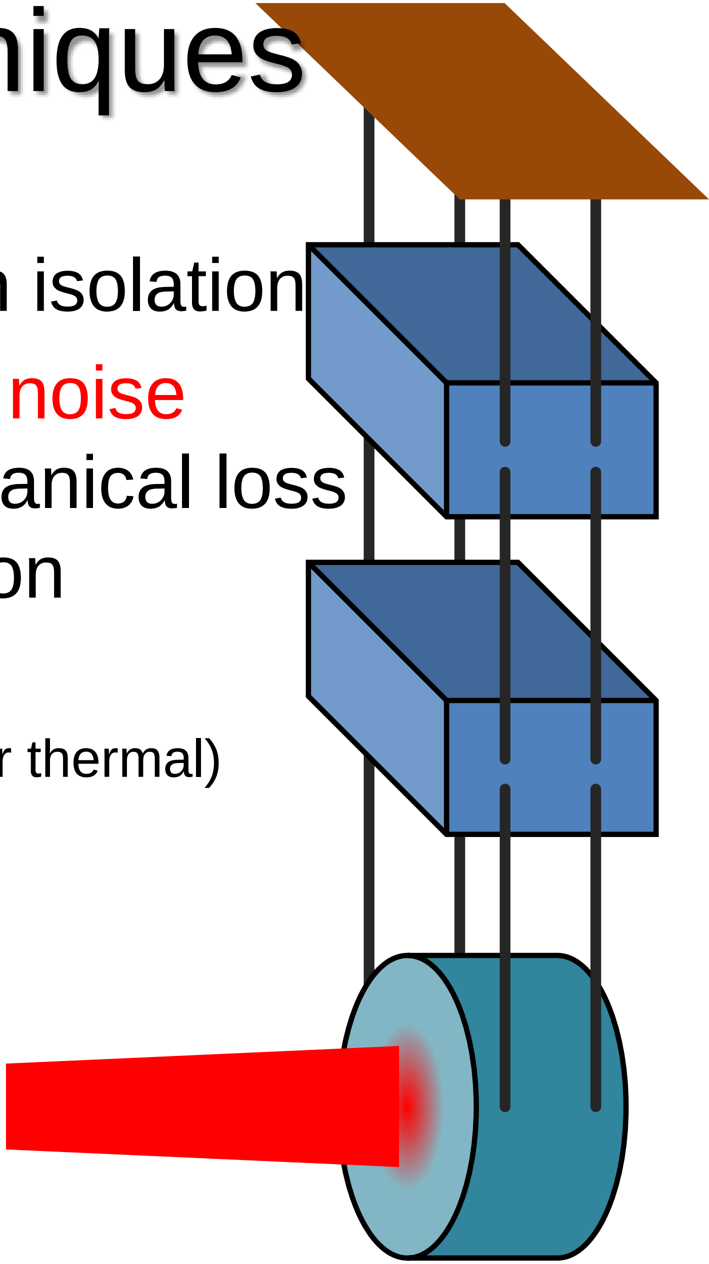
Noise Sources

- Similar for aLIGO designed sensitivity



LSC, Class. Quantum Grav. 32, 074001 (2015)

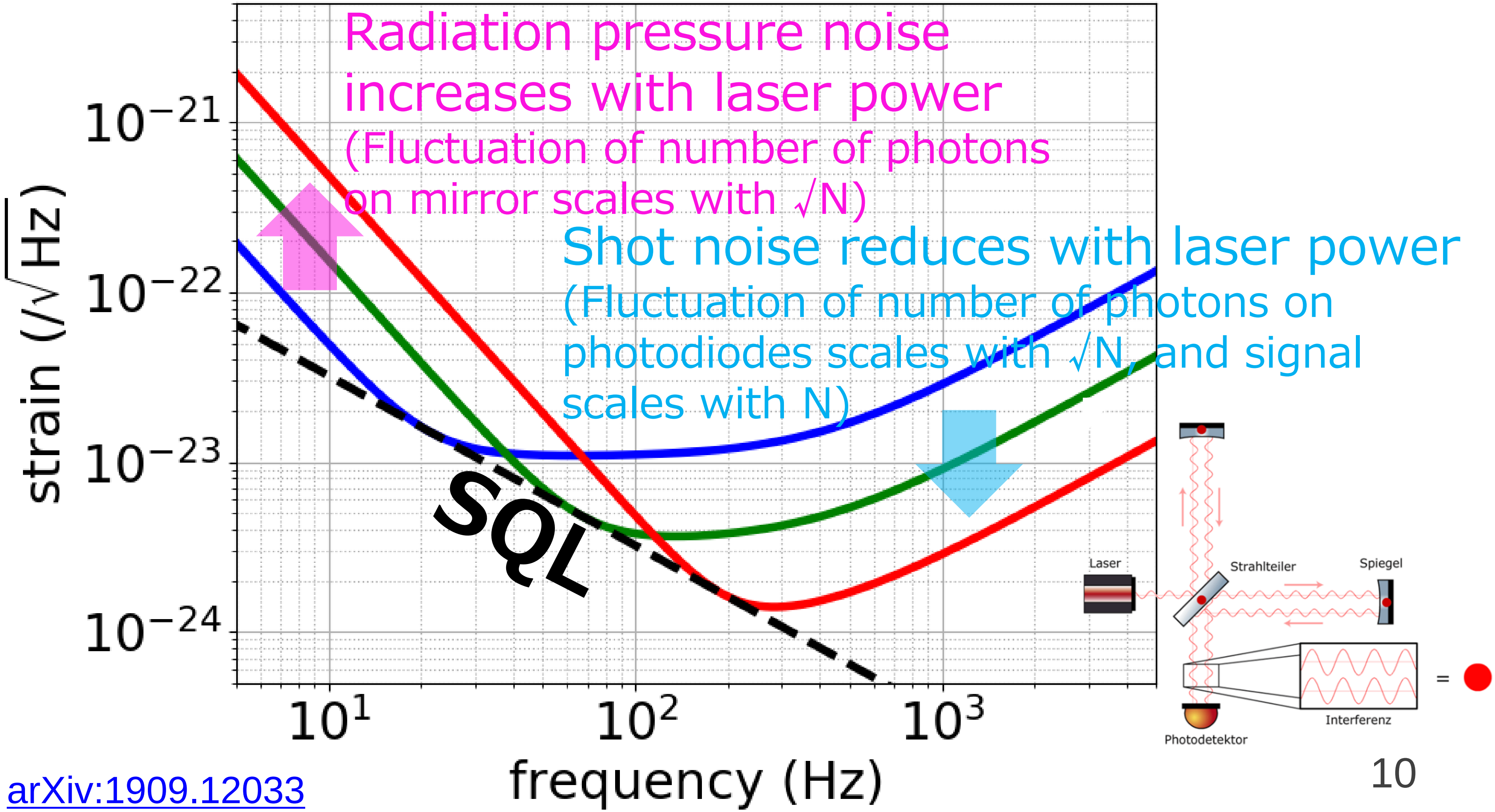
Noise Reduction Techniques



- Seismic noise
  - suspend mirrors for vibration isolation
- Mirror and suspension thermal noise
  - use materials with low mechanical loss
  - thinner and longer suspension
  - cryogenic cooling
  - use larger beam size (for mirror thermal)
- Quantum noise
  - optimize laser power
  - interferometer configuration
  - heavier mirror
- Longer arm is effective for reducing all noises

Quantum Noise and SQL

- You cannot surpass standard quantum limit just by changing the laser power



arXiv:1909.12033

Quantum Noise and SQL

- Quantum noise

$$\sqrt{S_h(f)} = \sqrt{\frac{h_{\mathrm{SQL}}^2}{2}\left(\frac{1}{\mathcal{K}} + \mathcal{K}\right)}$$

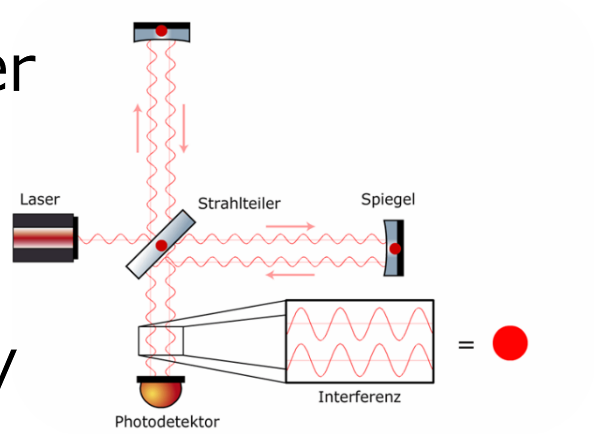
Shot noise　Radiation pressure noise

Laser frequency

Laser power at beamsplitter

$$\mathcal{K} = \frac{8\omega_0 I_0}{mL^2\omega^2(\gamma^2+\omega^2)}$$

Mirror mass　Arm length　Cavity linewidth　GW frequency



- SQL

$$h_{\mathrm{SQL}} = \sqrt{\frac{8\hbar}{m\omega^2 L^2}}$$

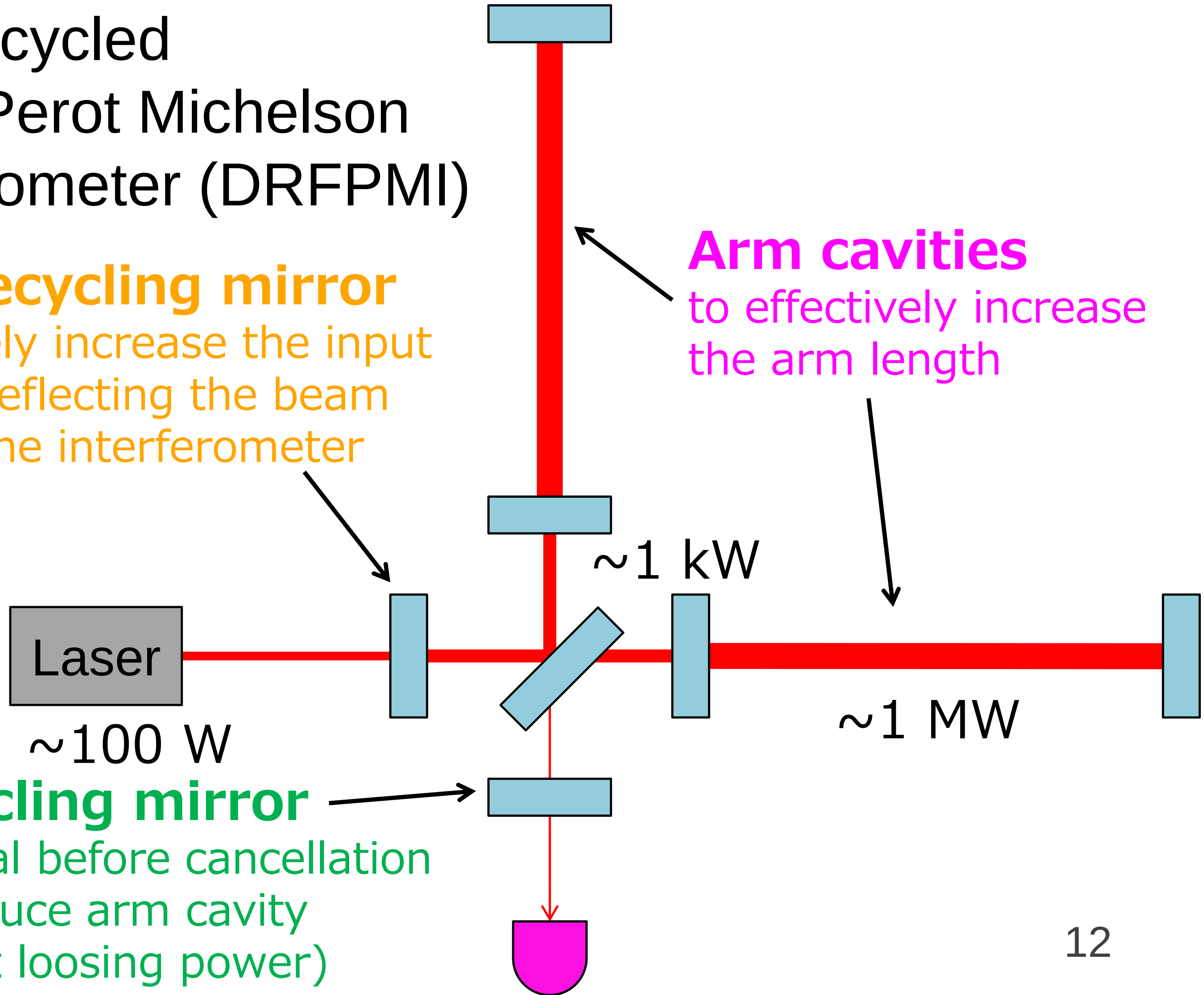
Heavier mass and longer arm are crucial

Advanced Interferometer

- Dual-recycled Fabry-Perot Michelson Interferometer (DRFPMI)

Power recycling mirror
to effectively increase the input power by reflecting the beam back into the interferometer

Arm cavities
to effectively increase the arm length



Signal recycling mirror
to extract signal before cancellation (effectively reduce arm cavity finesse without loosing power)

Advanced Interferometer

- Power recycling effectively increases laser power and signal recycling broadens the bandwidth

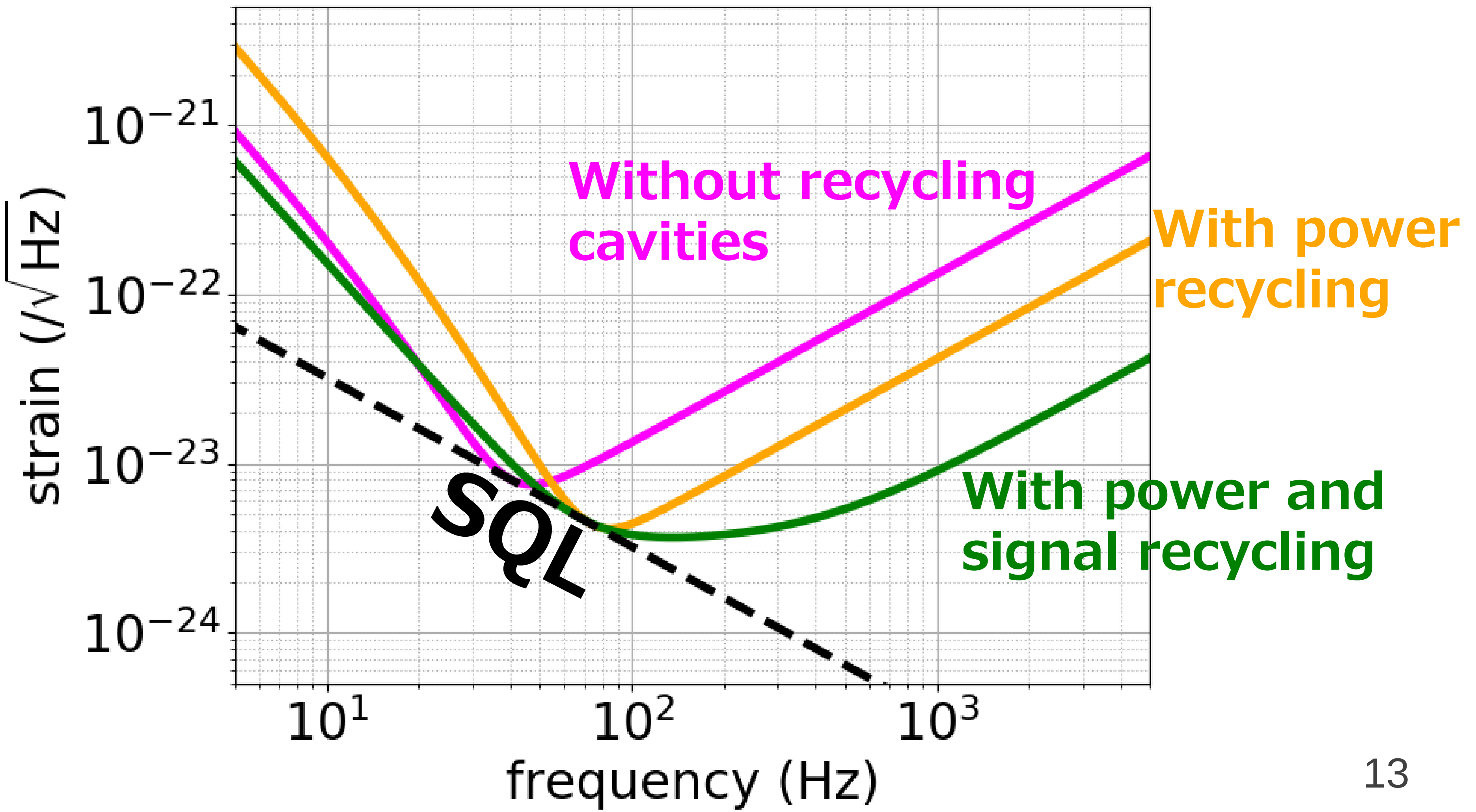
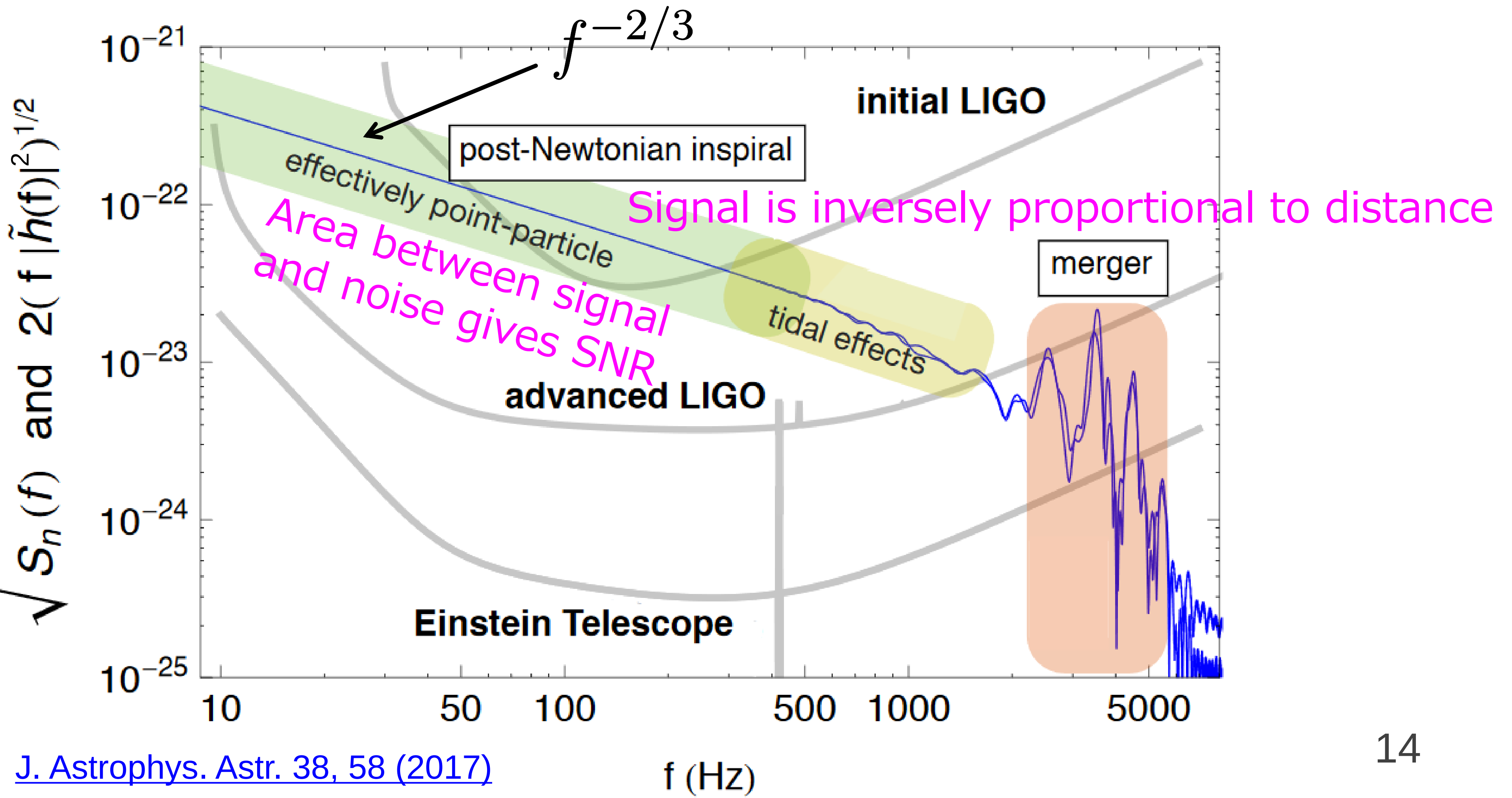


Figure of Merit for Sensitivity

- Usually use binary neutron star inspiral range
- Sky-averaged distance to which SNR > 8



J. Astrophys. Astr. 38, 58 (2017)

Inspiral Range

- Detectable distance using inspiral signal

$$\mathcal{R} = \frac{0.442}{\rho_{\mathrm{th}}} \left(\frac{5}{6}\right)^{1/2} \frac{c}{\pi^{2/3}} \left(\frac{G\mathcal{M}_{\mathrm{c}}}{c^3}\right) \left[\int_{f_{\min}}^{f_{\max}} \frac{f^{-7/3}}{S_{\mathrm{n}}(f)} \mathrm{d}f\right]^{1/2}$$

Sky average for source location and polarization angle

SNR threshold (usually 8)

Detector noise

Frequency dependence of inspiral signal in squared characteristic strain

Chirp mass (detector frame)

- ISCO frequency

$$f_{\max} = \frac{c^3}{6^{3/2}\pi G M_{\mathrm{tot}}}$$

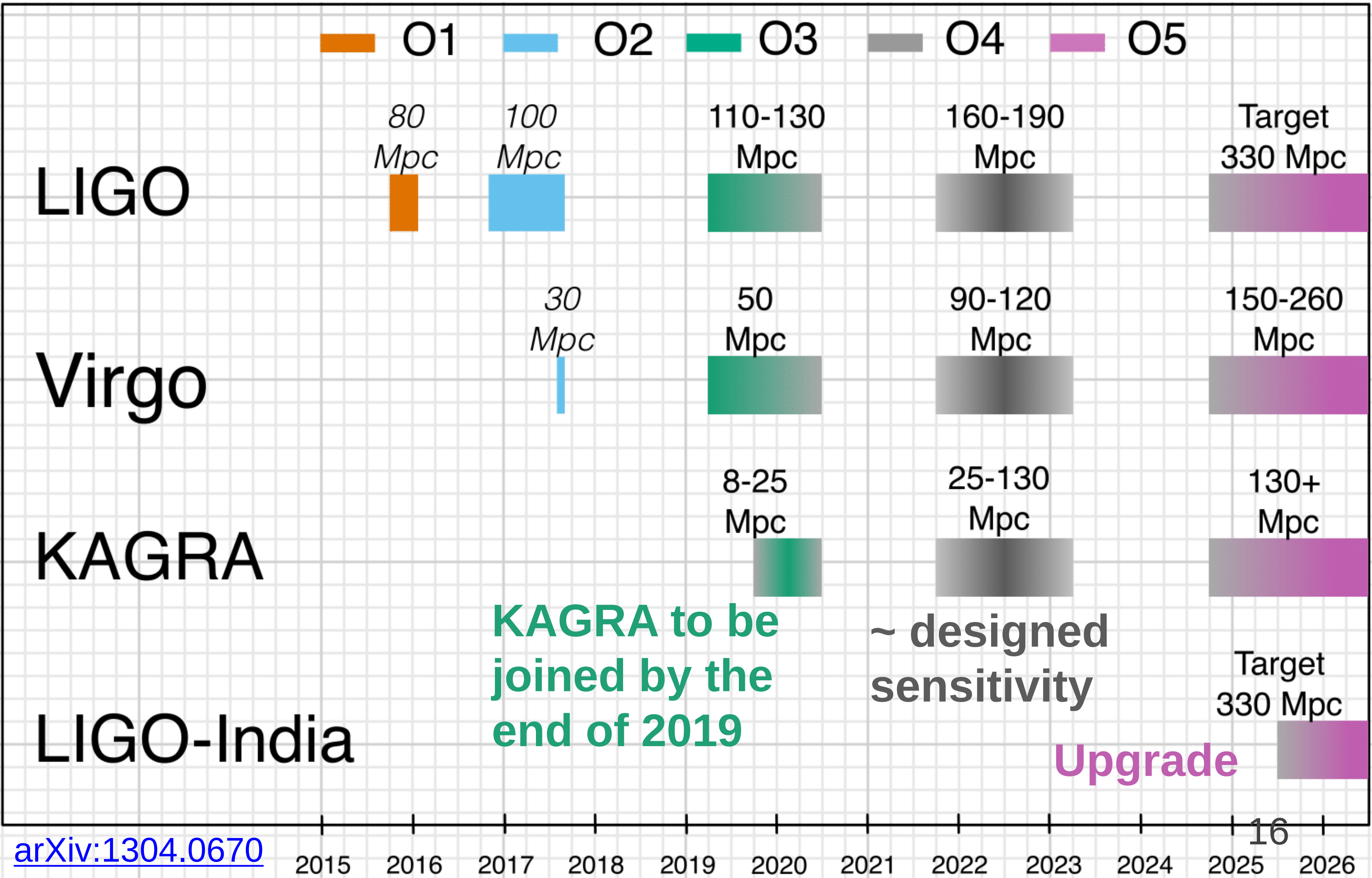
$$\mathcal{M}_{\mathrm{c}} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

In source frame,
$m_{\mathrm{source}} = m_{\mathrm{detector}}/(1+z)$

- Range ∝ Sensitivity
- Event rate ∝ ~(Range)^3

Finn and Chernoff, PRD 47, 2198 (1993)

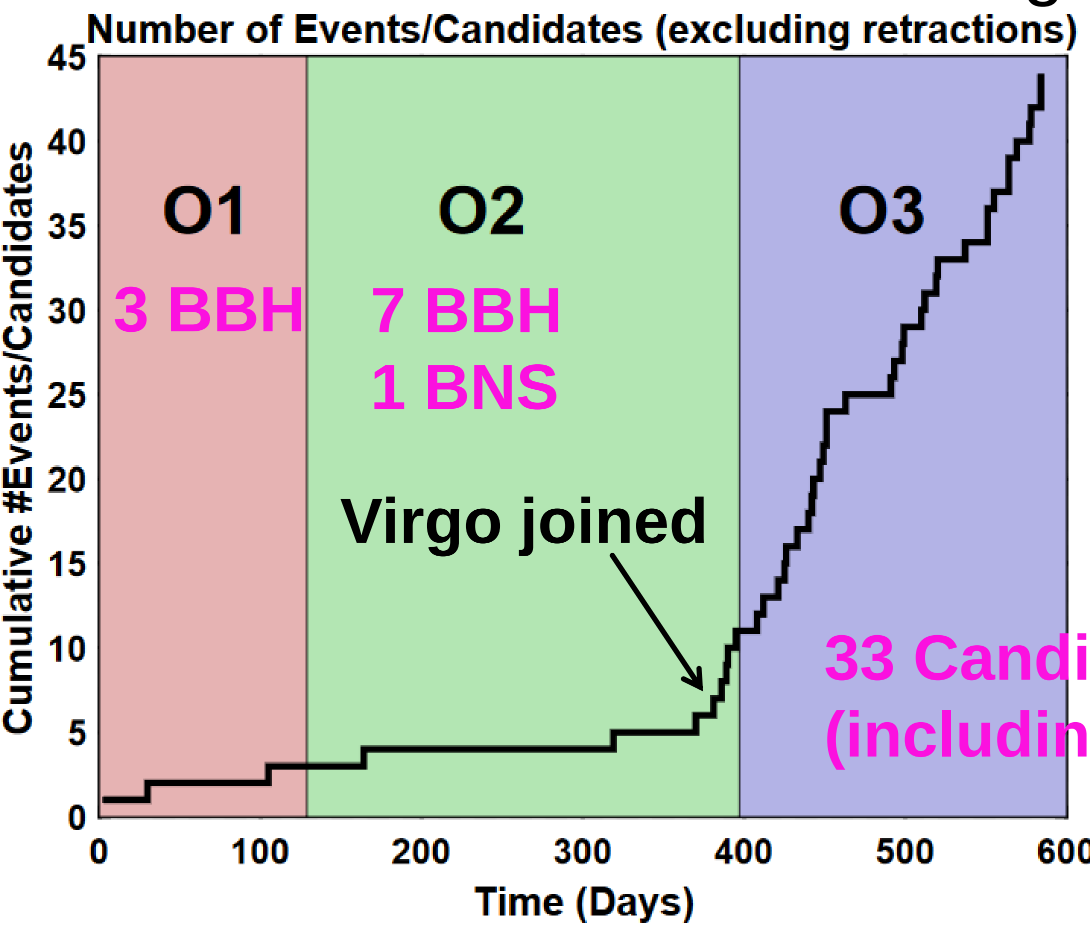
Observing Scenario of LVK



arXiv:1304.0670

Status of O3 Run by LIGO/Virgo

- Apr 1, 2019 – Sep 30, 2019: O3a
- Nov 1, 2019 – Apr 30, 2020: O3b planned
- Now under commissioning break for a month



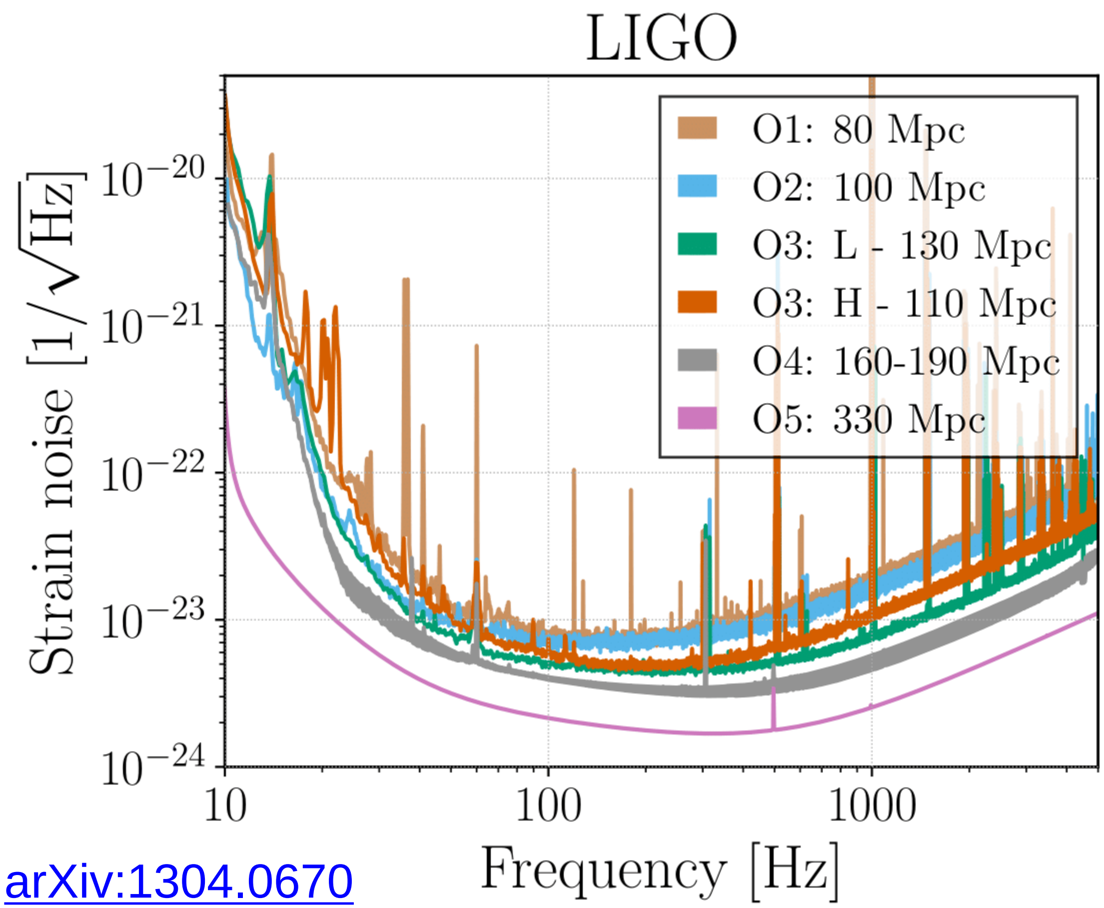
Details can be found below
https://gracedb.ligo.org/superevents/public/O3/

LIGO-G1901322

Advanced LIGO Situation

- 4 km arms, 40 kg silica mirrors, room temperature
- 330 Mpc with upgrades (A+) in O5

  coating improvements, frequency dependent squeezing



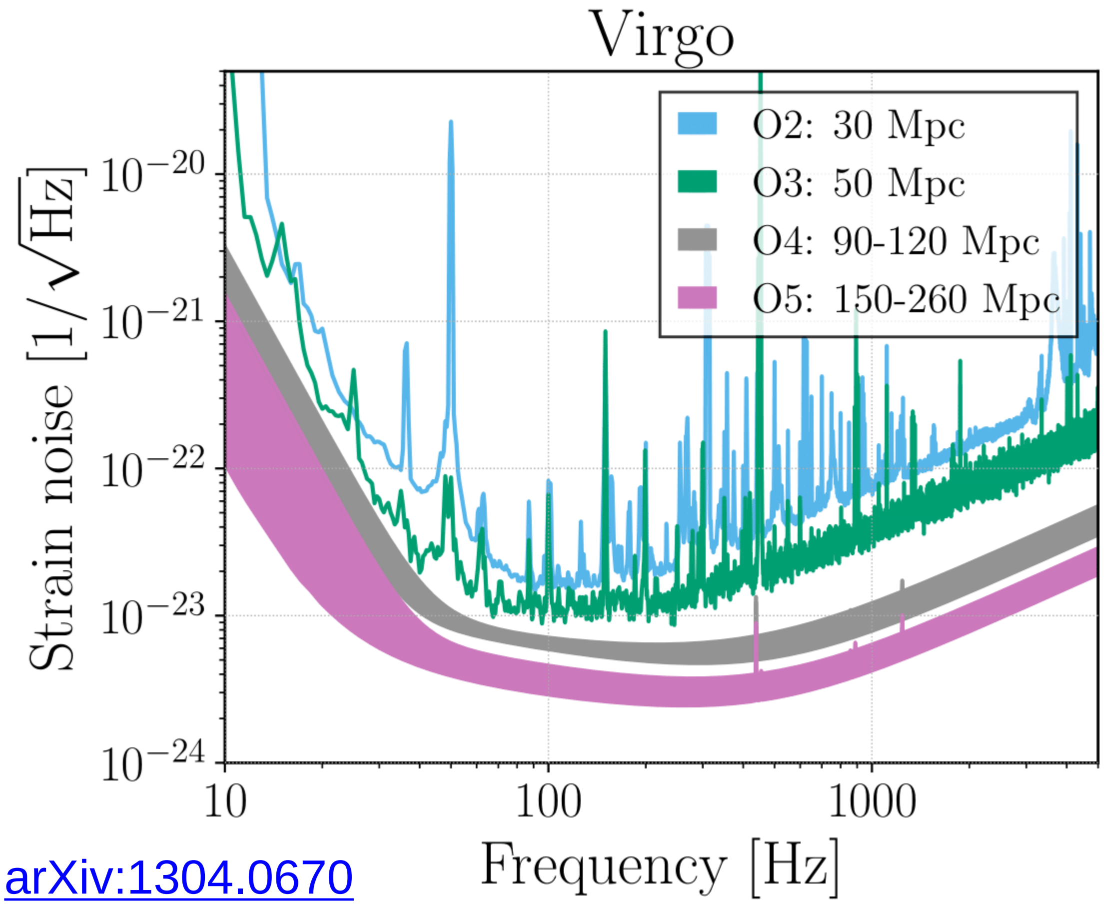
Budget approved
NSF $20.4M
UKRI £10.7M
+ Australia

arXiv:1304.0670

Advanced Virgo Situation

- 3 km arms, 42 kg silica mirrors, room temperature
- 260 Mpc with upgrades (AdV+) in O5

  frequency dependent squeezing, larger test mass etc.

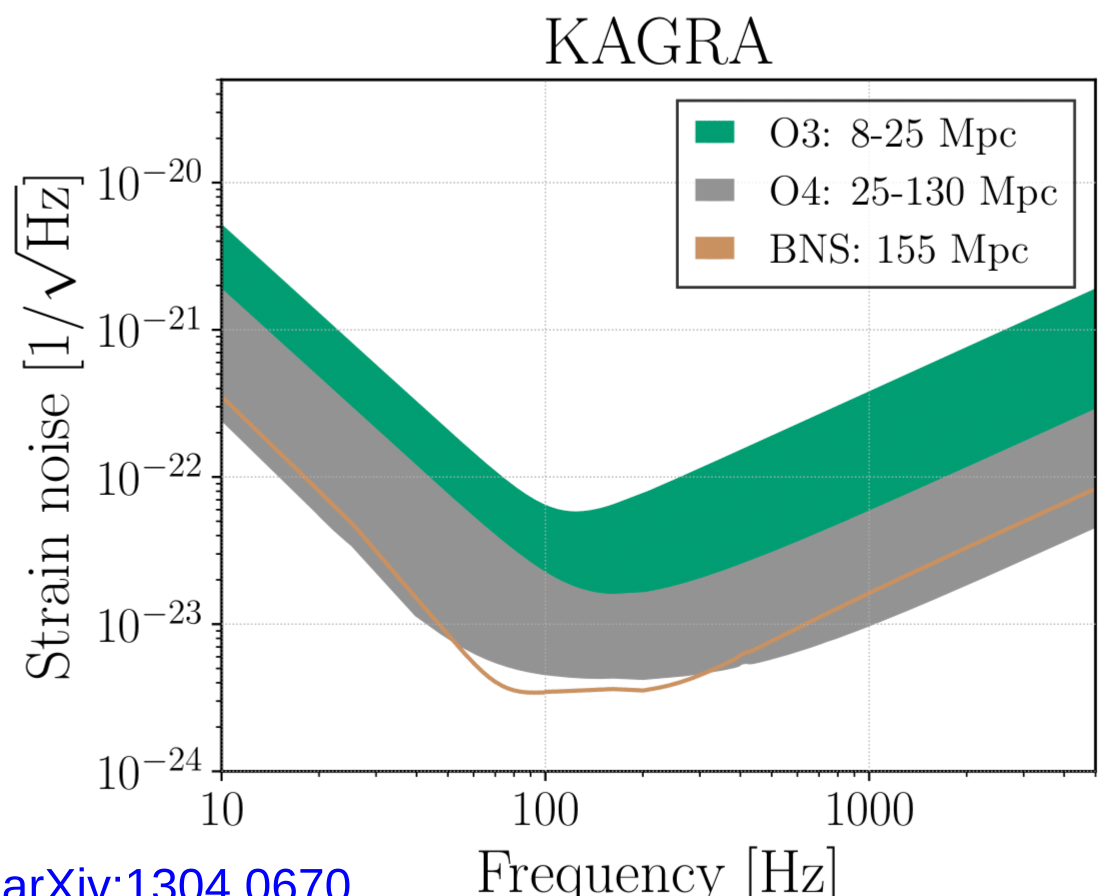


Not good at high frequencies since signal recycling is not done yet

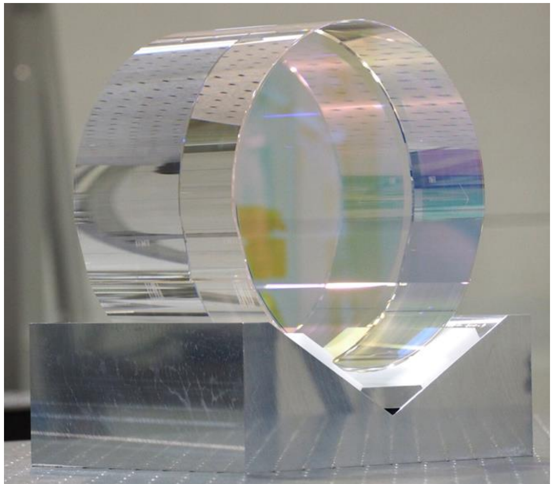
arXiv:1304.0670

KAGRA Situation

- 3 km arms, 23 kg sapphire mirrors, cryogenic
- 153 Mpc with designed sensitivity (detuned configuration to optimize quantum noise to BNS)



Join O3 by the end of 2019 even if the sensitivity is not as good.
Upgrade plans under discussion.

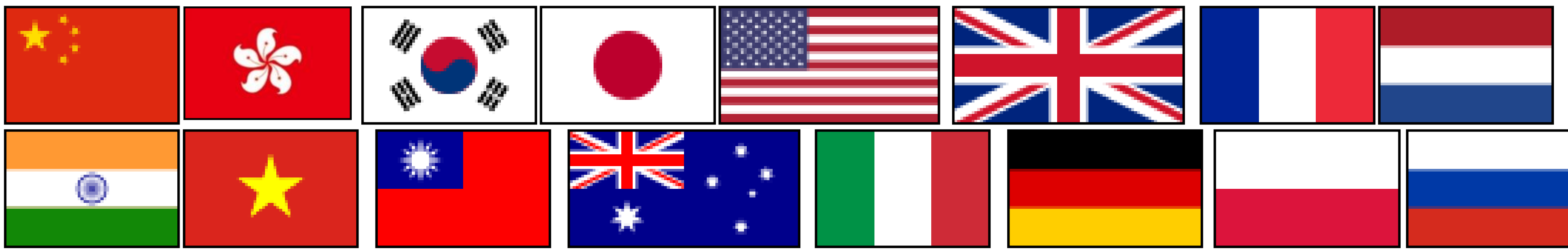


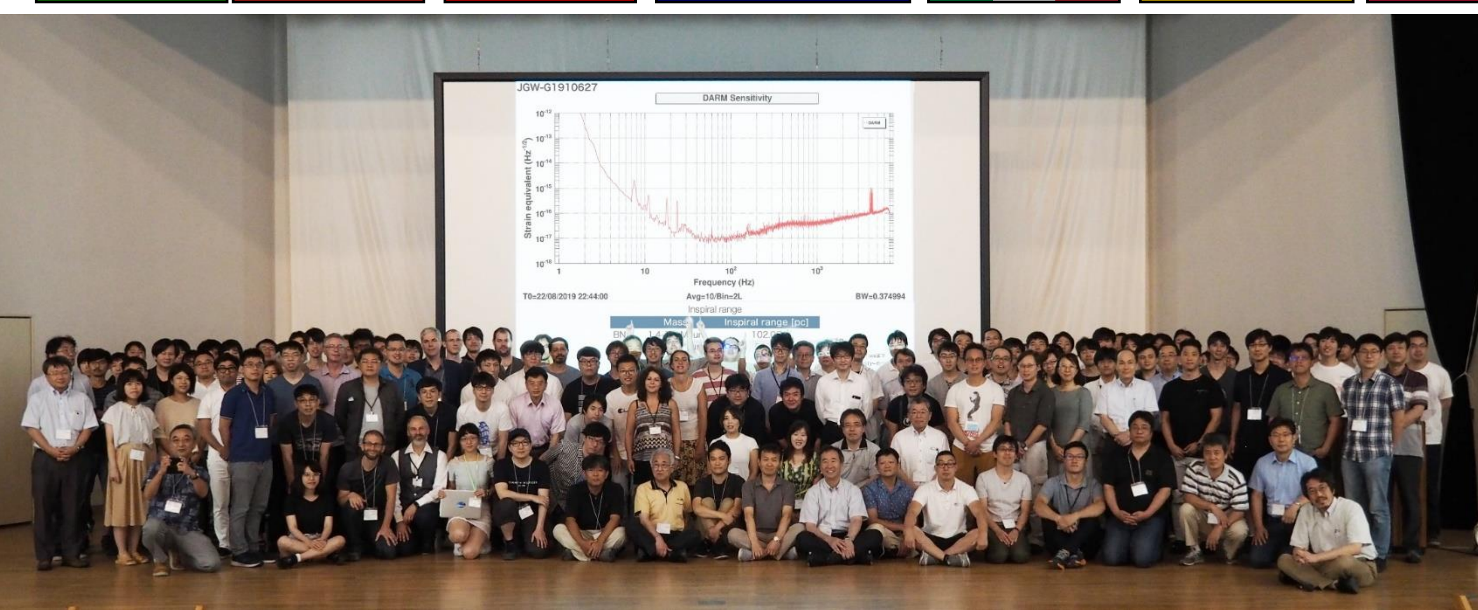
arXiv:1304.0670

KAGRA Project

- Budget approved in 2010
- 110 institutes, 450+ collaborators (200 authors)
- Cryogenic and underground

Join us!

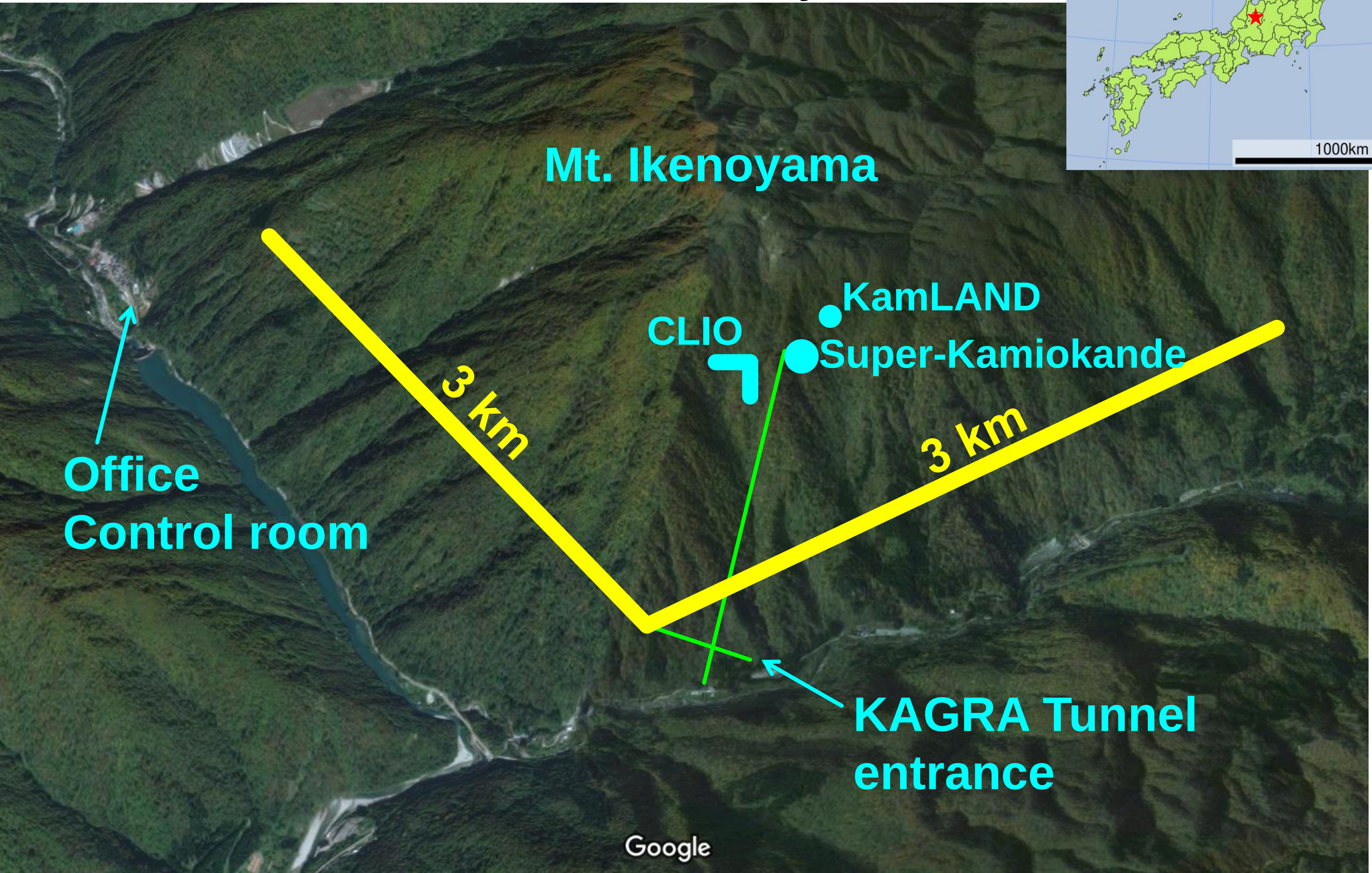




Aug 2019
F2F meeting
@ Toyama

KAGRA Location

- 1 hour drive south from Toyama station



KAGRA Tunnel

- Laser beam goes back and forth inside two 3 km vacuum tubes

Entrance
(2016.2.8)

KAGRA Timeline

2014
2015
2016
2017
2018
2019
2020

Tunnel excavation done

Inauguration of initial-phase facility

First test run at room temp. (iKAGRA)

KAGRA Collaboration, PTEP 2018, 013F01 (2018)

First cryogenic test run (Phase 1)

KAGRA Collaboration, arXiv:1901.03569

MoA between LIGO and Virgo signed

Expect to join observing run O3

Completion Ceremony on Oct 4

- Almost all components installed
- Agreement between LIGO/Virgo signed

https://www.u-tokyo.ac.jp/focus/ja/articles/z0508_10010.html

KAGRA Joining Observation

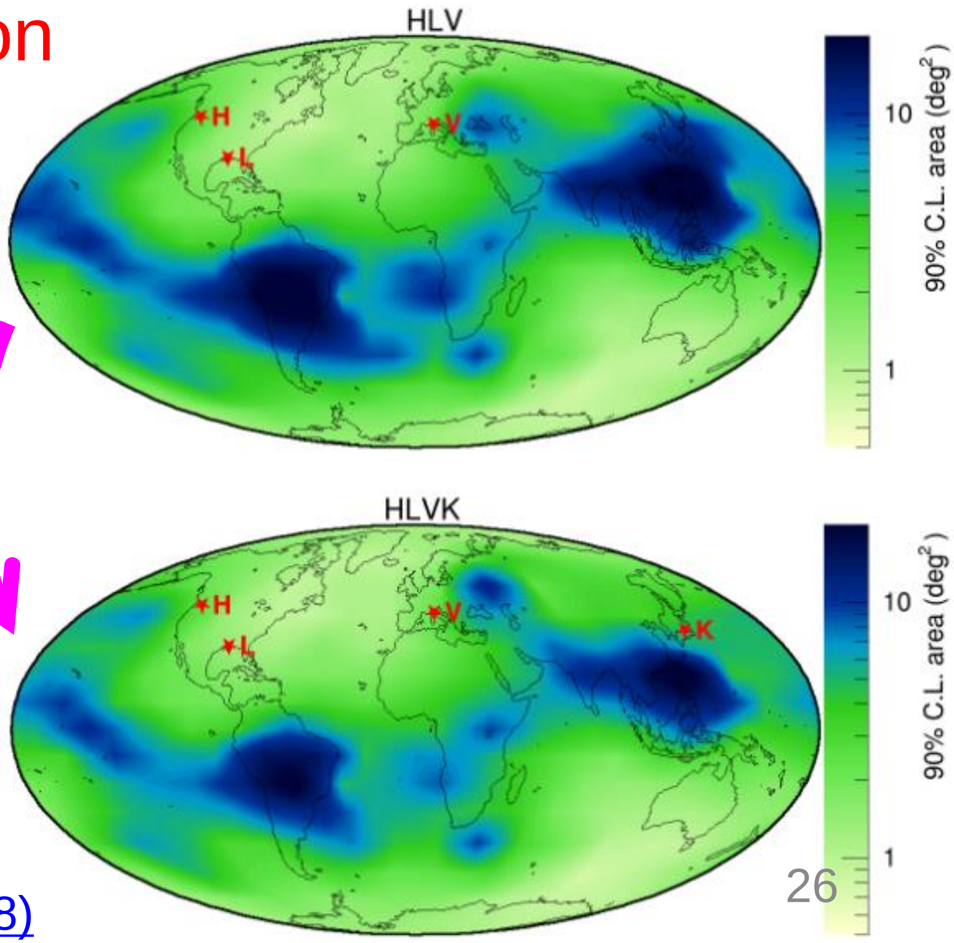
- Improves 3+ detector duty factor
  LHV 34 % → LHVK 65 %
  (assuming 70 % duty factor for single detector)

S. Haino, JGW-G1808212

- Improves sky localization

  1.5-1.25 Msun BNS at 40 Mpc
  LH: 120 Mpc
  V: 60 Mpc
  K: 10 Mpc

With KAGRA



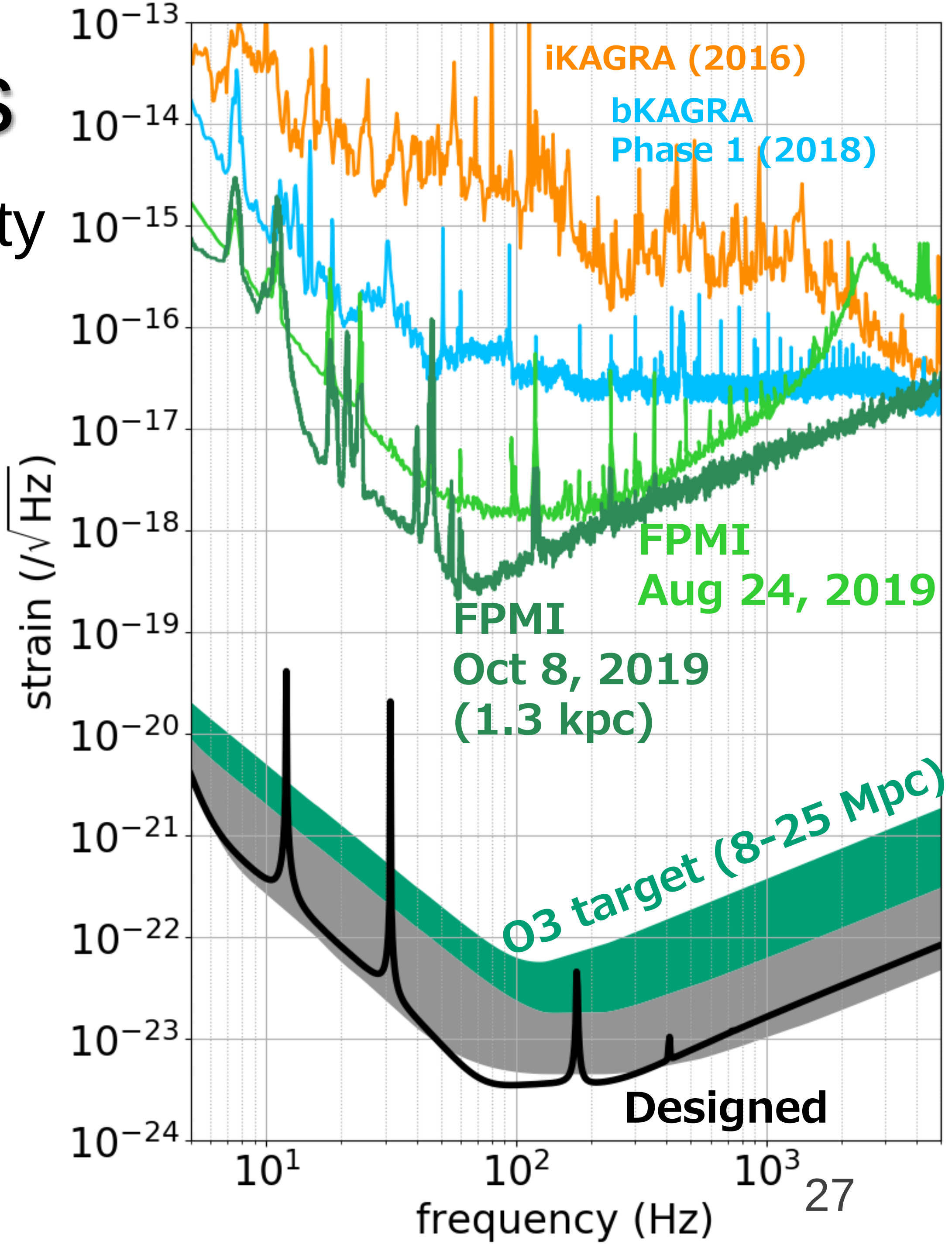
- Enables better GW polarization measurements, distinguish non-GR polarization

H. Takeda+, PRD 98, 022008 (2018)

KAGRA Status

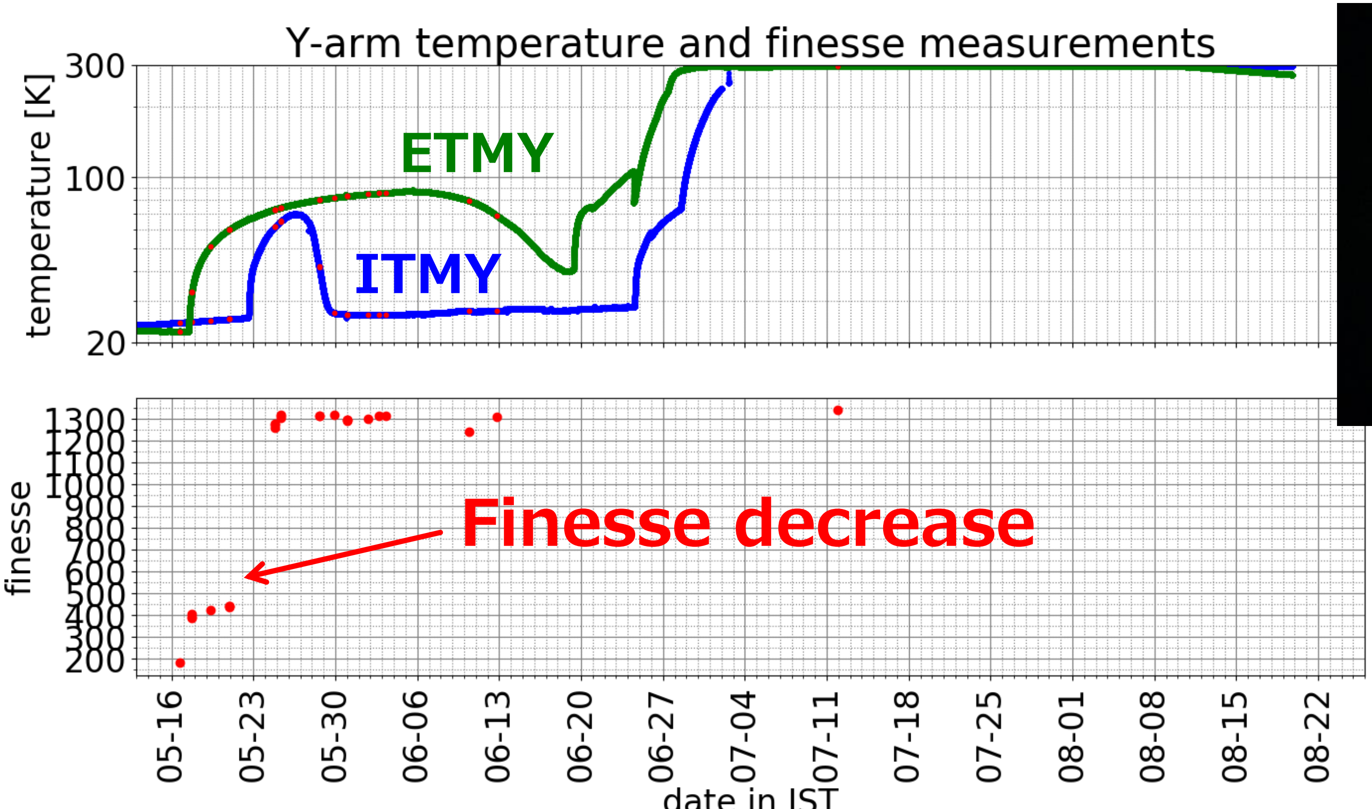
- First FPMI sensitivity on August
- Now around 1 kpc
- Two big problem found in May-June:
  - Frosting
  - Birefringence

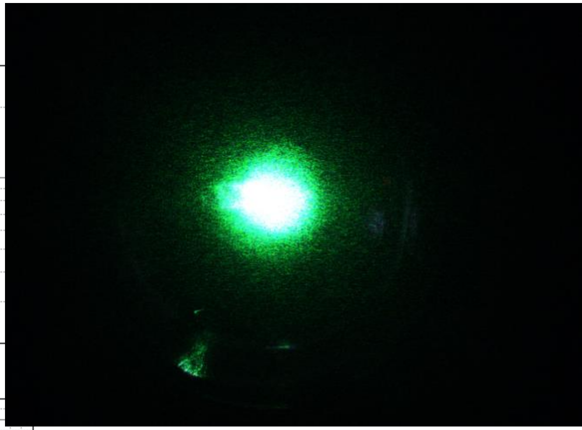
  of sapphire mirrors
- Now mirrors are at ~250 K, power and signal recycling cavities cannot be locked until now



Effect of Frosting

- Finesse decreases at cryogenic temperatures (below ~30 K)
- Frosting from residual gas adsorption on mirrors
- Need to cool down the mirror at good vacuum

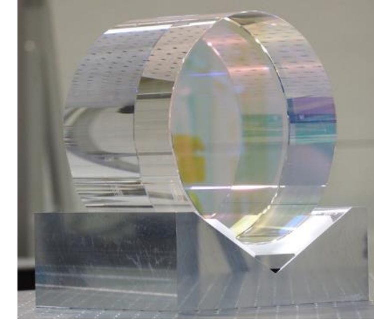




Frosted mirror seen with green laser

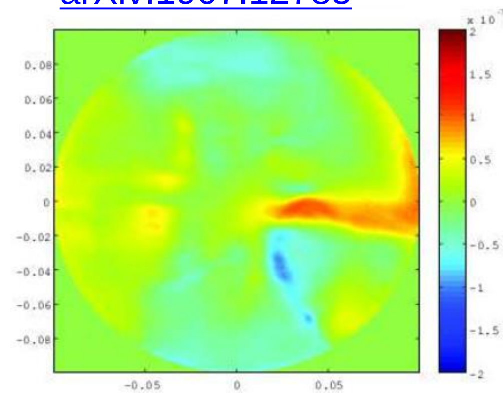
Y. Enomoto+, klog #9861

Effect of Birefringence

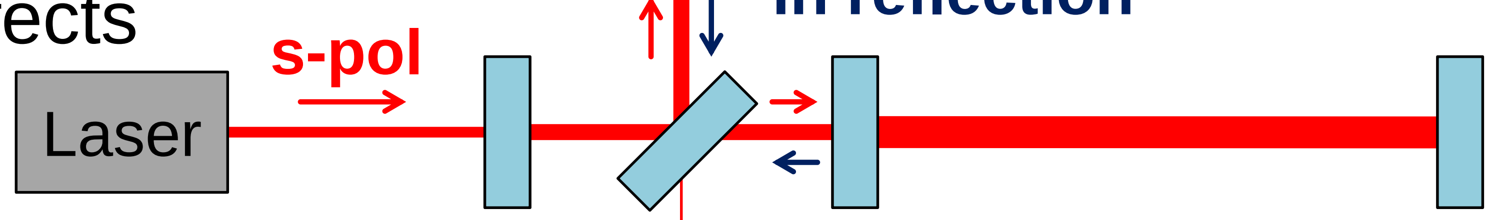


- Sapphire crystal axis and beam axis was not aligned well enough, and there's also inhomogeneity
- Hard to lock power and signal recycling cavities due to large losses and dirty effects

K. Somiya+, arXiv:1907.12785



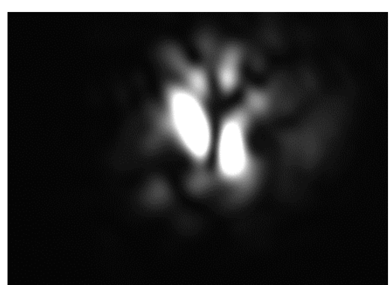
a few % p-pol in reflection



Power and signal recycling cavities contaminated by p-pol

Ask me later if you are curious about why this happened

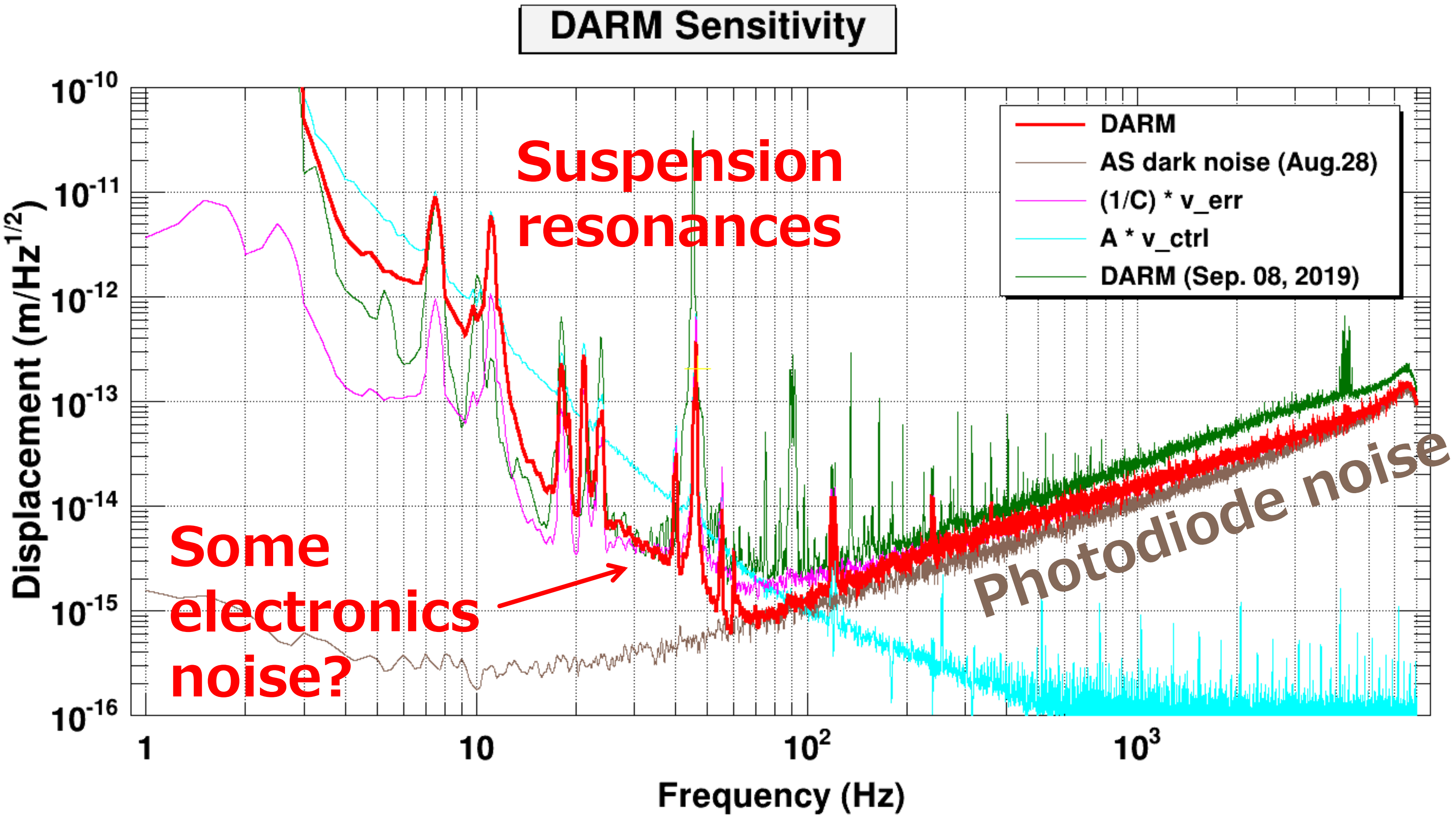
p-pol beam shape from ITM reflection



K. Kokeyama+, klog #9495

Current KAGRA Sensitivity

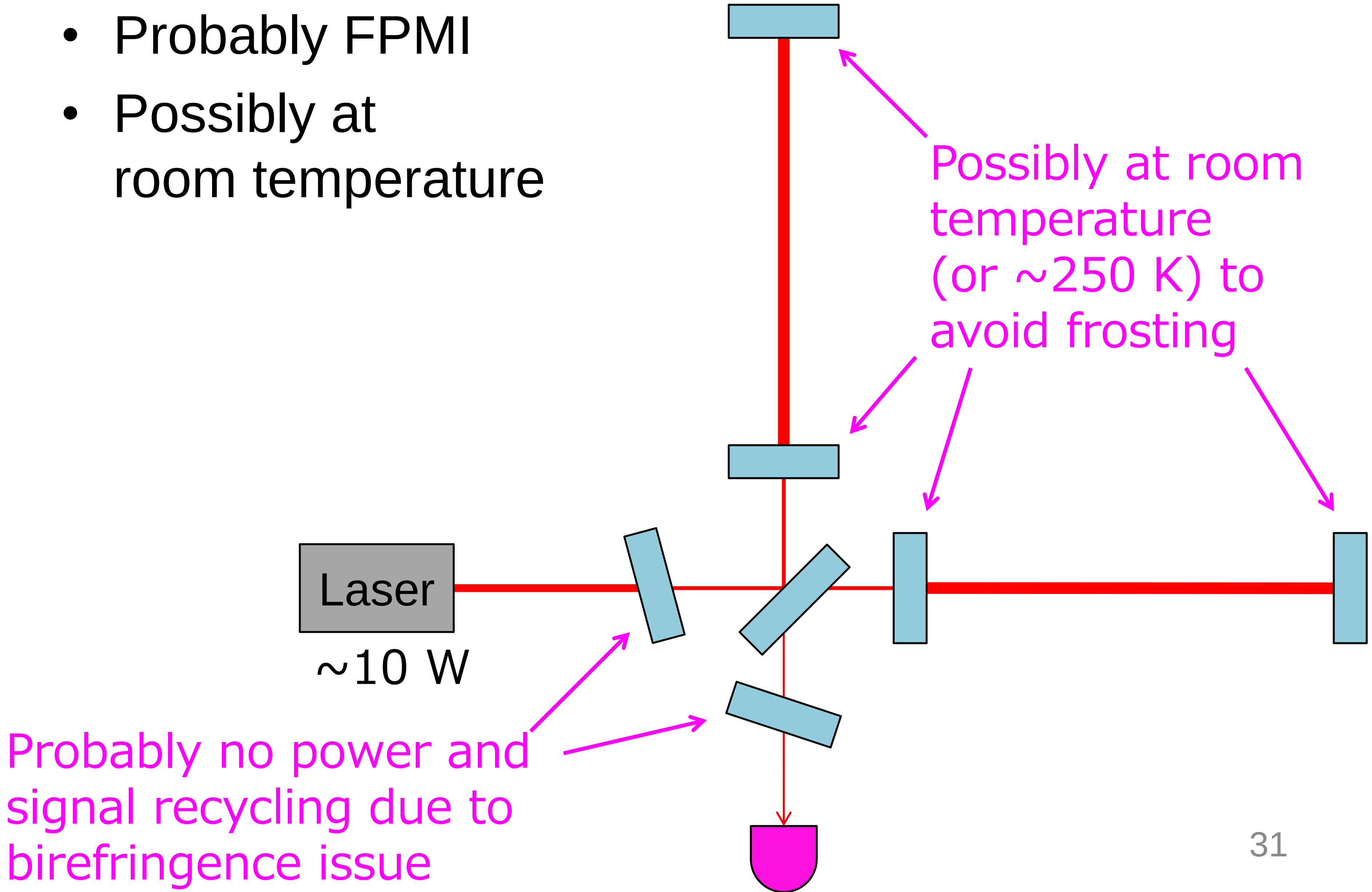
- Limited by technical noises and can be reduced



M. Nakano+, [klog #10869]

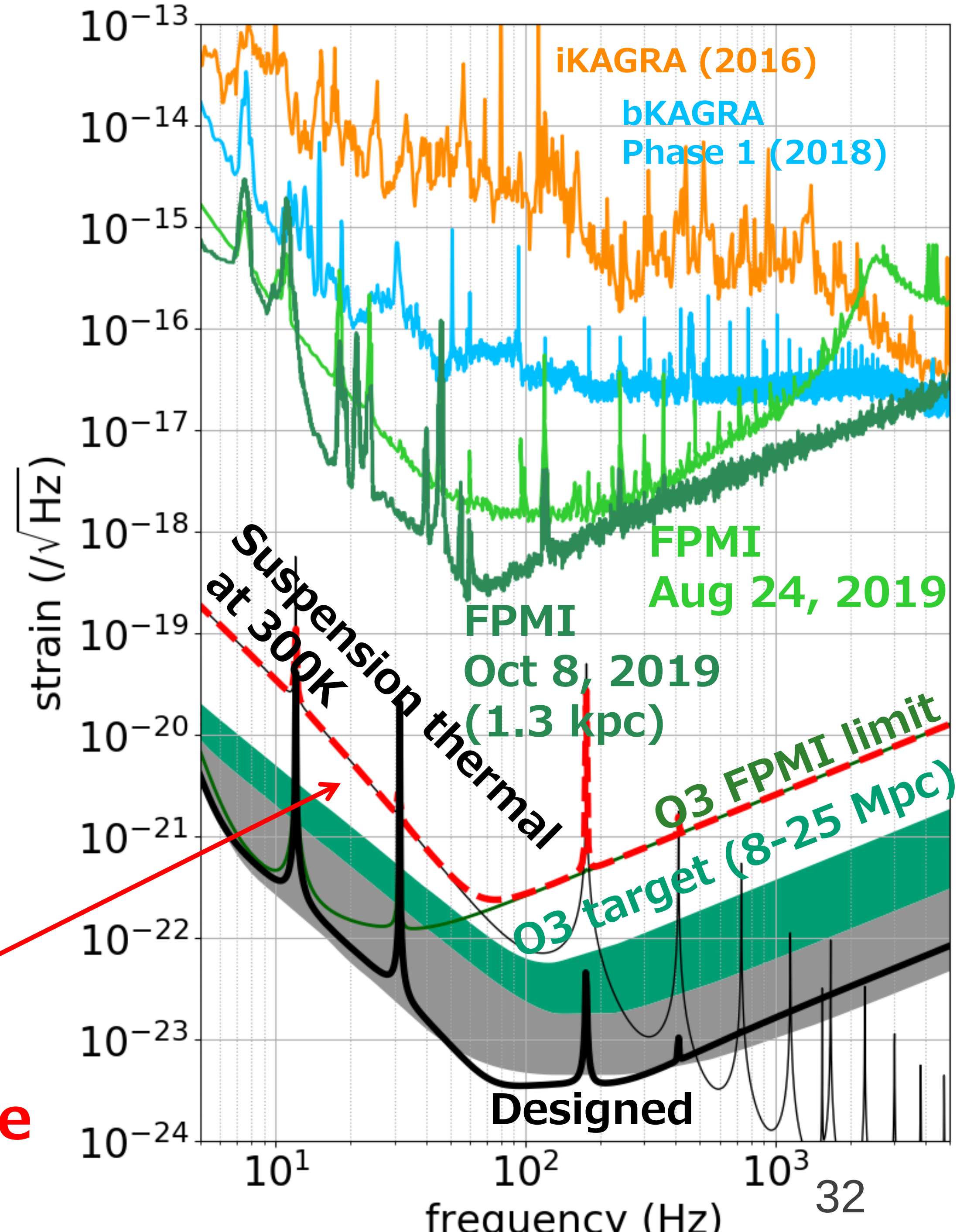
KAGRA in O3 (2019-2020)

- Probably FPMI
- Possibly at room temperature



O3 Sensitivity

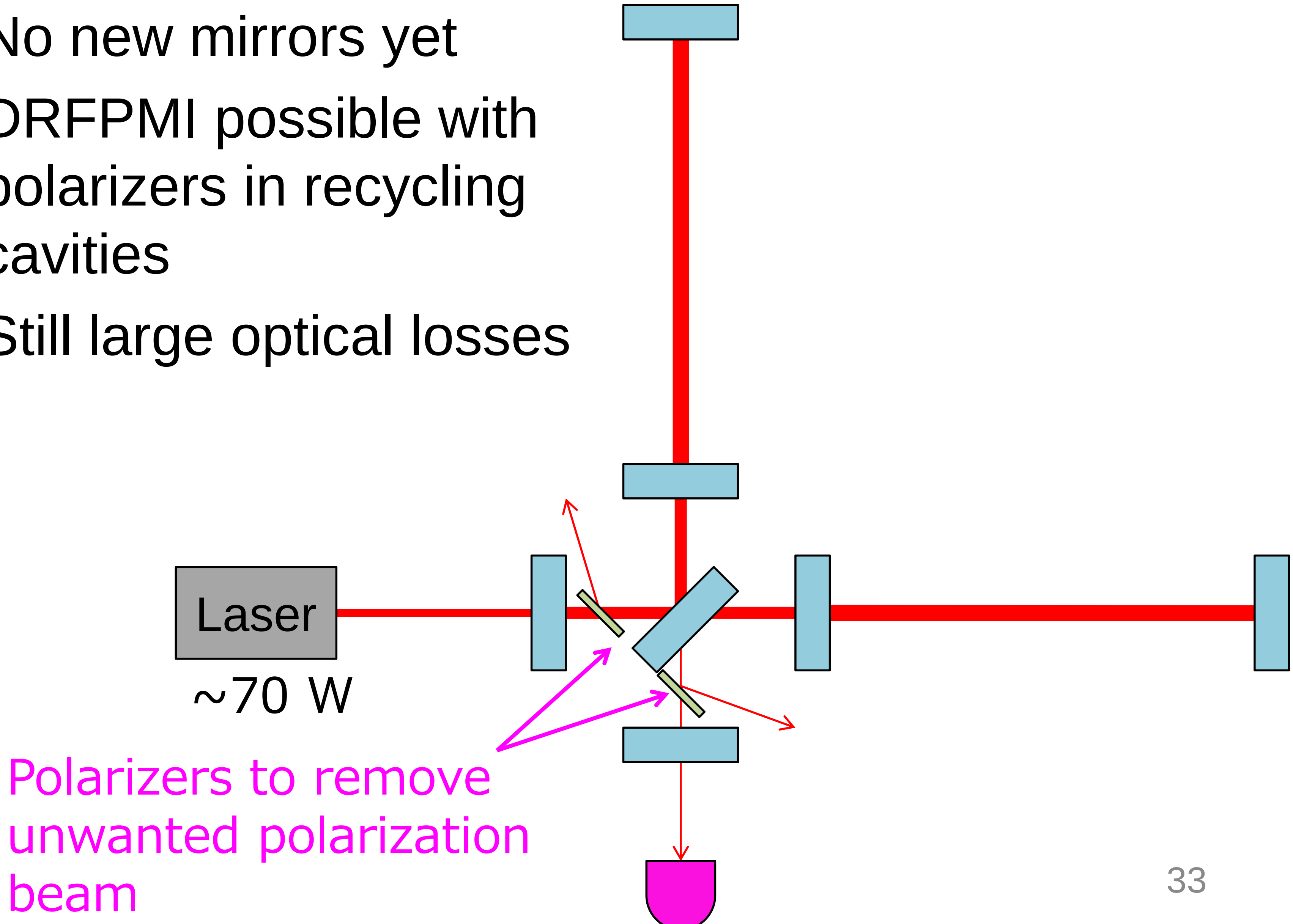
- Probably FPMI
- Possibly at room temperature
  → a few Mpc
  at max



O3 FPMI limit at room temperature (~2 Mpc)

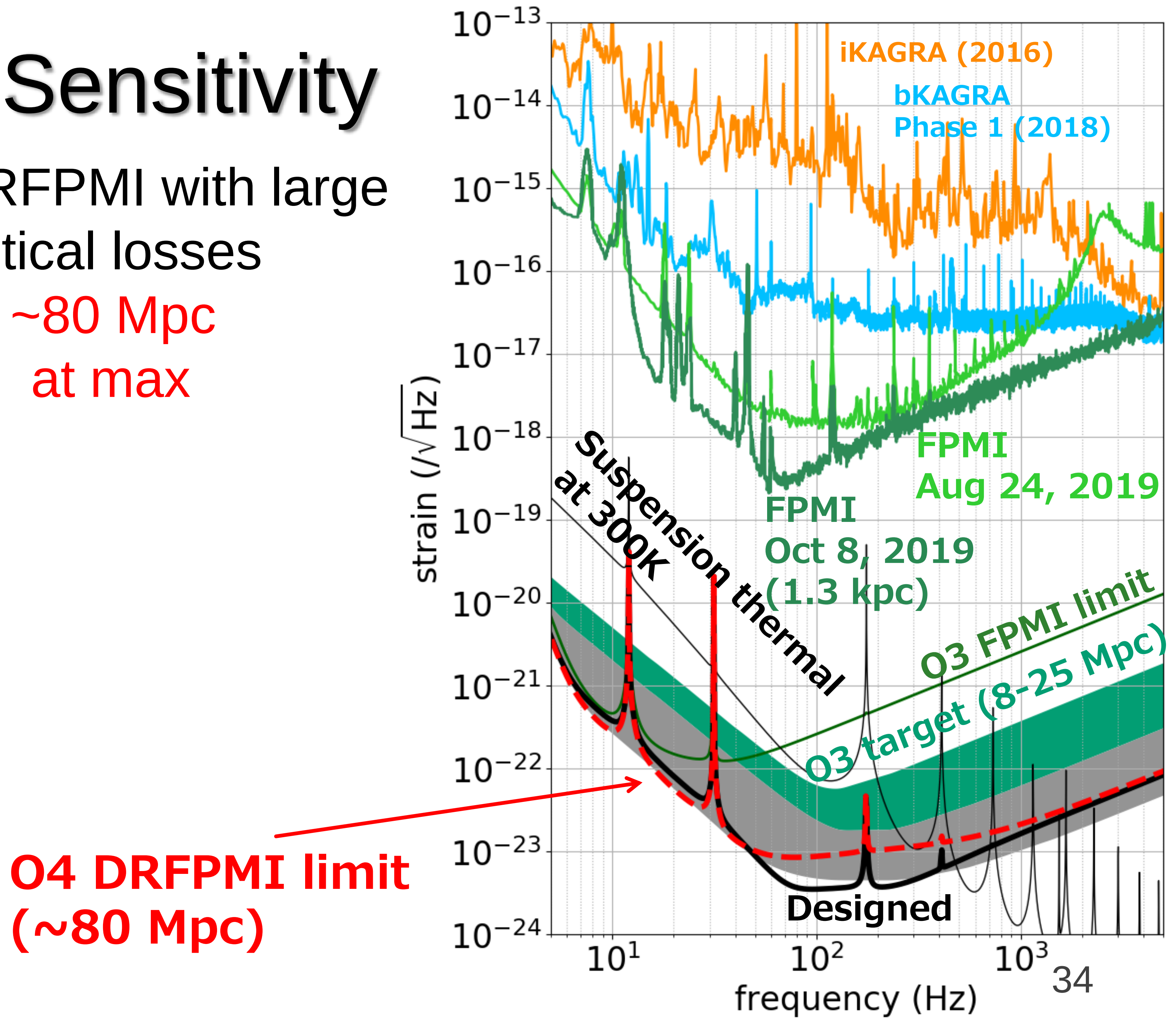
KAGRA in O4 (2021-2023)

- No new mirrors yet
- DRFPMI possible with polarizers in recycling cavities
- Still large optical losses



O4 Sensitivity

- DRFPMI with large optical losses
  → ~80 Mpc
  at max

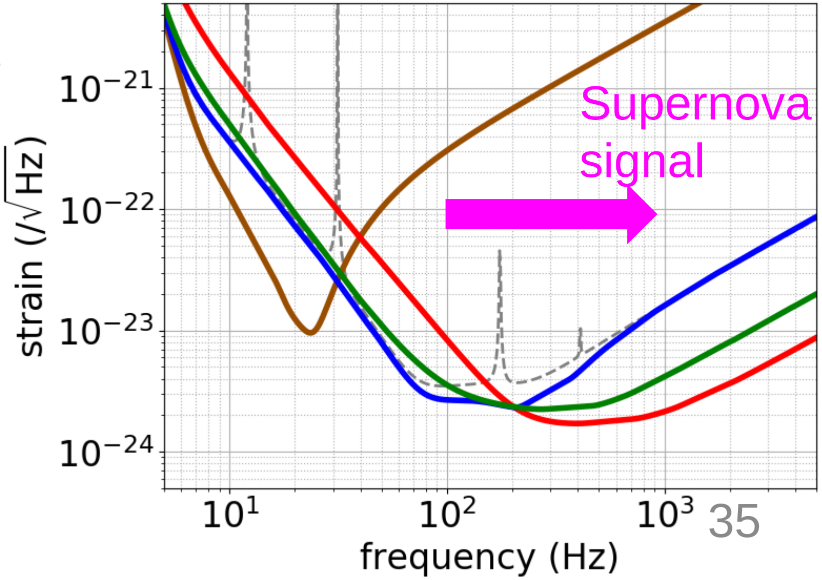


Future Plan for O5?

- Options will be
  - Reduce power to focus on low frequencies (intermediate-mass black holes)
  - Increase power to focus on high frequencies (neutron star physics)
  - Heavier mirror for better mid-frequencies
  - Frequency dependent squeezing for broadband

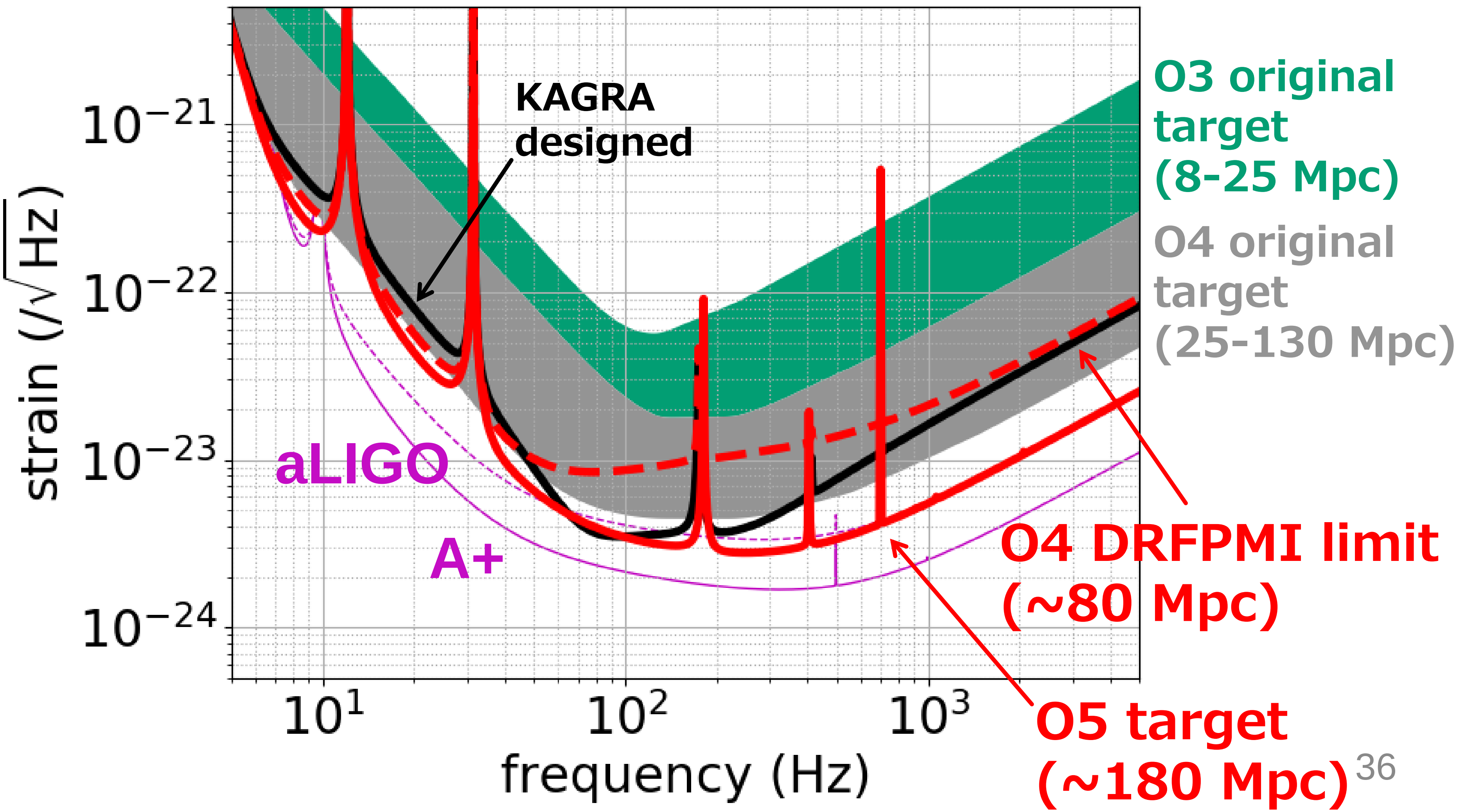
YM+, arXiv:1906.02866

- FDSQZ seems to be technically most feasible, and broadband improvement was favored not to miss any science



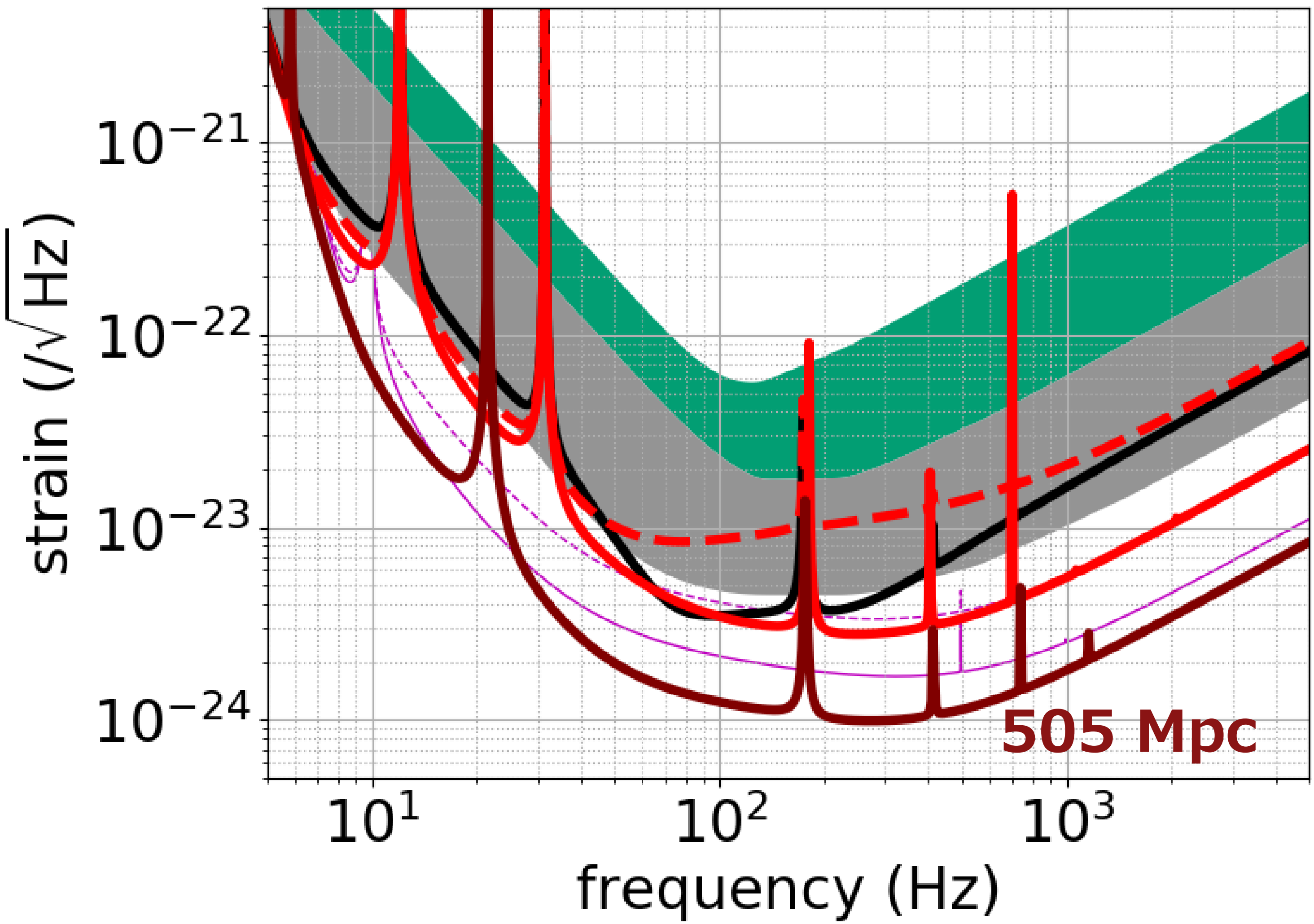
O5 Prospects

- With non-birefringent mirrors and frequency dependent squeezing (60 m filter cavity, 10 dB injected)



Beyond O5, Longer Term Plan

- If we are very optimistic (but not too crazy), further improvement is possible



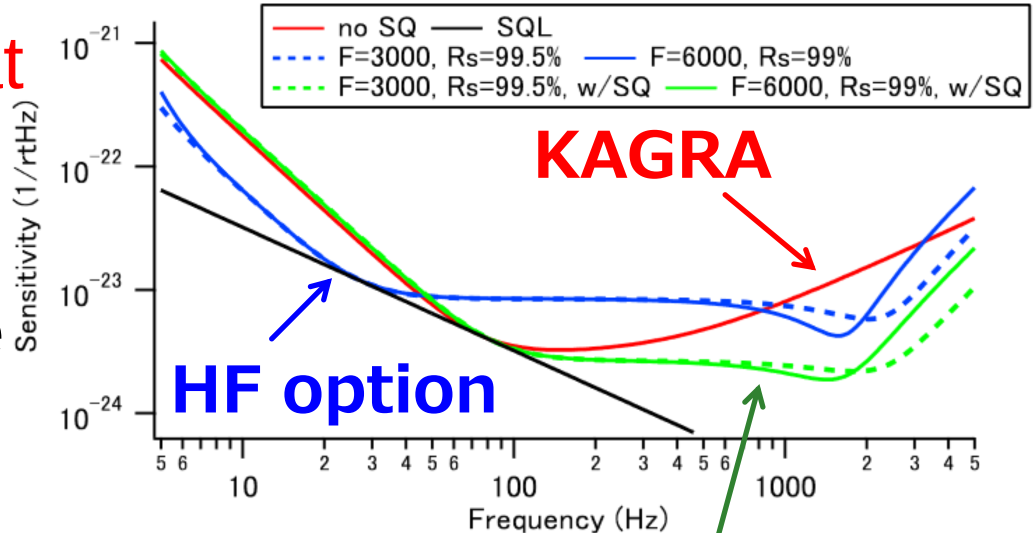
200 kg mirror
4.8 kW at BS
10 ppm/cm
300 m filter cavity
10 dB injected squeezing

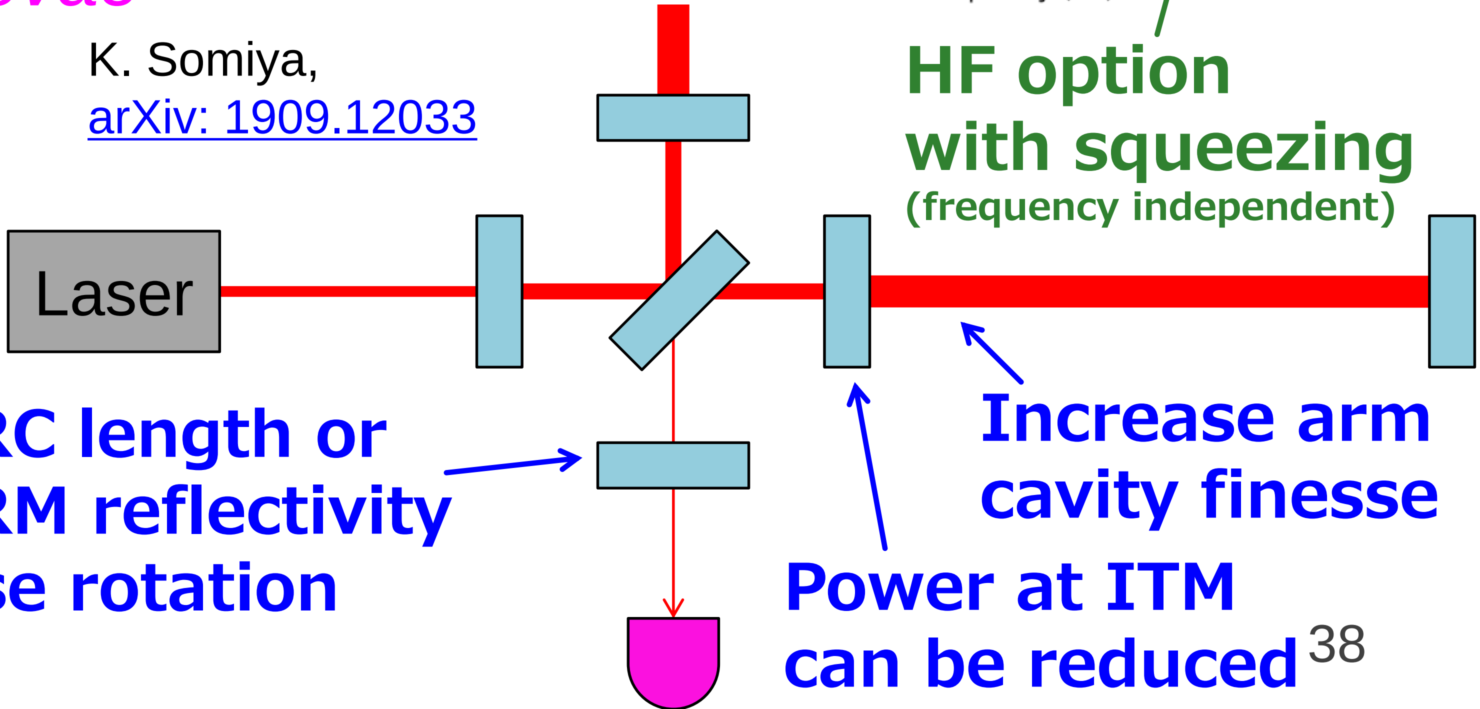
S. Haino, JGW-G1910533

High Frequency Option?

- We can make a dip at high frequency to probe neutron star physics, enhance the chance of detecting *supernovae*

K. Somiya, arXiv: 1909.12033





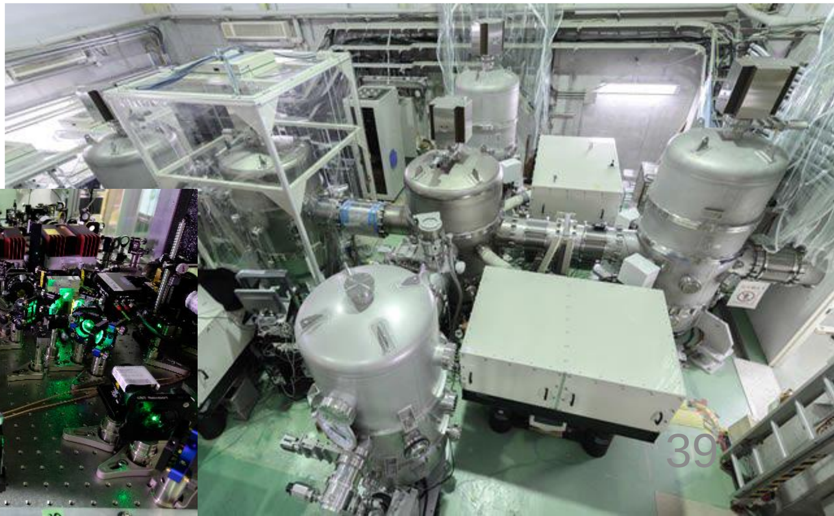
Increase SRC length or Increase SRM reflectivity → SRC phase rotation creates dip

Active R&D Ongoing

- Frequency dependent squeezing experiment using TAMA300 facility (NAOJ) E. Capocasa+, PRD 93, 082004 (2016)
- Sapphire mirror absorption and birefringence measurements (NAOJ)
  different company? annealing?
- Coating thermal noise measurement at cryogenic temperatures (NAOJ)

JGW-G1808966

- Newtonian noise detector development (UTokyo)
- Optical spring experiments (Tokyo Tech, UTokyo) etc…



Summary

- The first sensitivity without recycling cavities was obtained, and currently under commissioning to reduce noises (now ~1 kpc)
- KAGRA starts observing run by the end of 2019
- Prospects for KAGRA sensitivity

  O3b (2019-2020): a few Mpc at max

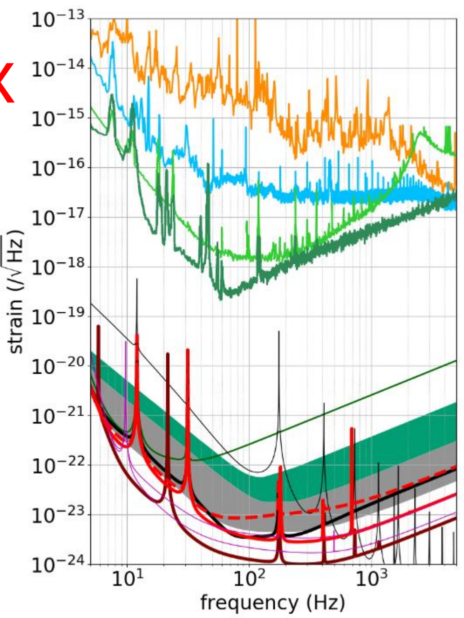
  O4 (2021-2023): ~80 Mpc at max

  ↓ Improved mirrors, squeezing

  O5 (2024-): ~180 Mpc

  ↓ 200 kg mirrors, squeezing etc.

  Ultimately 500 Mpc?

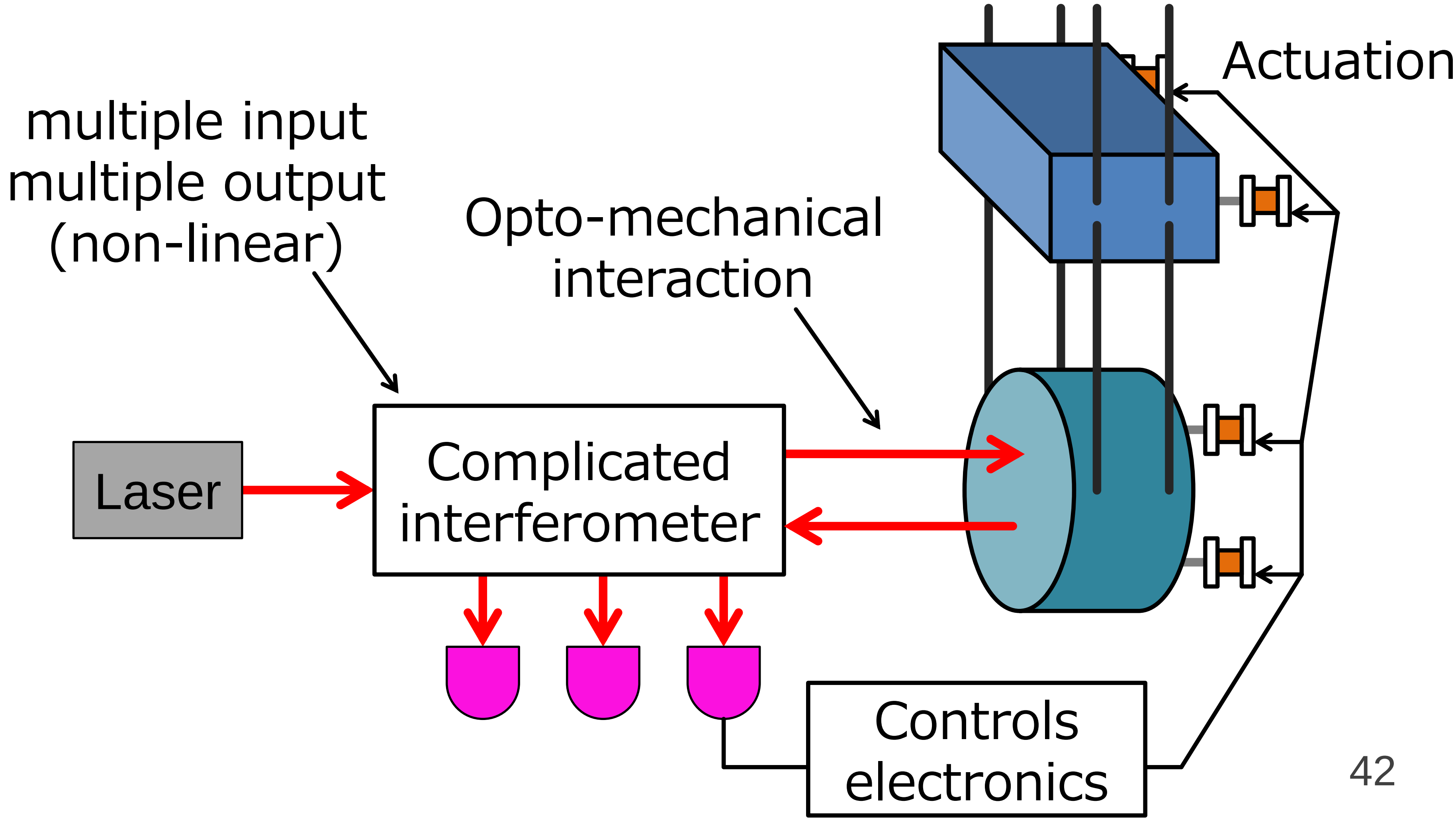


- Option to focus on high freq. for supernovae?

Supplemental Slides

Profound World of Interferometer

- Interferometer controls and sensitivity design is really complicated and interesting



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)

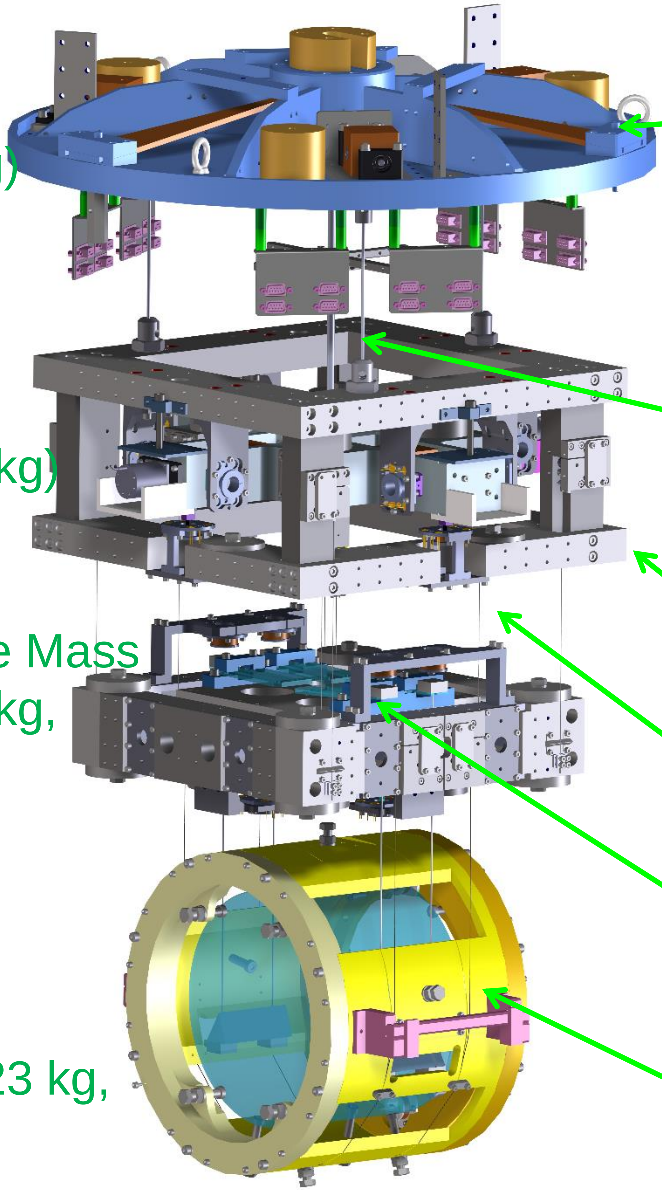
KAGRA Detailed Parameters

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

Figure by T. Ushiba and A. Hagiwara



Platform
(SUS, 65 kg)

3 CuBe blade springs

Marionette
(SUS, 22.5 kg)

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

Heat link attached to MN

Intermediate Mass
(SUS, 20.1 kg,
16 K)

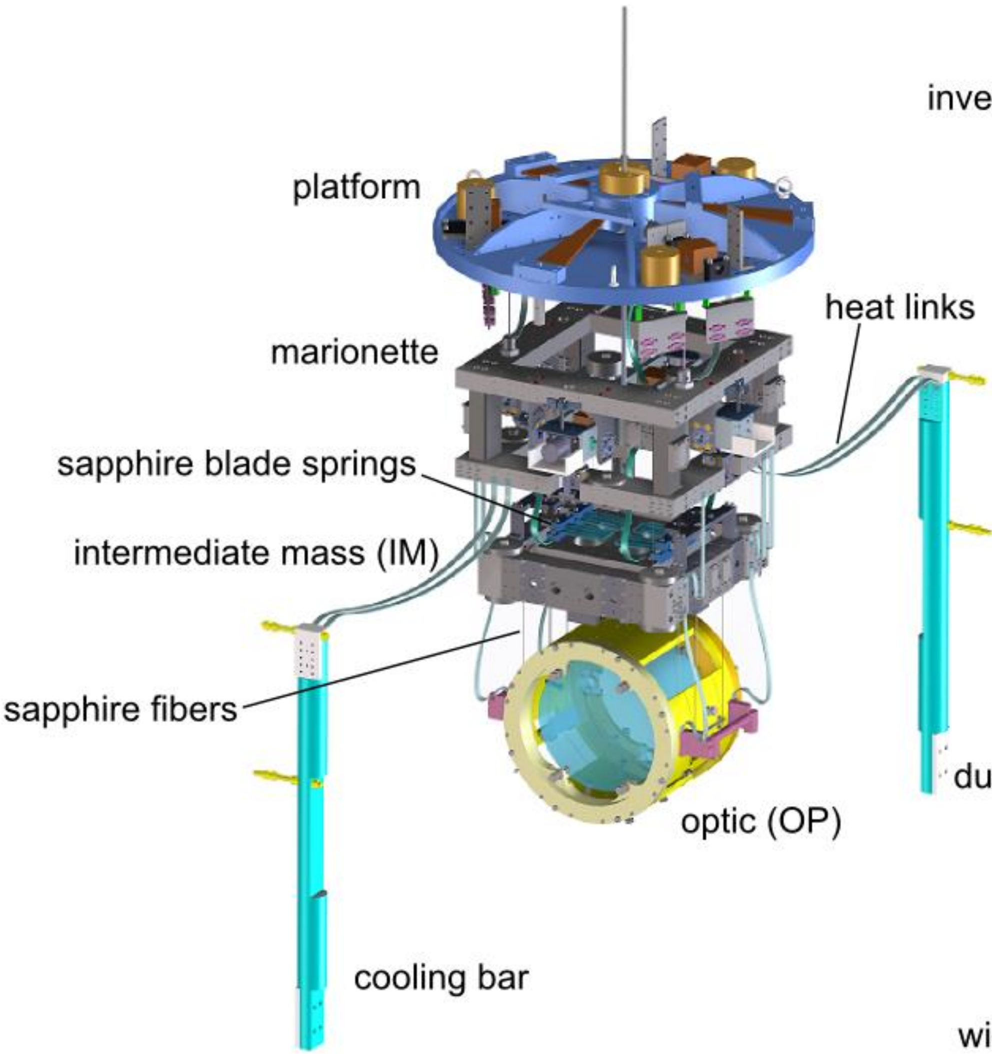
IM suspended by 4 CuBe fibers
(24 cm long, 0.6 mm dia)
IRM suspended by 4 CuBe fibers

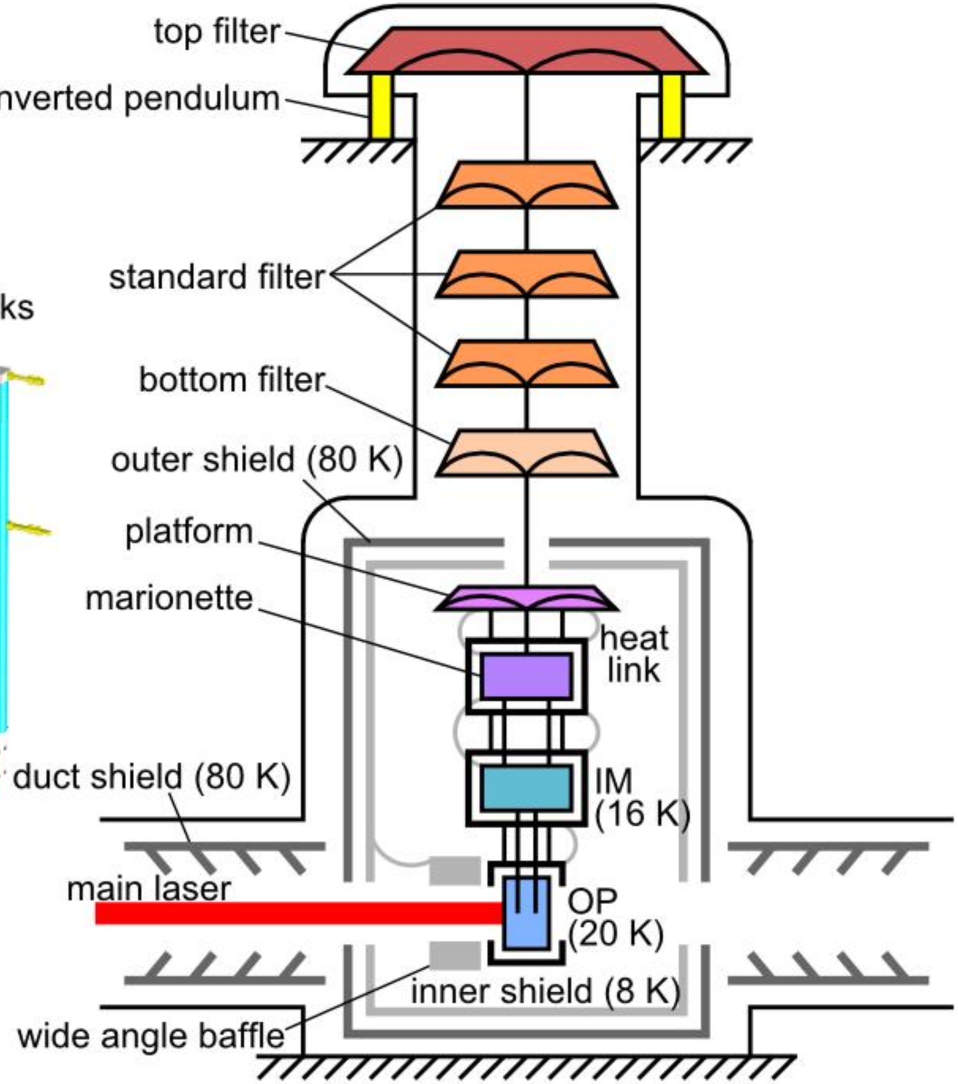
4 sapphire blades

Test Mass
(Sapphire, 23 kg,
22 K)

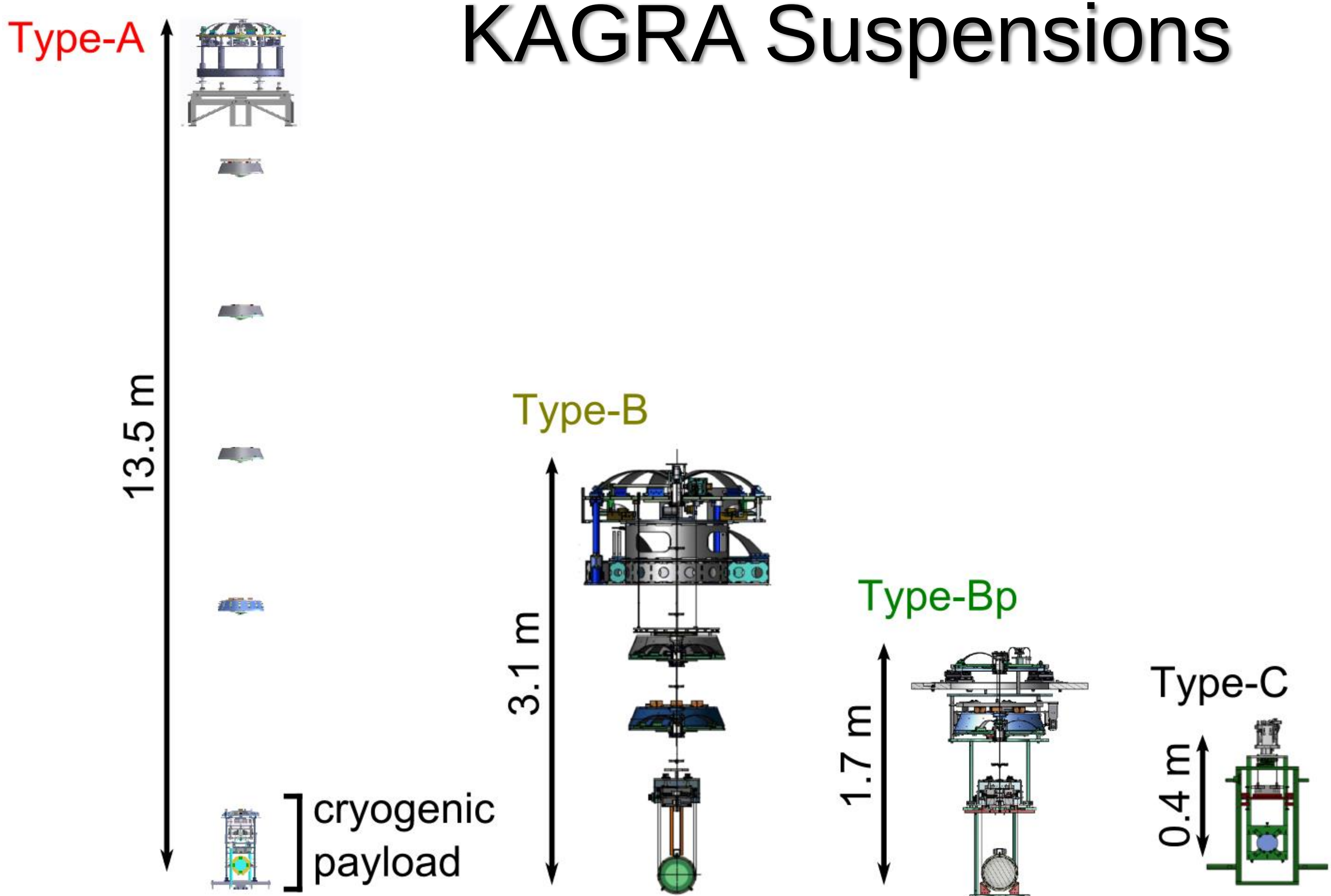
TM suspended by 4 sapphire fibers
(35 cm long, 1.6 mm dia.)
RM suspended by 4 CuBe fibers

KAGRA Cryostat Schematic

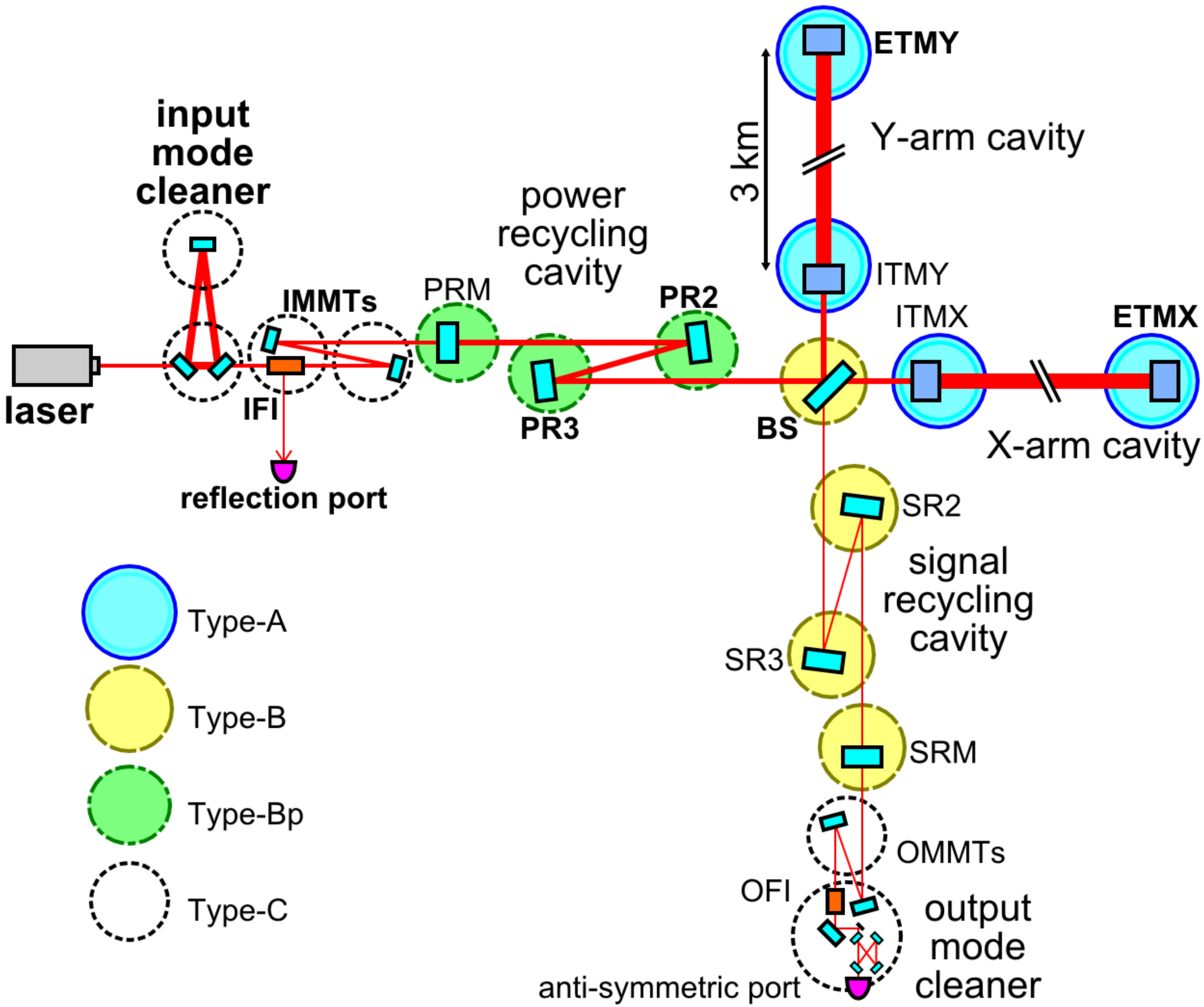




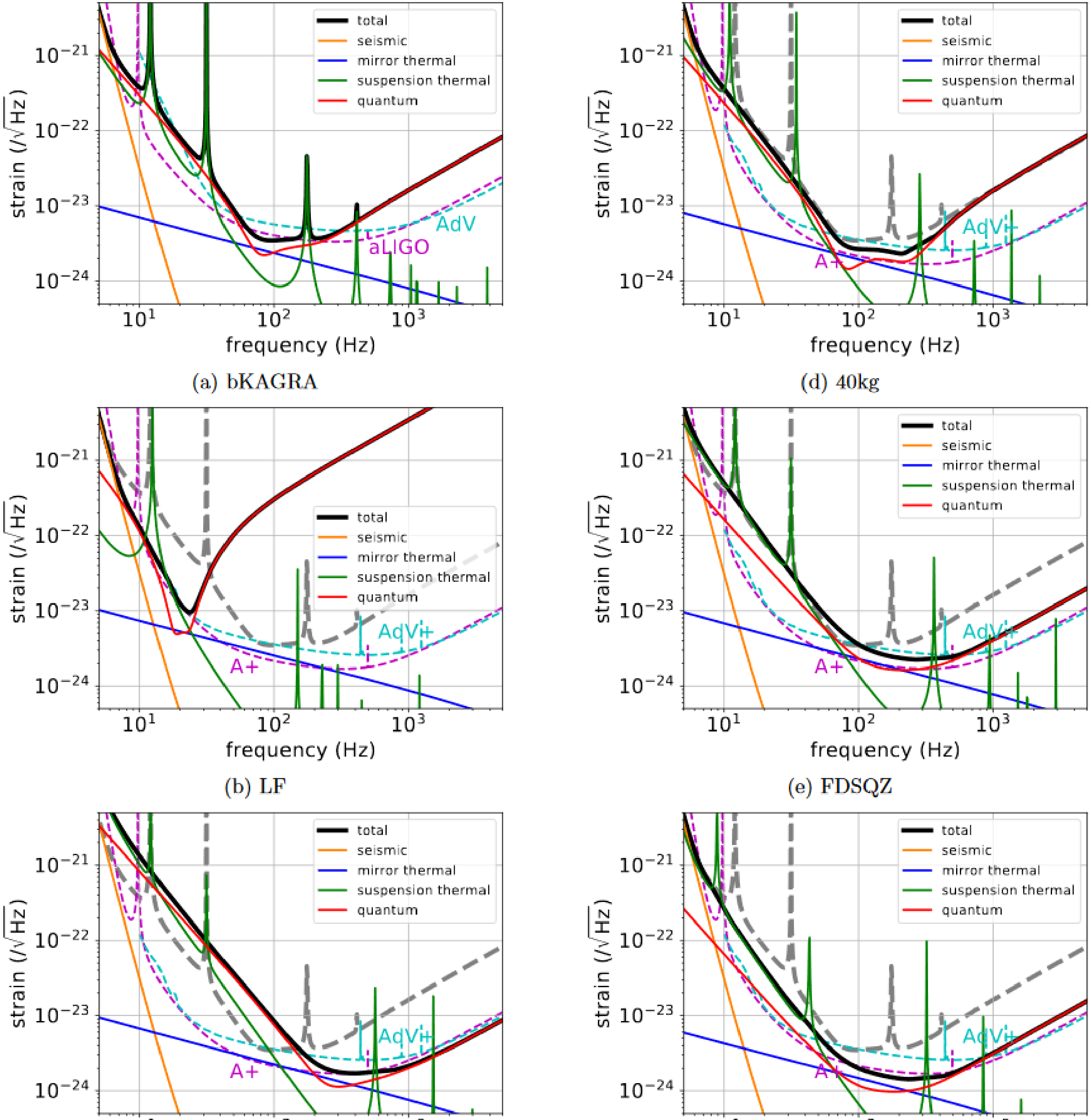
KAGRA Suspensions



KAGRA Interferometer



Possible KAGRA Upgrade Plans



(a) bKAGRA (d) 40kg (b) LF (e) FDSQZ (c) HF (f) Combined

Y. Michimura+, [PRD 97, 122003 (2018)](); [JGW-T1809537]()

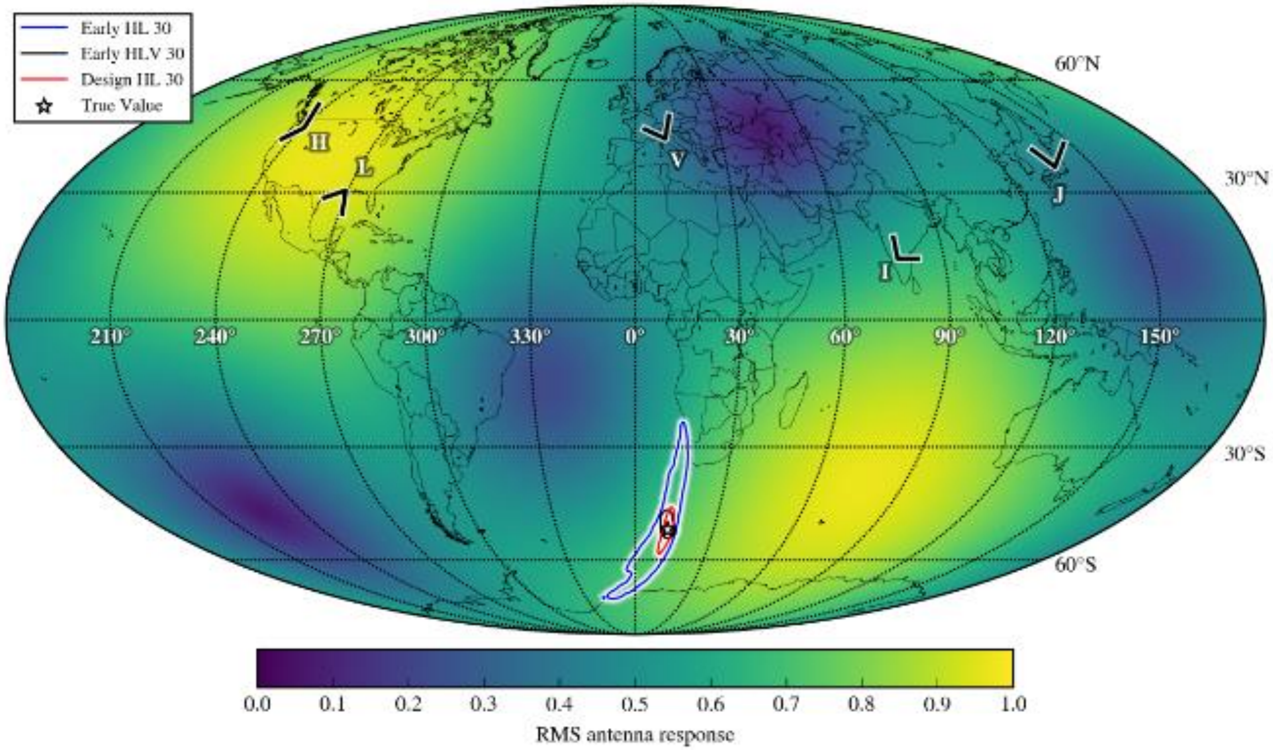
Possible KAGRA Upgrade Plans

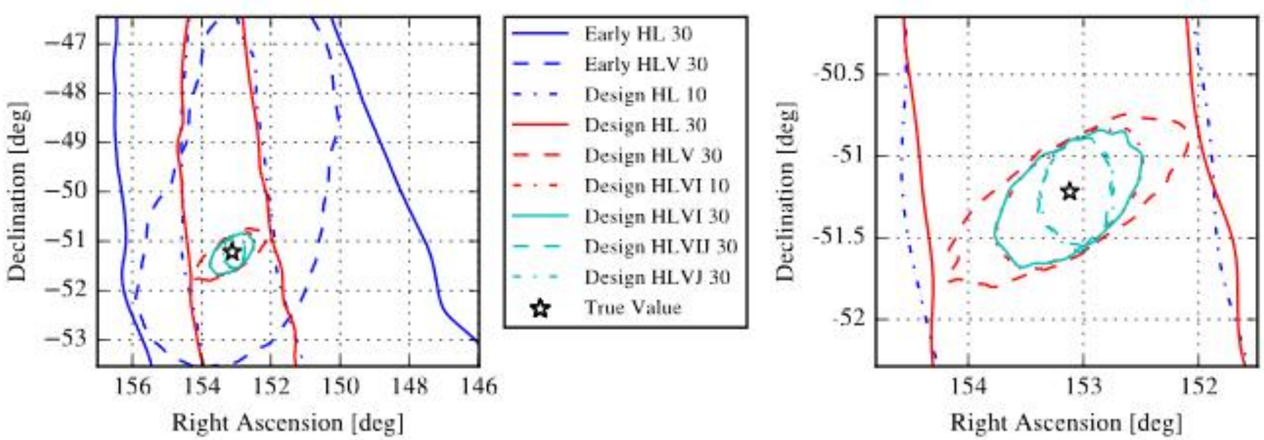
Y. Michimura+,
PRD 97, 122003 (2018);
JGW-T1809537

		bKAGRA	LF	HF	40kg	FDSQZ	Combined
detuning angle (deg)	$\phi_{\rm det}$	3.5	28.5	0.1	3.5	0.2	0.3
homodyne angle (deg)	ζ	135.1	133.6	97.1	123.2	93.1	93.0
mirror temperature (K)	$T_{\rm m}$	22	23.6	20.8	21.0	21.3	20.0
SRM reflectivity (%)	$R_{\rm SRM}$	84.6	95.5	90.7	92.2	83.2	80.9
fiber length (cm)	$l_{\rm f}$	35.0	99.8	20.1	28.6	23.0	33.1
fiber diameter (mm)	$d_{\rm f}$	1.6	0.45	2.5	2.2	1.9	3.6
mirror mass (kg)	m	22.8	22.8	22.8	40	22.8	100
input power at BS (W)	I_0	673	4.5	3440	1500	1500	3470
maximum detected squeezing (dB)		0	0	6.1	0	5.2 (FC)	5.1 (FC)
$100M_\odot$-$100M_\odot$ inspiral range (Mpc)		353	**2099**	114	412	318	702
$30M_\odot$-$30M_\odot$ inspiral range (Mpc)		1095	1094	271	1269	855	1762
$1.4M_\odot$-$1.4M_\odot$ inspiral range (Mpc)		**153**	85	156	**202**	**179**	**307**
median sky localization error (deg^2)		0.183	0.507	**0.105**	0.156	0.119	0.099

GW150914 with KAGRA

[CQG 34, 174003 (2017)](https://doi.org/10.1088/1361-6382/aa7bef)





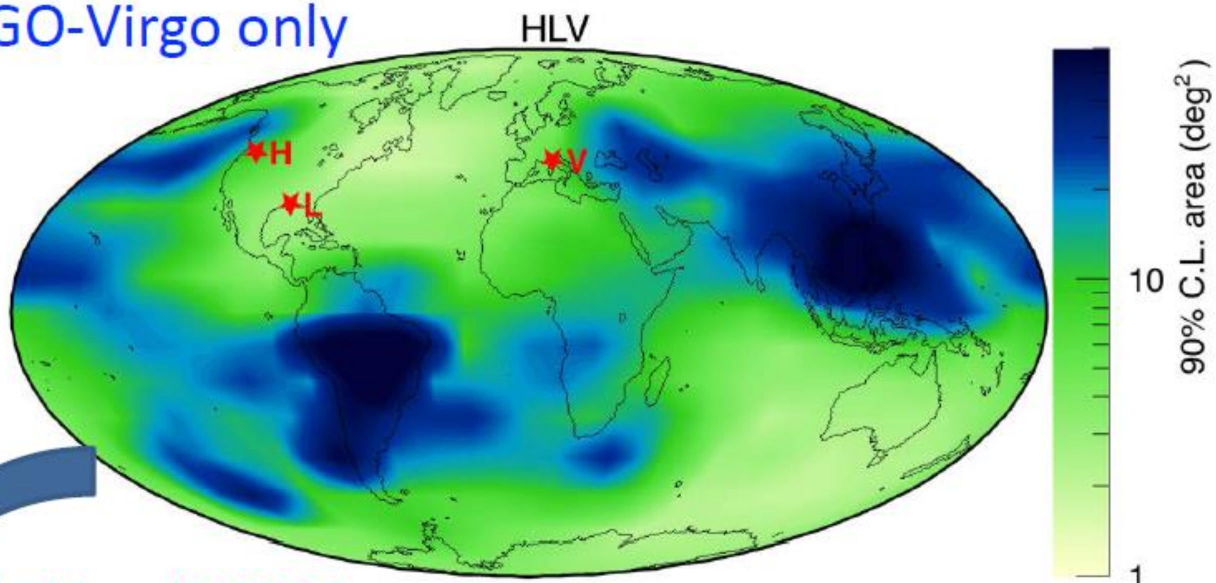
Sky localization
HLV 0.57 deg^2
HLVK 0.13 deg^2

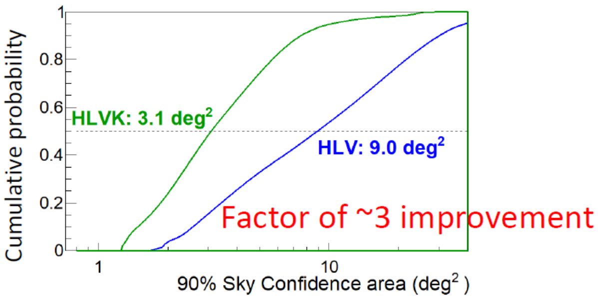
Distance error
HLV 179 Mpc
HLVK 98 Mpc

(with designed sensitivity, 90% credible)

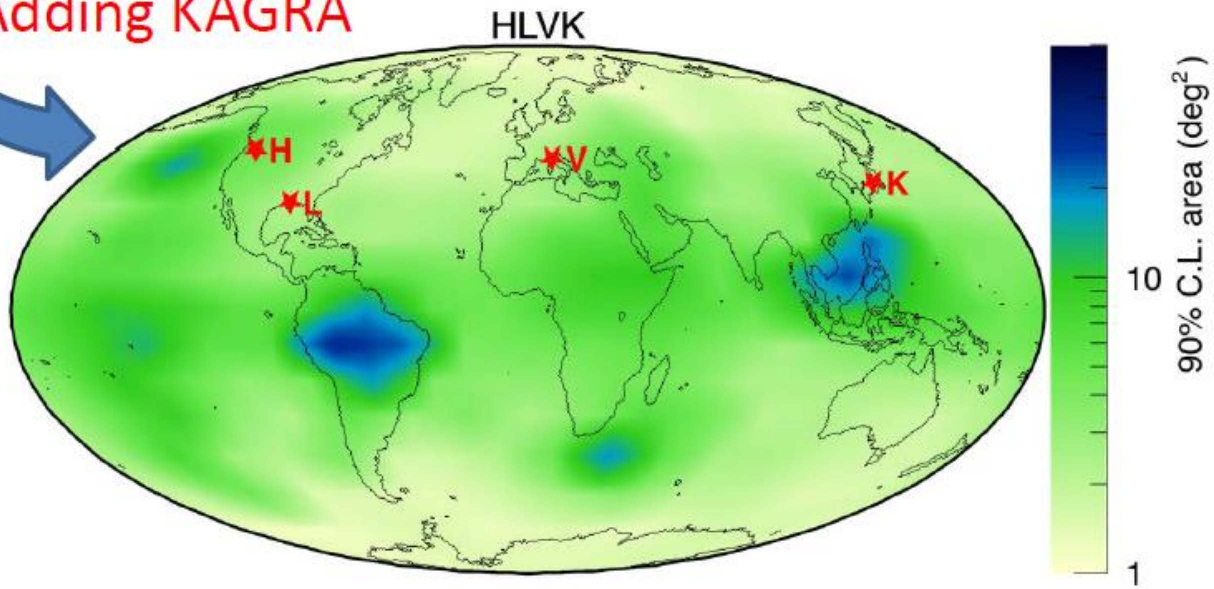
Sky Localization

LIGO-Virgo only





Adding KAGRA



BNS at 150 Mpc
(with designed sensitivity)

Calculation
by S. Haino