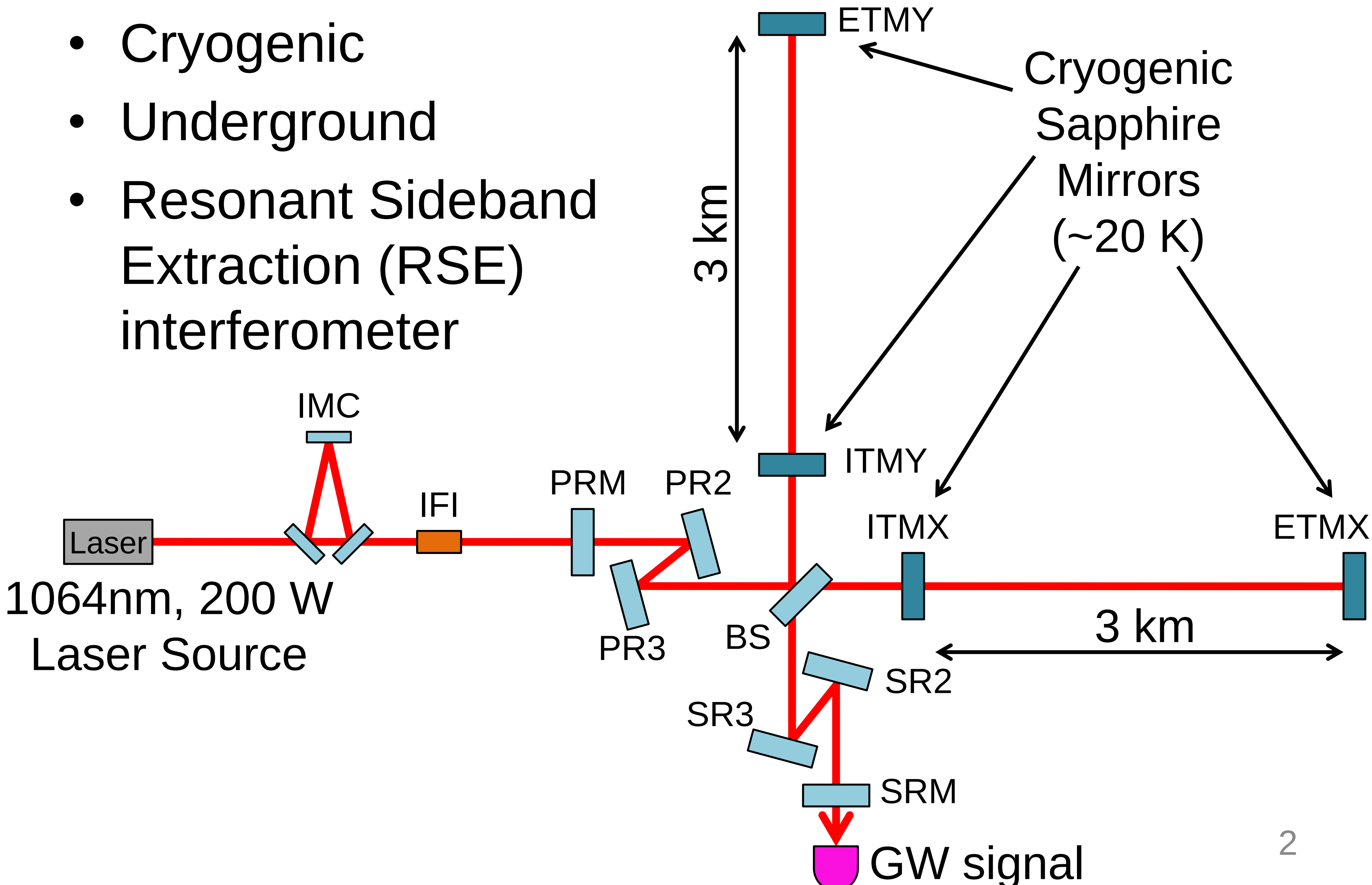
Possibility of Upgrading KAGRA

Yuta Michimura
Department of Physics, University of Tokyo

with much help from
Kentaro Komori, Yutaro Enomoto, Koji Nagano,
Kentaro Somiya, Sadakazu Haino ……

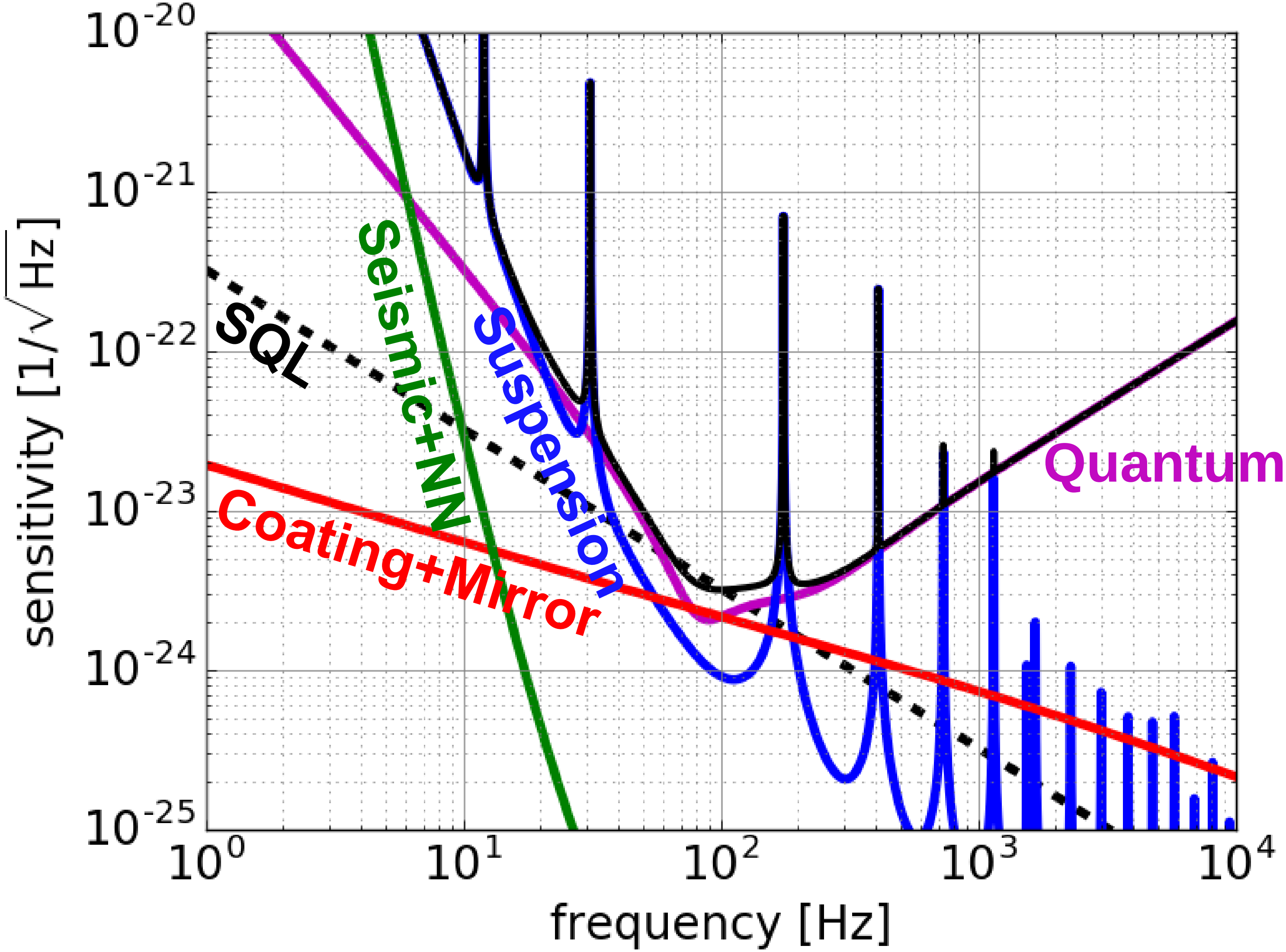
KAGRA Configuration

- Cryogenic
- Underground
- Resonant Sideband Extraction (RSE) interferometer



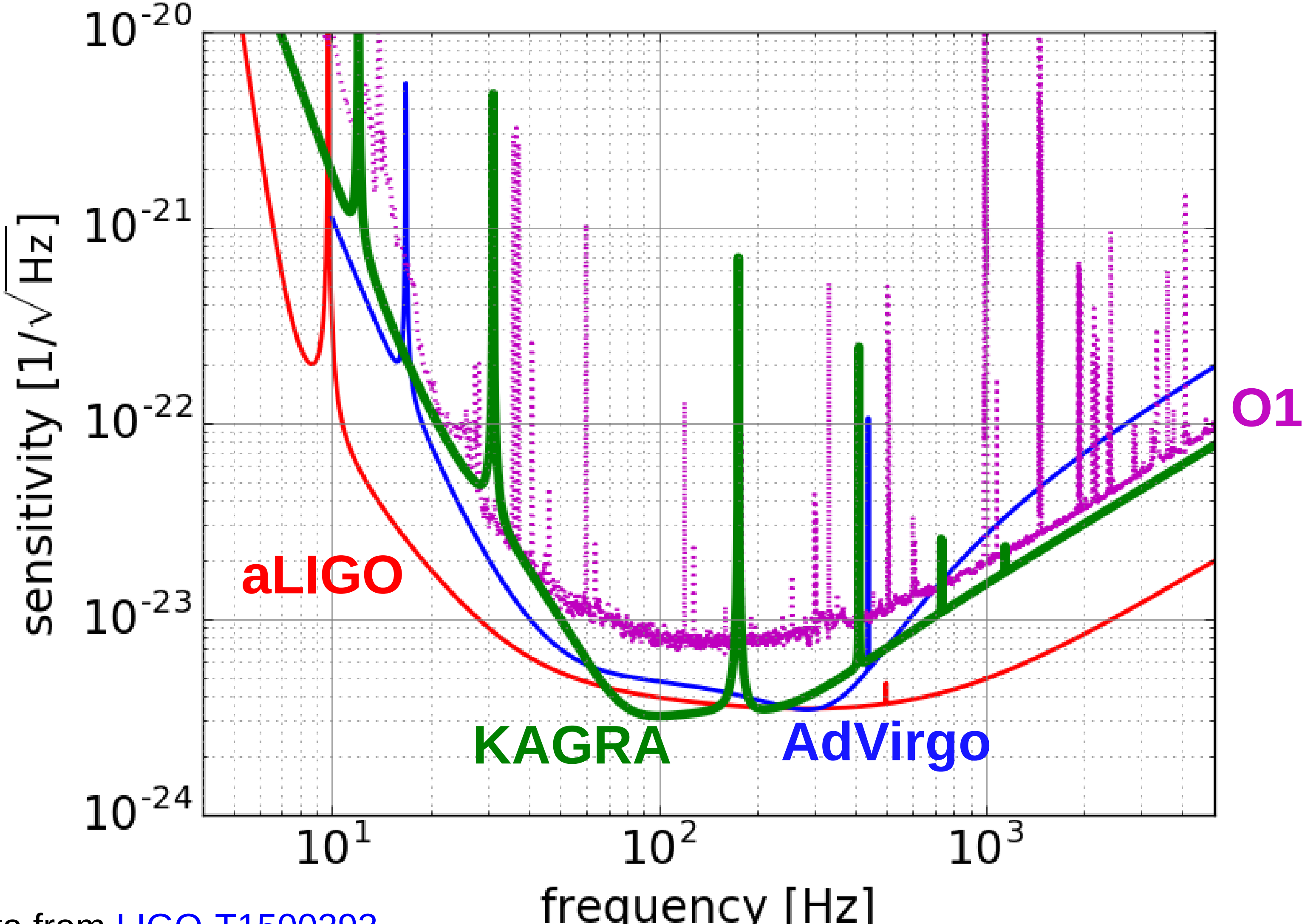
KAGRA Sensitivity (v2017)

- BNS range 158 Mpc, BBH(30Msun) range 1.0 Gpc



KAGRA vs Other 2G

- Not better even with cryogenic and underground

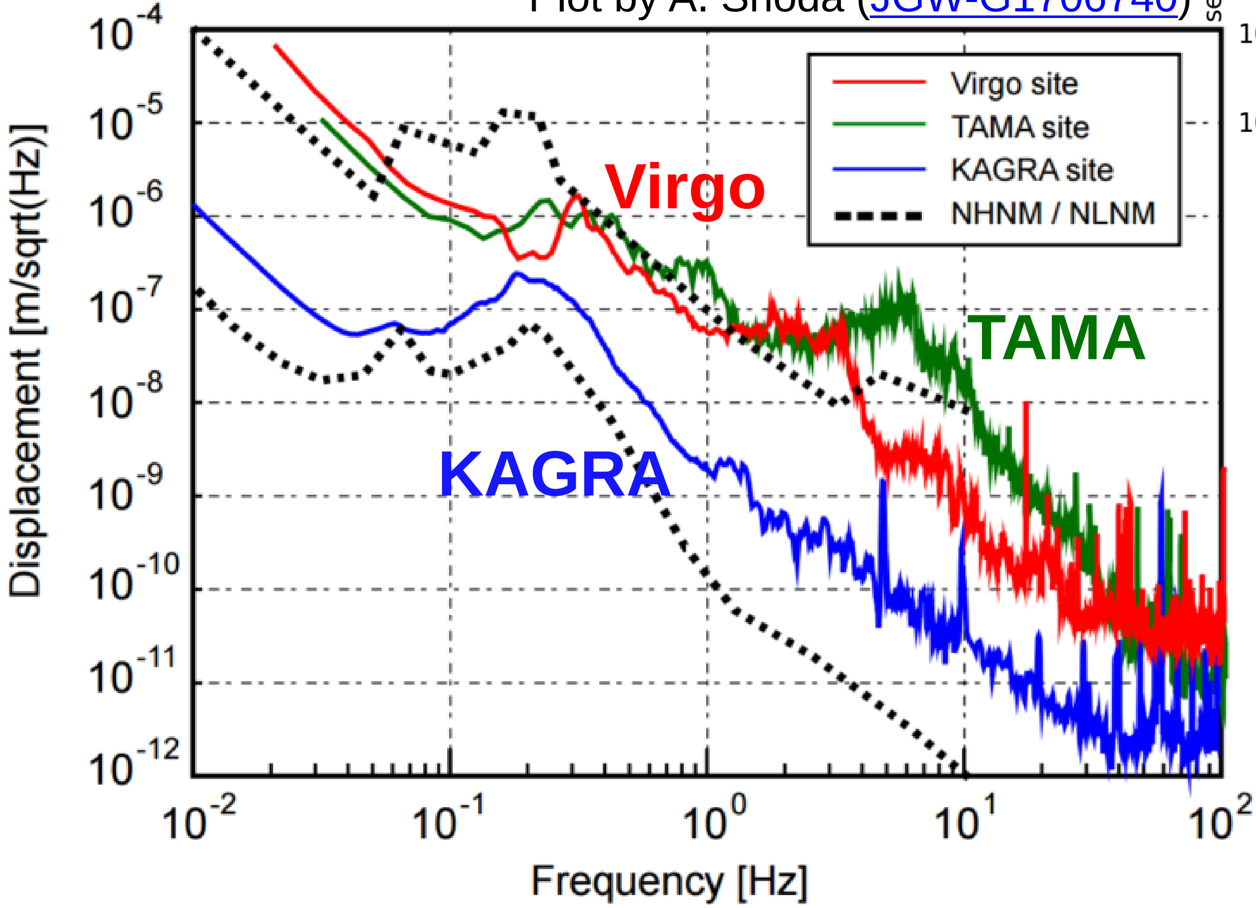


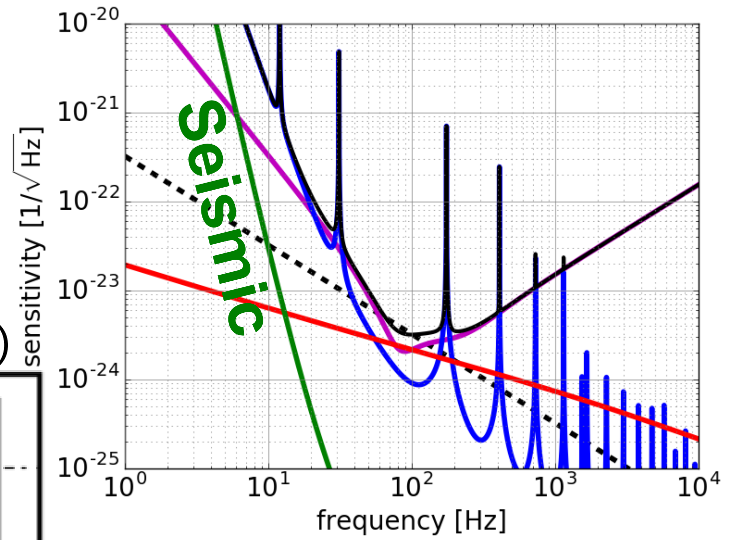
Spectra data from LIGO-T1500293

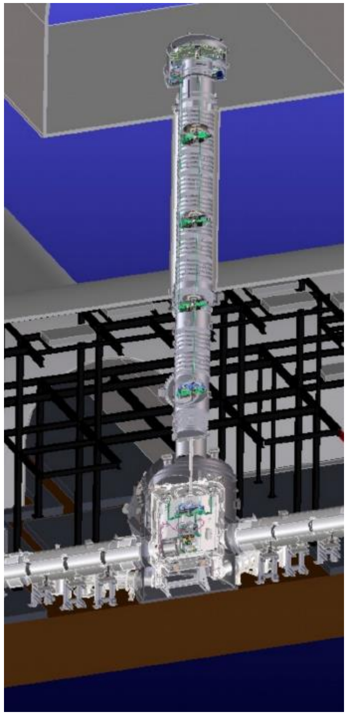
Seismic Noise

- Basically low, thanks to underground and tower suspensions

Plot by A. Shoda (JGW-G1706740)

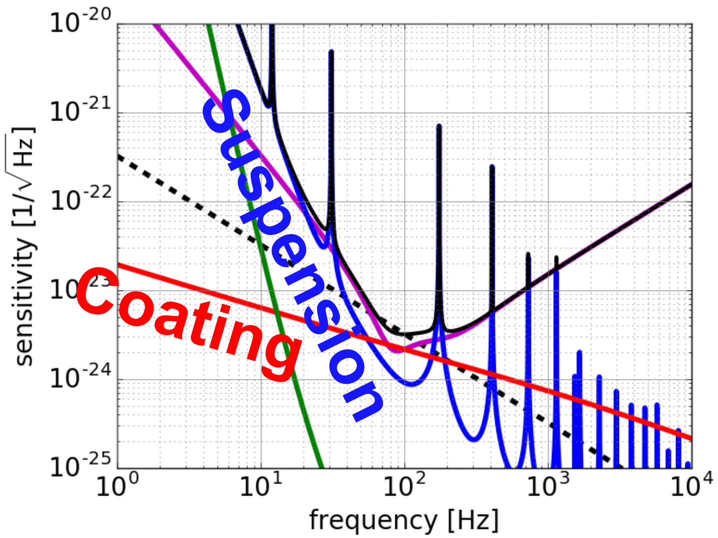


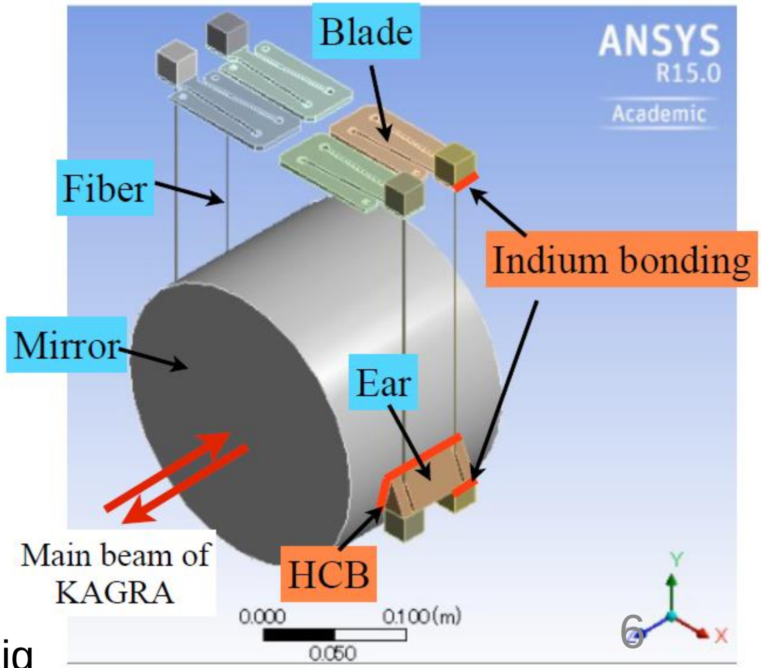




Thermal Noise

- Cryogenic temperature high Q (low loss) sapphire reduces thermal noise
- Thick sapphire fibers to extract heat increase suspension thermal noise
- Smaller beam sizes because of smaller mirrors increase coating thermal noise





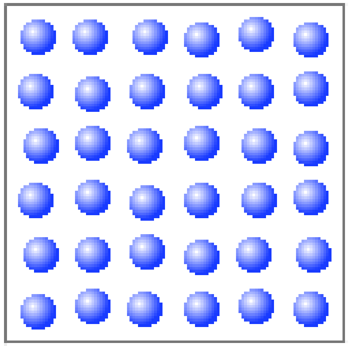
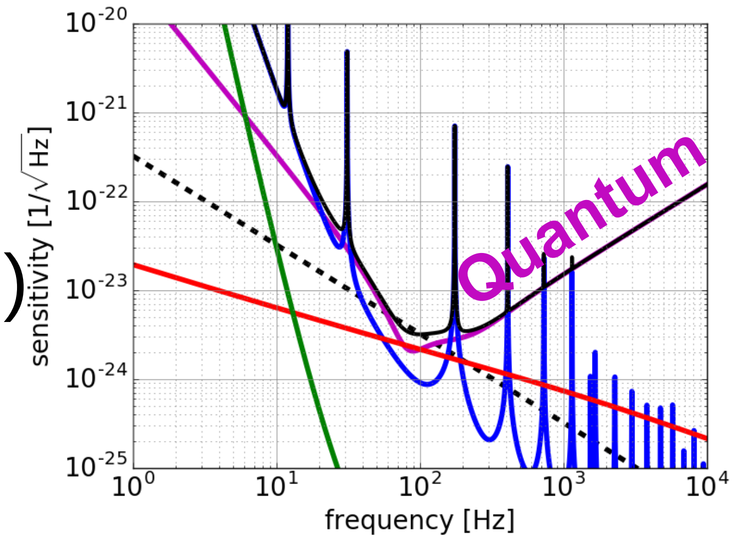


Figure from K. Craig

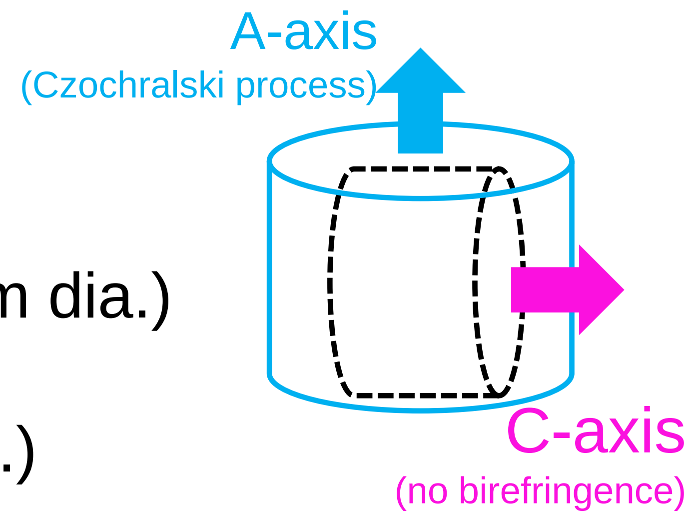
Quantum Noise



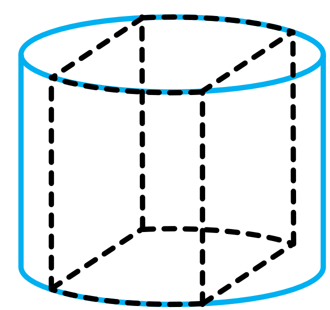
- 23 kg mirror was the largest sapphire mirror we can get (aLIGO: 40 kg, AdVirgo: 42 kg)
- Smaller mirror increases radiation pressure noise
- Less laser power because of limited heat extraction
  - Intra-cavity power
    - KAGRA: 400 kW, aLIGO/AdVirgo: 700 kW

Ideas for Improving Sensitivity

- Increase the mass
  - GAST project (upto 30 cm dia. ?)
  - composite mass
  - A-axis sapphire (upto 50 kg, 26 cm dia.)
  - non-cylindrical mass (upto 30 kg)
  - go silicon (upto 200 kg, 45 cm dia.)

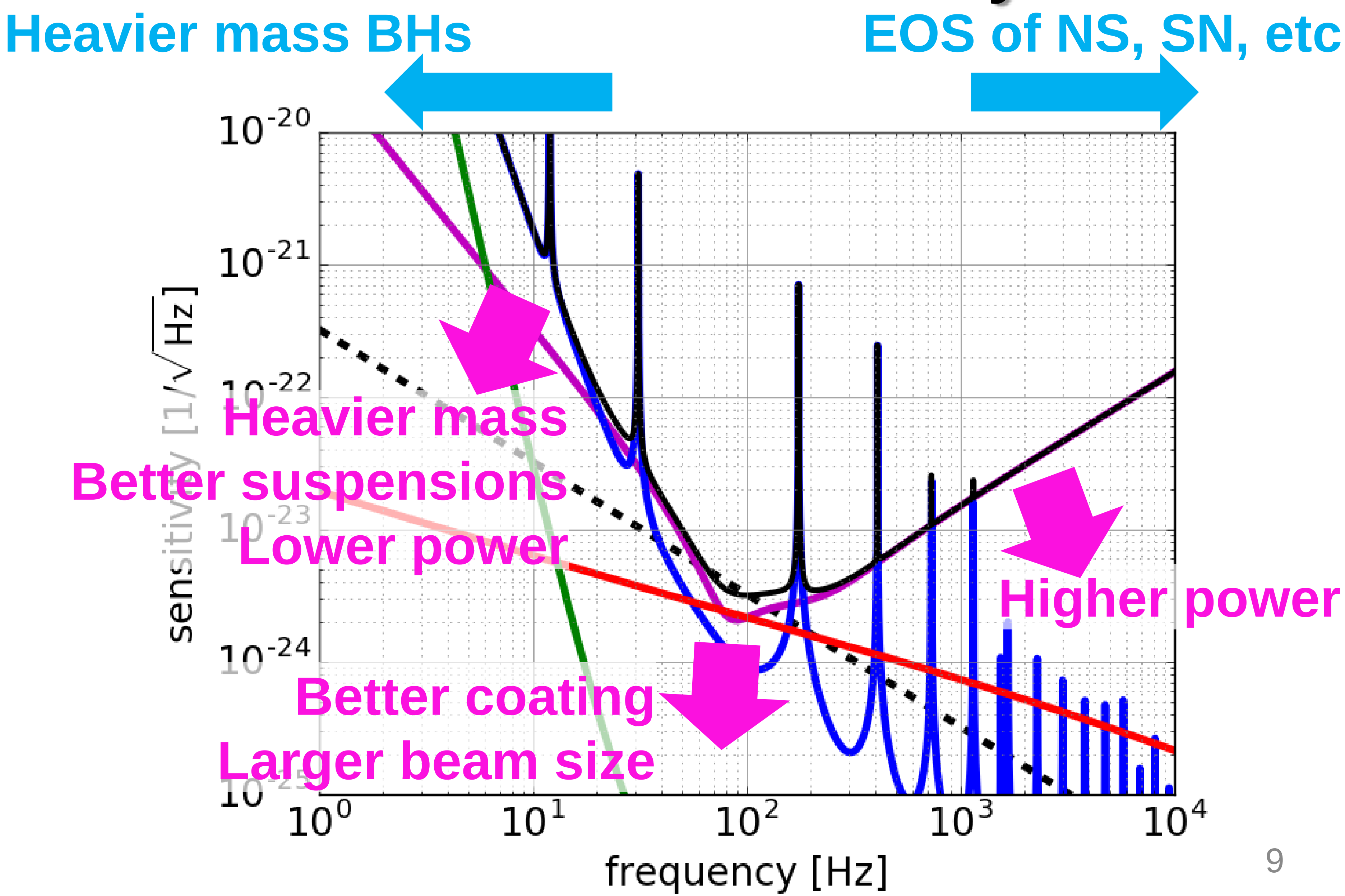


- Frequency dependent squeezing (Filter cavity)
  - effectively increase mass and laser power



- Better coating, low absorption mirror
- Better cryogenic suspension design
- ETM different from ITM, half-cryogenic, delay-line, folded arms, higher-order modes, suspension point interferometer …… ???

Effect in Sensitivity



Integrated Design Study

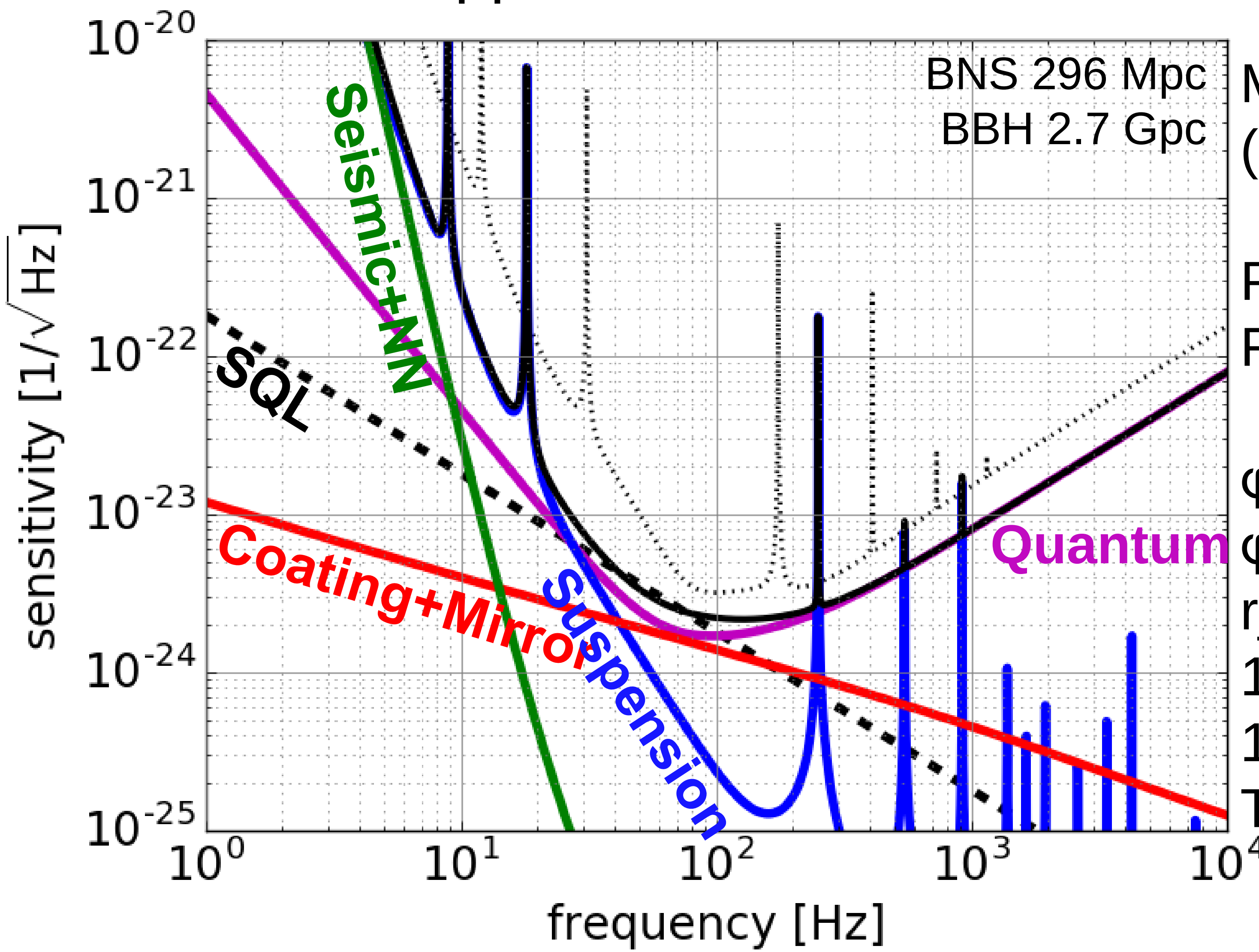
- We need a plan to integrate these ideas
  To begin with, some example plans were proposed
- Plan: **Blue** (by Yutaro Enomoto)
  use heavier sapphire mirrors
- Plan: **Black** (by Kentaro Komori)
  use silicon mirrors
- Plan: **Brown** (by Koji Nagano)
  lower the power to focus on low frequency
- Plan: **Red** (by Sadakazu Haino)
  increase the power to focus on high frequency

KAGRA+

(working title)

KAGRA+ Sensitivity: Blue

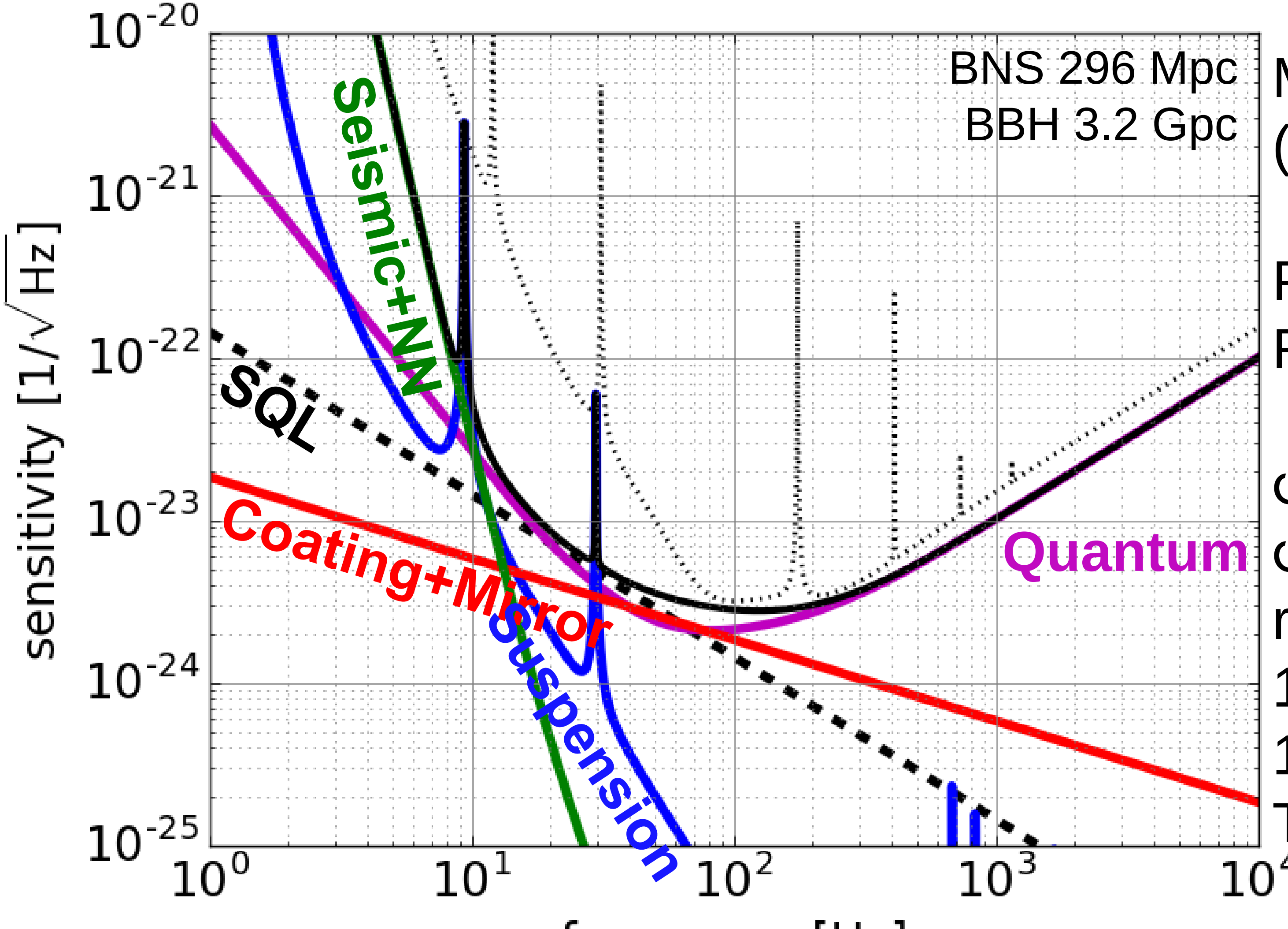
- Heavier sapphire and heavier IM, 20 K



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**

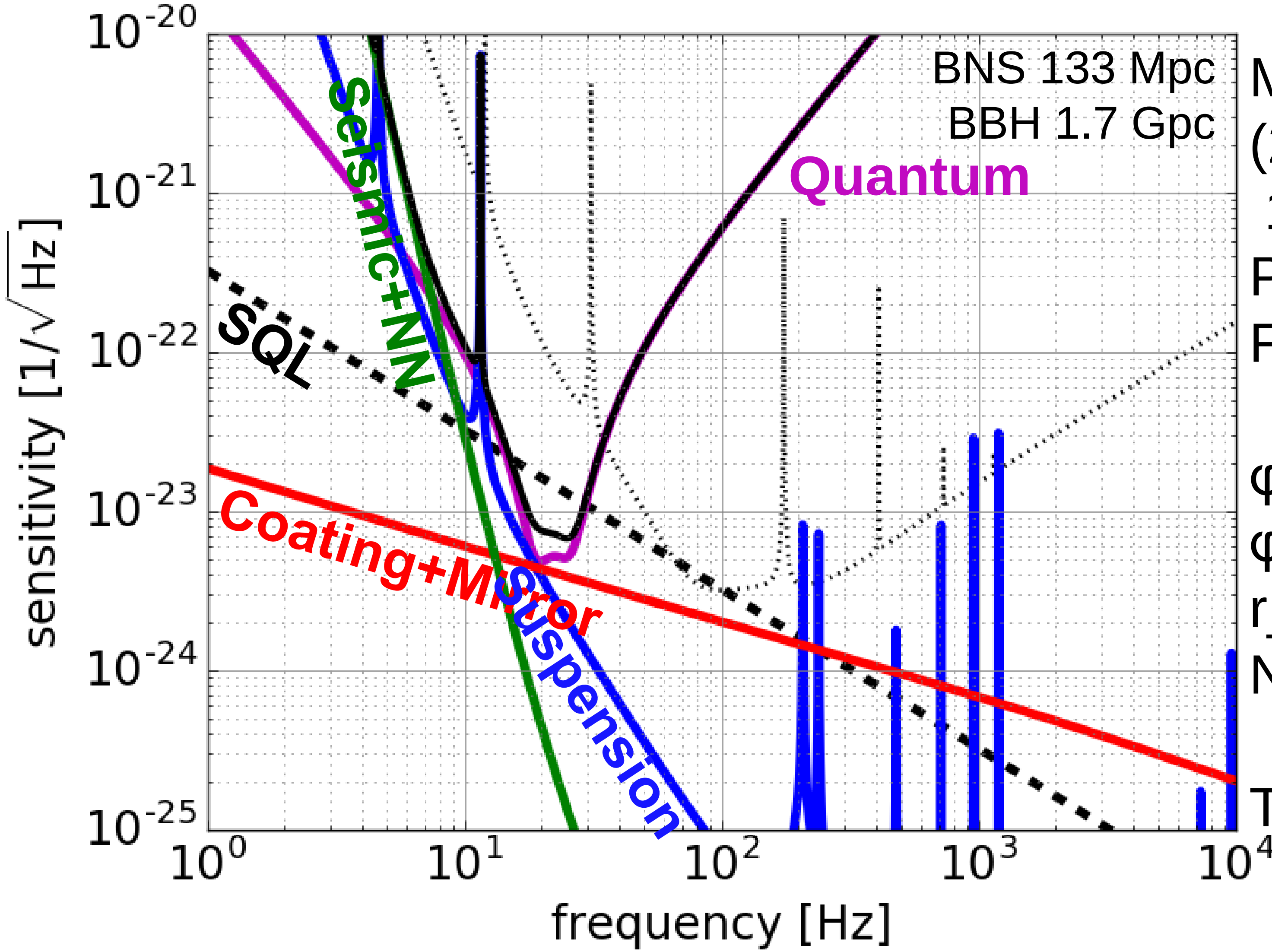
- Silicon 123 K, 1550 nm, radiative cooling



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

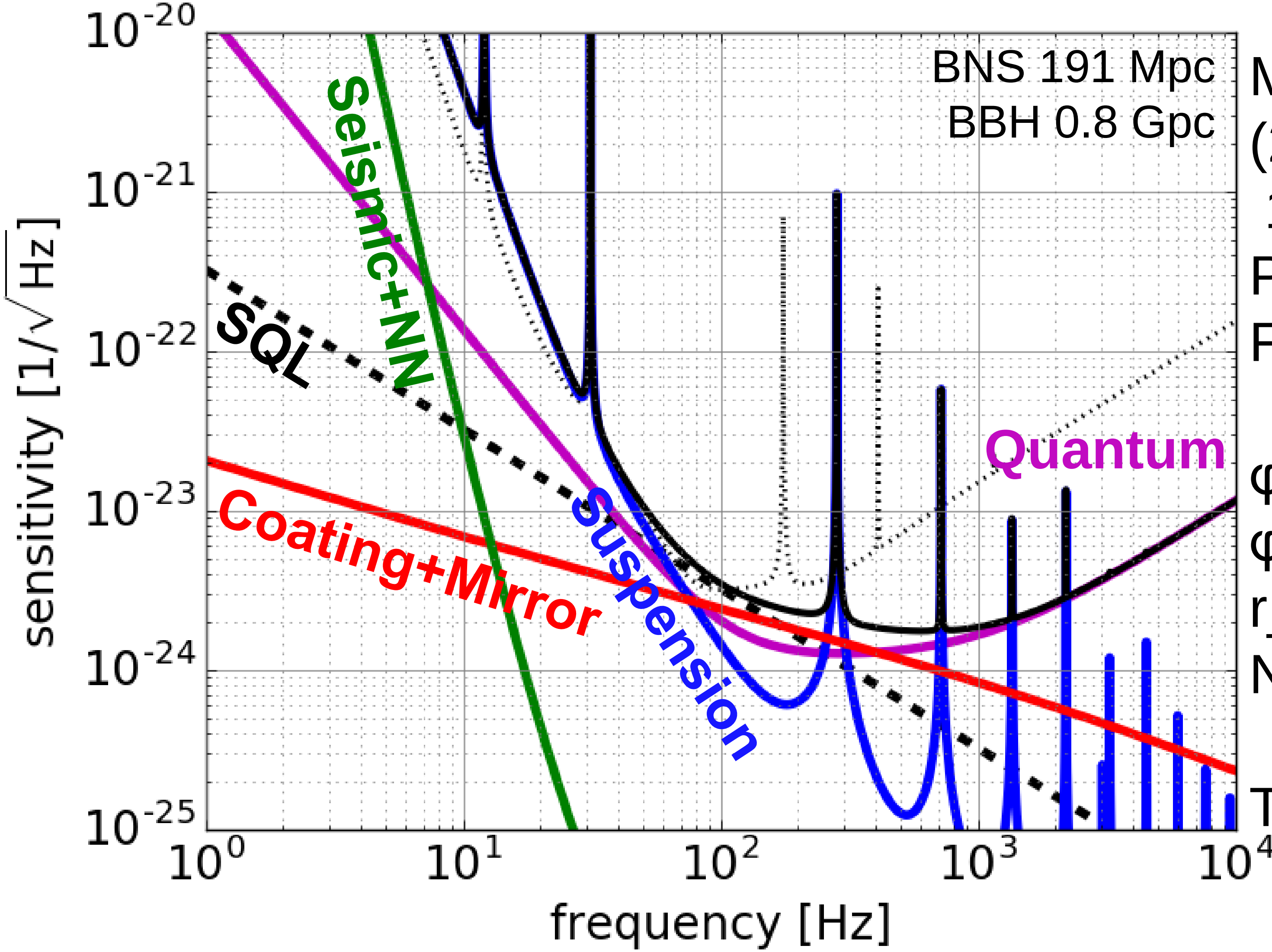


Mass: 23 kg
(22 cm dia.,
15 cm thick)
P_BS: 5.7 W
Fiber: 88 cm,
0.32 mm dia.
φ_susp: 2e-7
φ_coat: 5e-4
r_beam: 3.5 cm
No sqz

T_SRM: 4.35 %

KAGRA+ Sensitivity: Red

- Same test mass, high power, 24 K

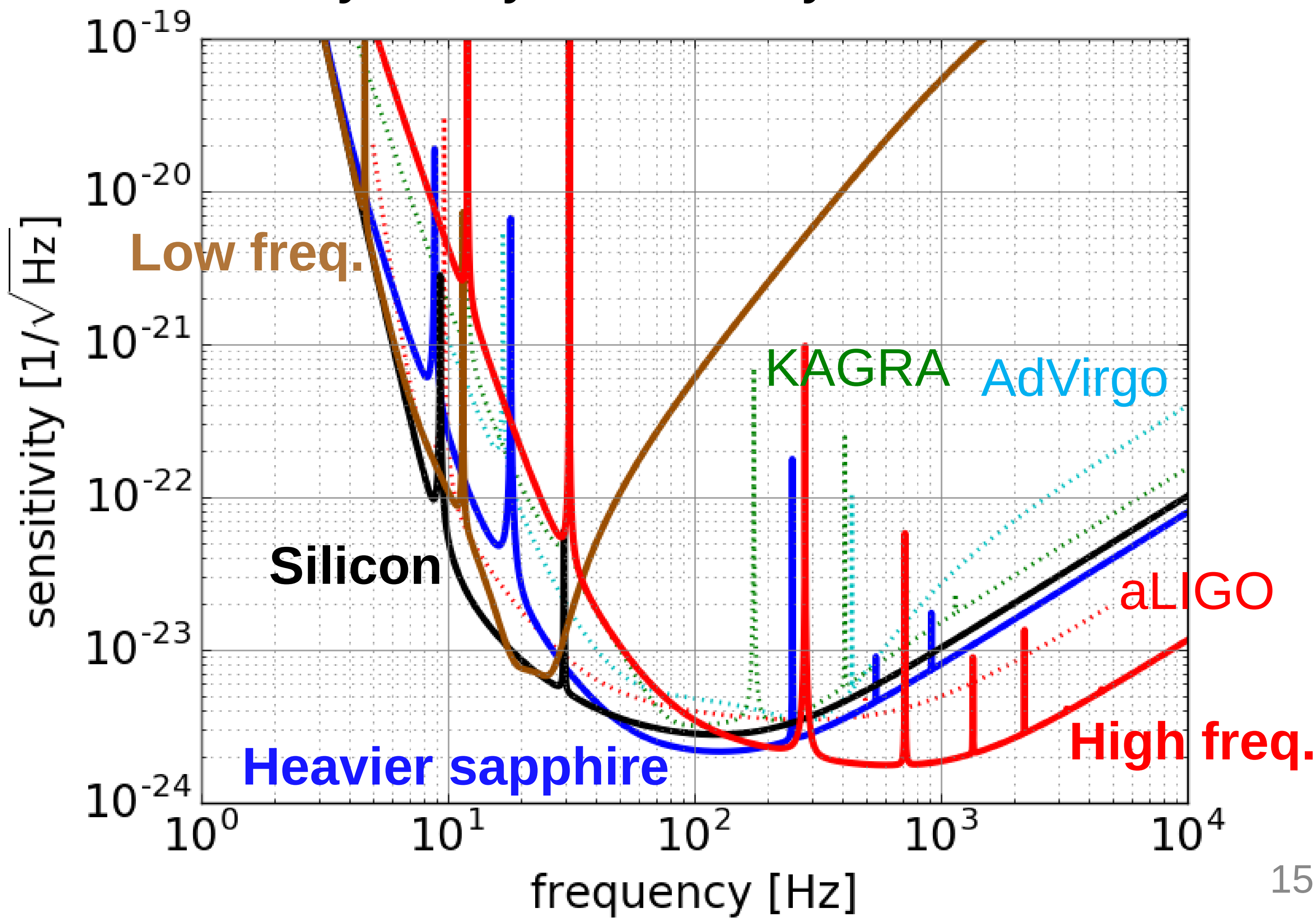


Mass: 23 kg
(22 cm dia.,
15 cm thick)
P_BS: 5.7 W
Fiber: 20 cm,
2.4 mm dia.
φ_susp: 2e-7
φ_coat: 5e-4
r_beam: 3.5 cm
No sqz

T_SRM: 4.94 %

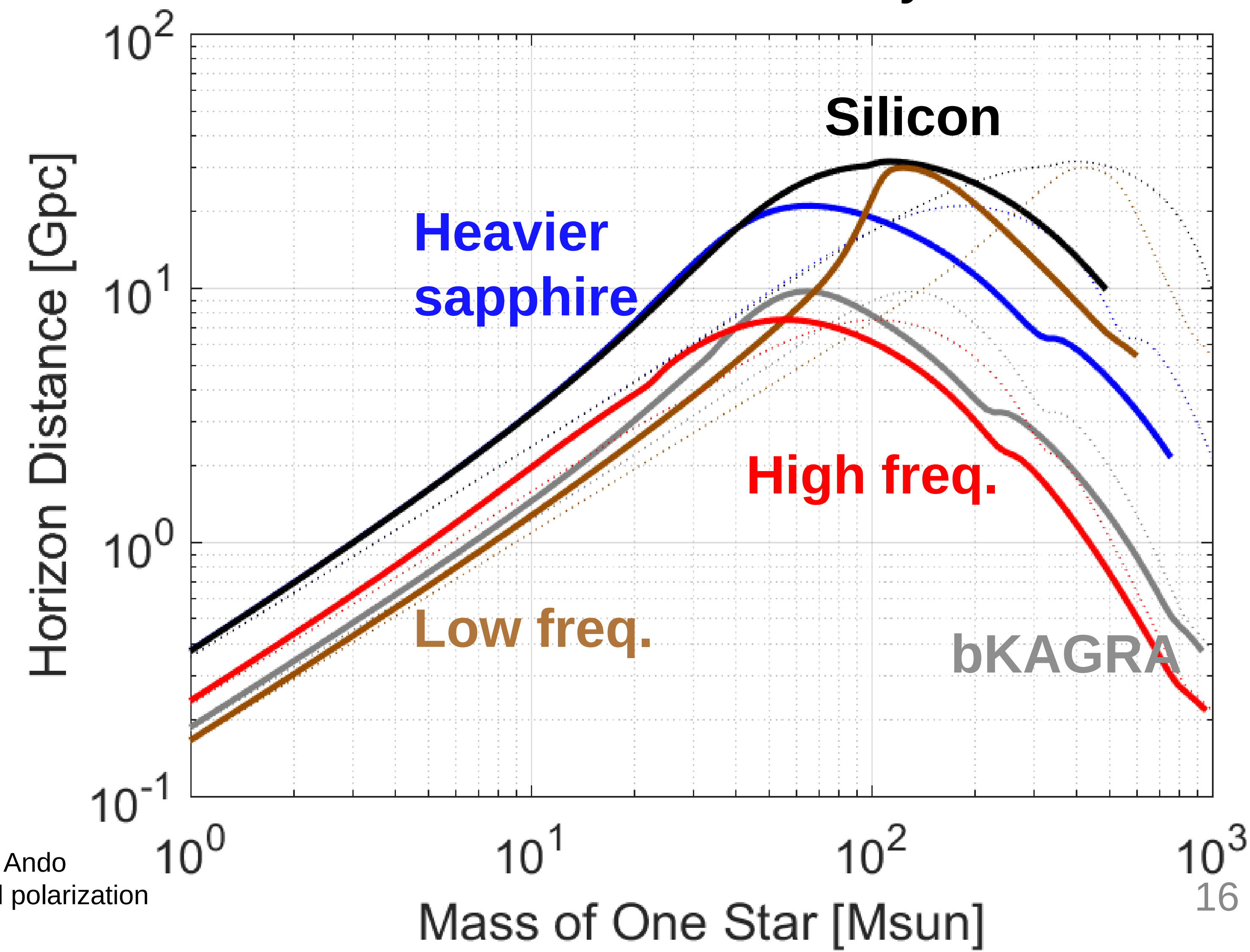
Sensitivity Comparison

- Also feasibility study necessary



Astrophysical Reach Comparison

- Science case discussion is necessary



Code provided by M. Ando
Optimal direction and polarization
SNR threshold 8

Summary

- Many ideas for improving the sensitivity have been proposed, and some R&D are on going
- Sensitivity design study on future KAGRA upgrade to integrate these ideas is necessary
- Some example plans are proposed
- Need more serious discussion based on feasibility, budget, timeline and science
- Any comments? New ideas?

Supplementary Slides

KAGRA Timeline

2016 — Initial KAGRA (iKAGRA)
- 3-km Michelson
- room temperature
- simplified suspensions
- First test operation

2017

2018 — Phase 1
- 3-km Michelson
- cryogenic temperature

2019 — Phase 2
- 3-km RSE
- cryogenic temperature

2020 — Phase 3
- 3-km RSE
- cryogenic temperature
- observation runs

Phases 1–3: Baseline KAGRA (bKAGRA)

2021

2022

KAGRA+ ?

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]	21	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]	78	125	125	125	140
Arm power [kW]	400	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

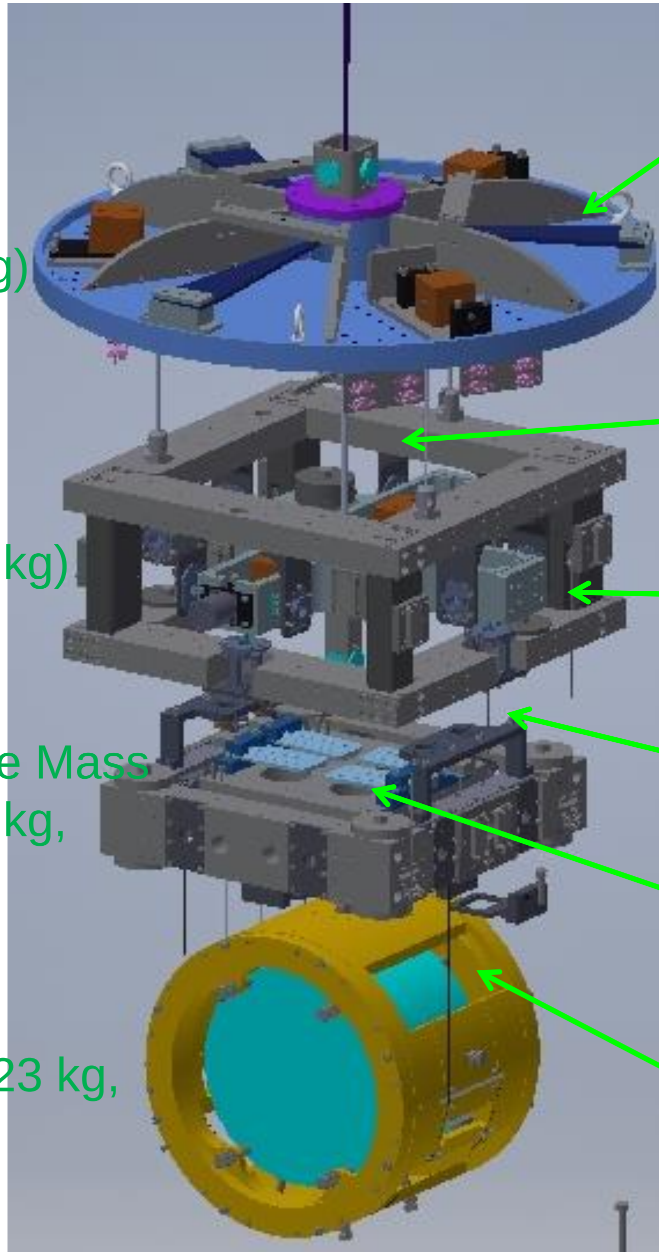
LIGO parameters from LIGO-T1600119, AdVirgo parameters from JPCS 610, 01201 (2015)

KAGRA Detailed Parameters

- **Optical parameters**
  - Mirror transmission: 0.4 % for ITM, 10 % for PRM, 15.36 % for SRM
  - Power at BS: 780 W
  - Detune phase: 3.5 deg (DRSE case)
  - Homodyne phase: 133 deg (DRSE case)
- **Sapphire mirror parameters**
  - TM size: 220 mm dia., 150 mm thick
  - TM mass: 22.8 kg
  - TM temperature: 21.5 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: 9 for ITM, 18 for ETM
  - Coating absorption: 0.5 ppm
  - Substrate absorption: 20 ppm/cm
- **Suspension parameters**
  - TM-IM fiber: 35 cm long, 1.6 mm dia.
  - IM temperature: 16.3 K
  - Heat extraction: 6580 W/m/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,
16.3 K)

Test Mass
(Sapphire, 23 kg,
21.5 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

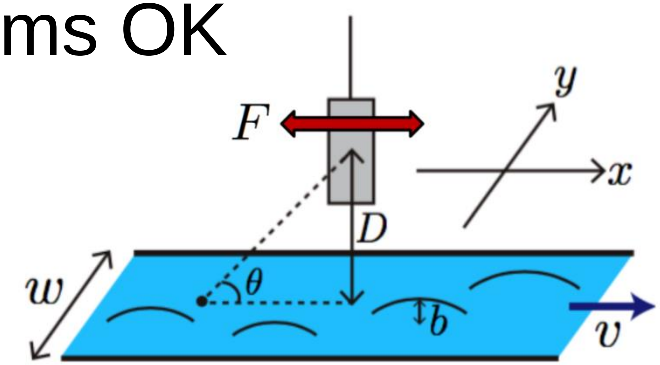
4 sapphire blades

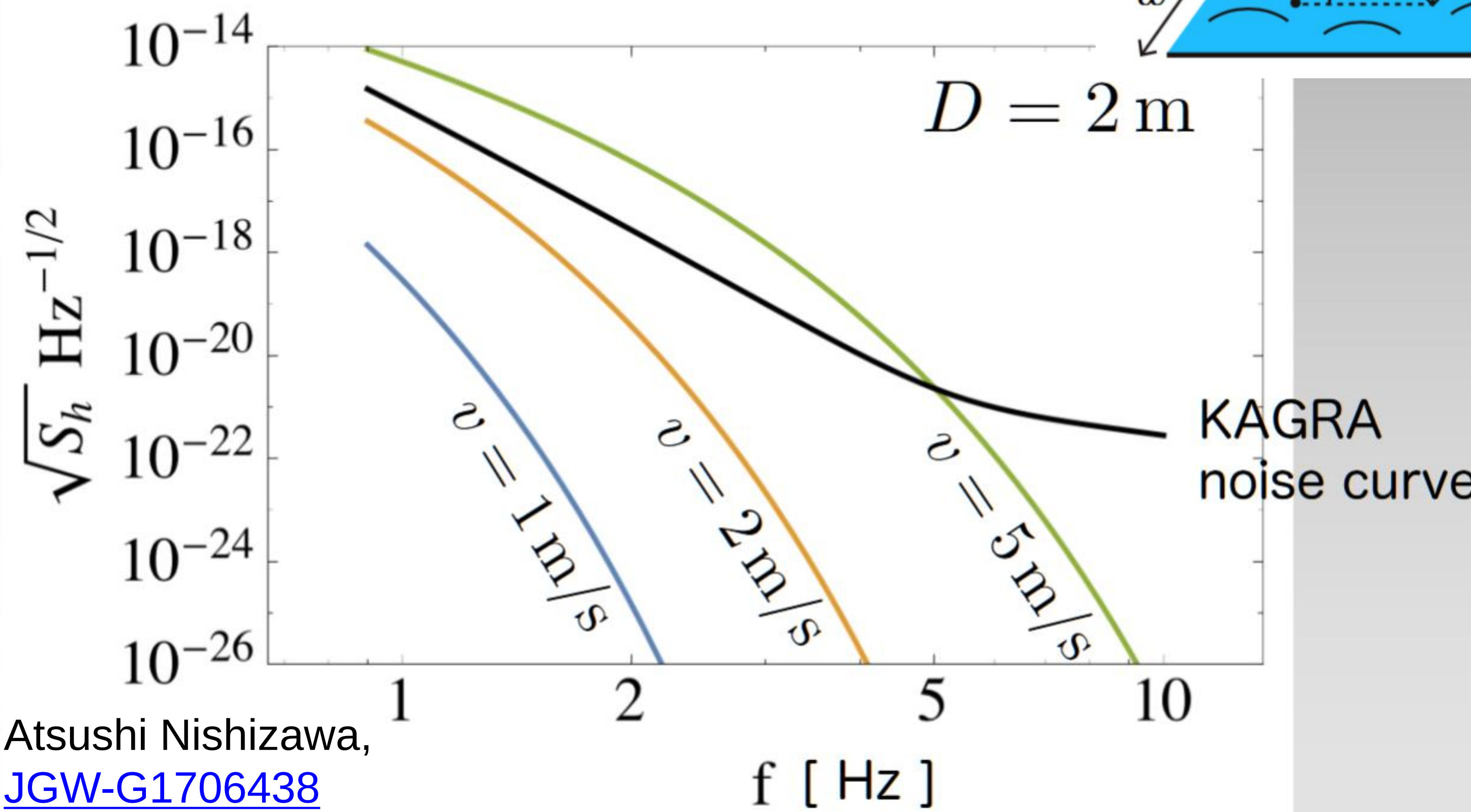
TM suspended by 4 sapphire fibers
(35 cm long, 1.6 mm dia.)
RM suspended by 4 CuBe fibers

Newtonian Noise from Water

- Measured v = 0.5~2 m/s → seems OK

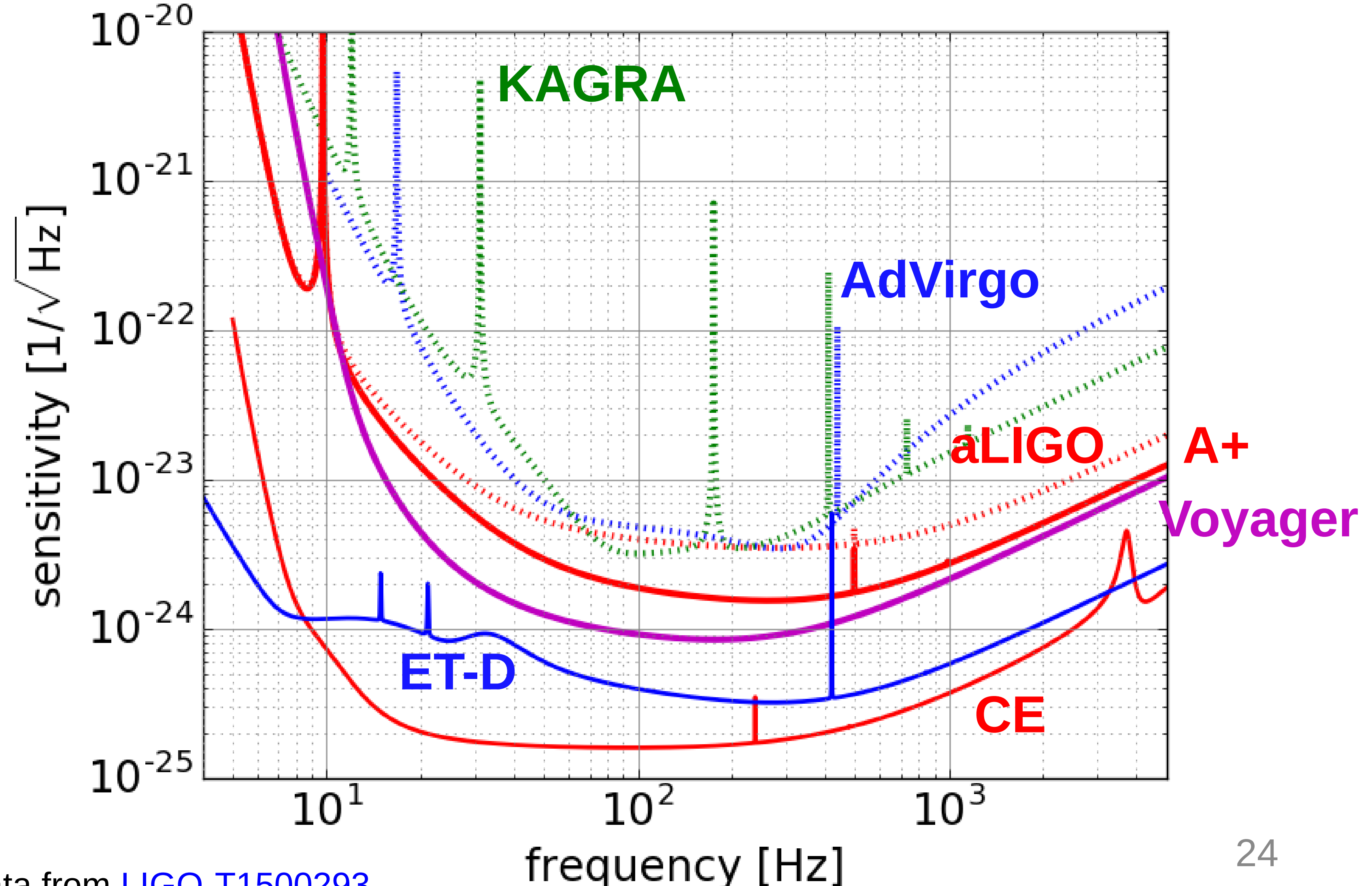
$$\sqrt{S_h(\Omega)} = \frac{2G\rho w}{\Omega L v} K_0\left(\frac{\Omega D}{v}\right)\sqrt{S_b(\Omega)}$$





Atsushi Nishizawa, JGW-G1706438

2-3G Sensitivity Comparison



Spectra data from [LIGO-T1500293]