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

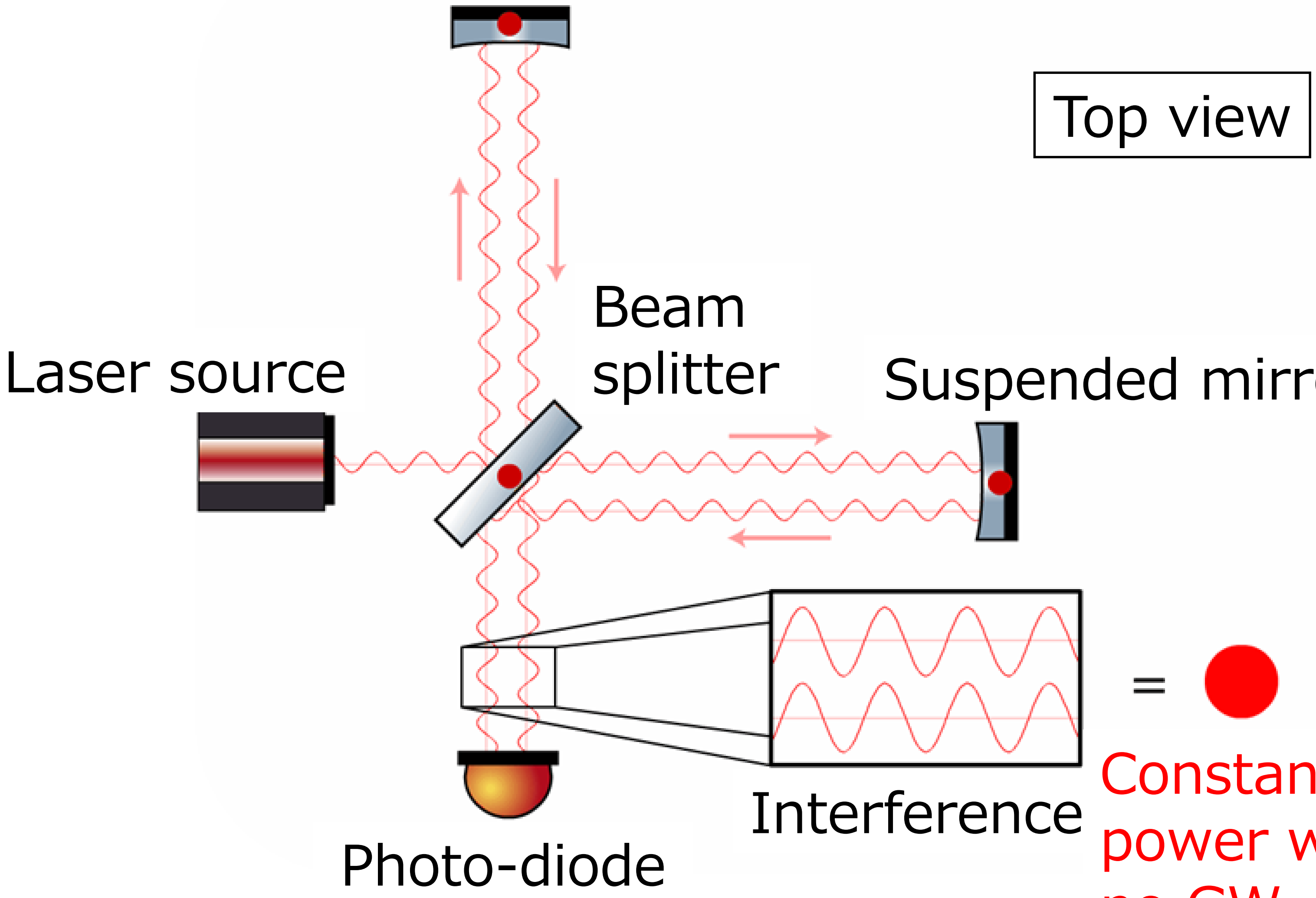
- Status and future of KAGRA
  - Introduction to KAGRA project
  - Impact of KAGRA joining observing runs
  - Status of KAGRA commissioning
  - Upgrade plans for KAGRA

Global Network of GW Detectors

- Network of ground-based Advanced interferometric gravitational wave detectors

Laser Interferometric GW Detector

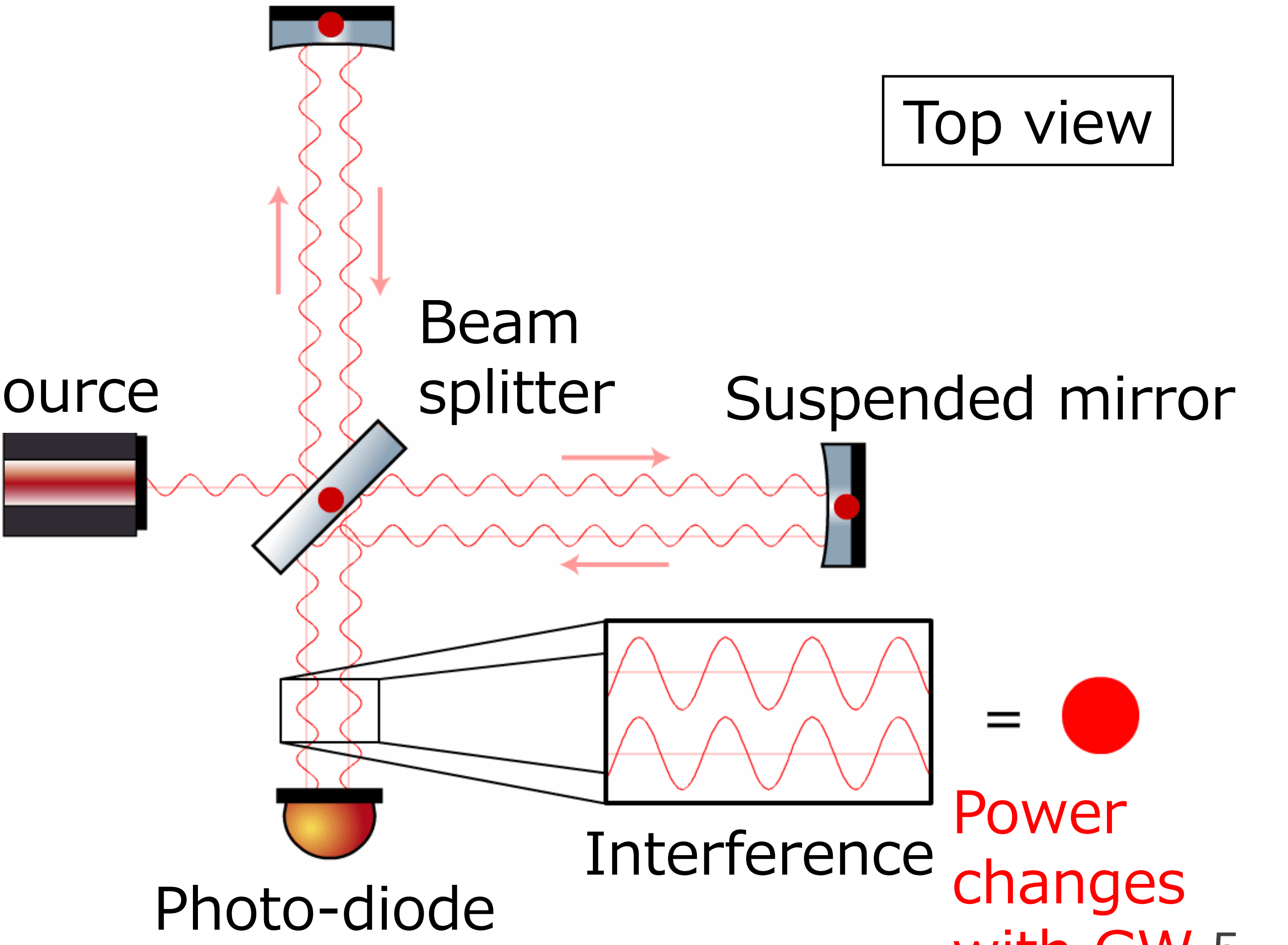
- measure differential arm length change



Constant power when no GW

Laser Interferometric GW Detector

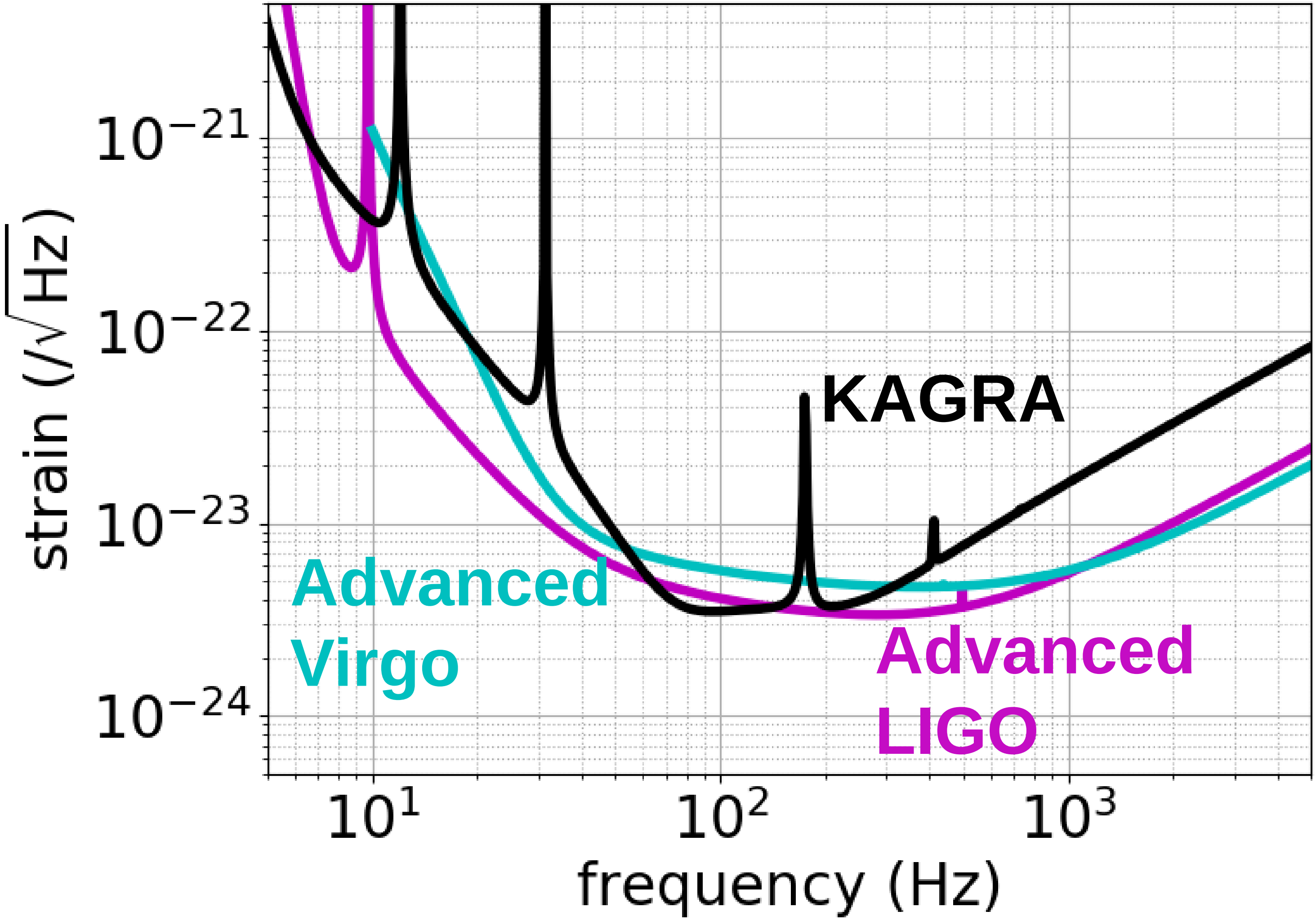
- measure differential arm length change



Power changes with GW

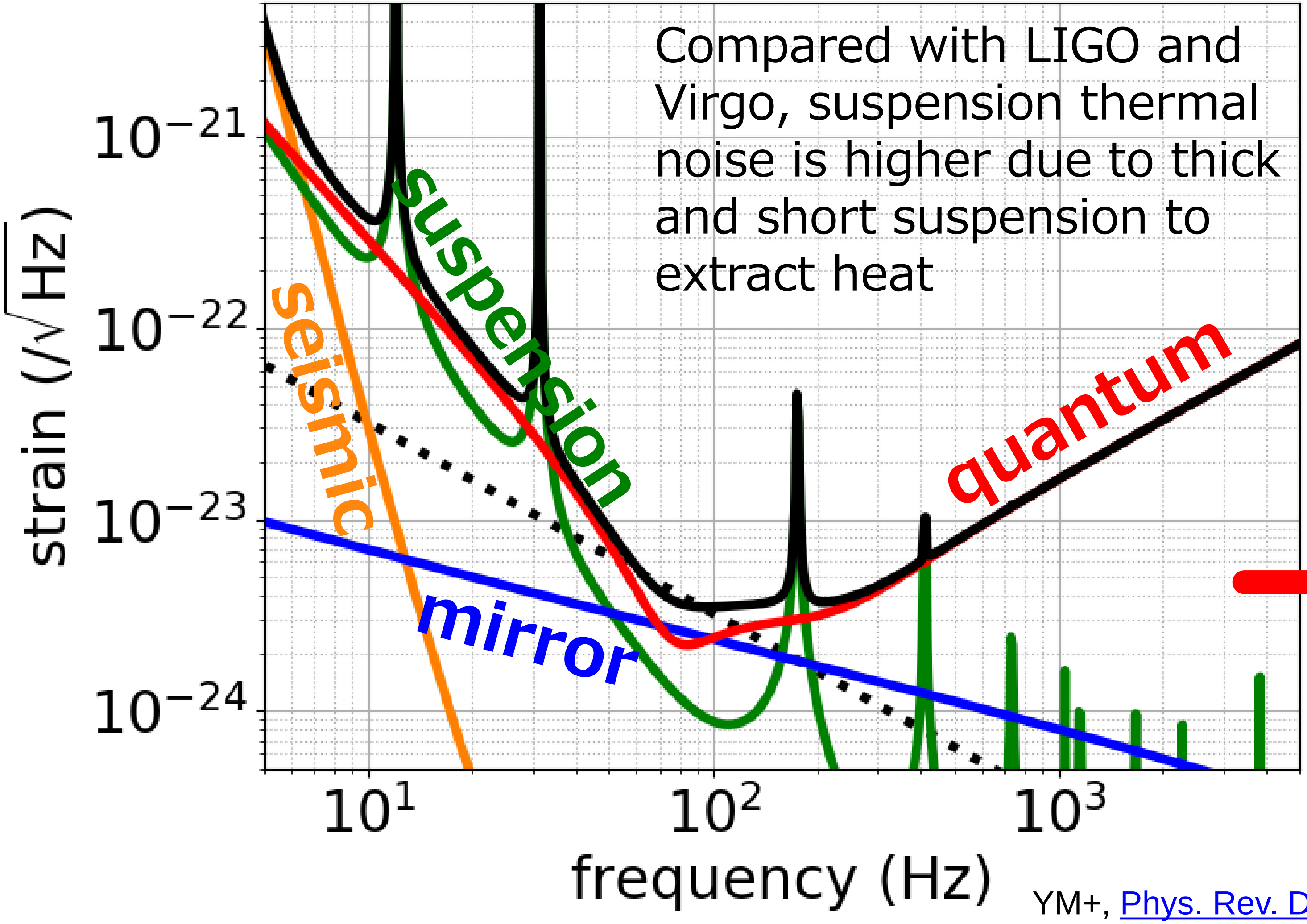
Designed Sensitivity

- aLIGO, AdV and KAGRA has similar designed sensitivity

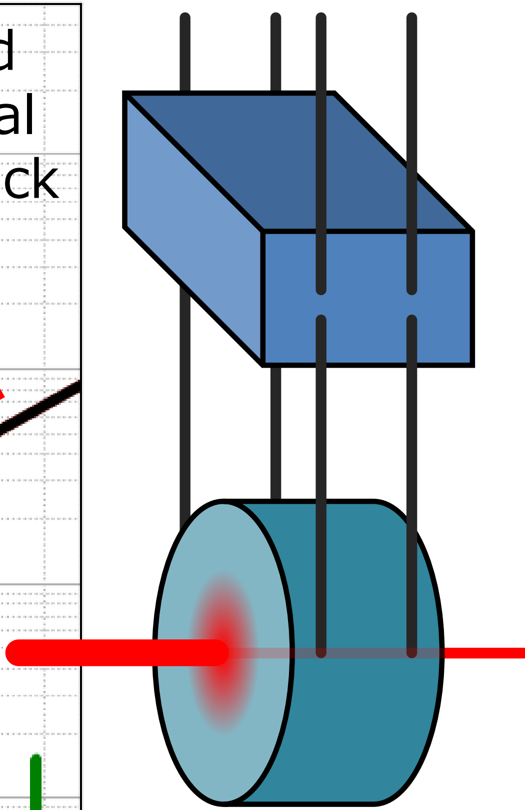


Noise Sources

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



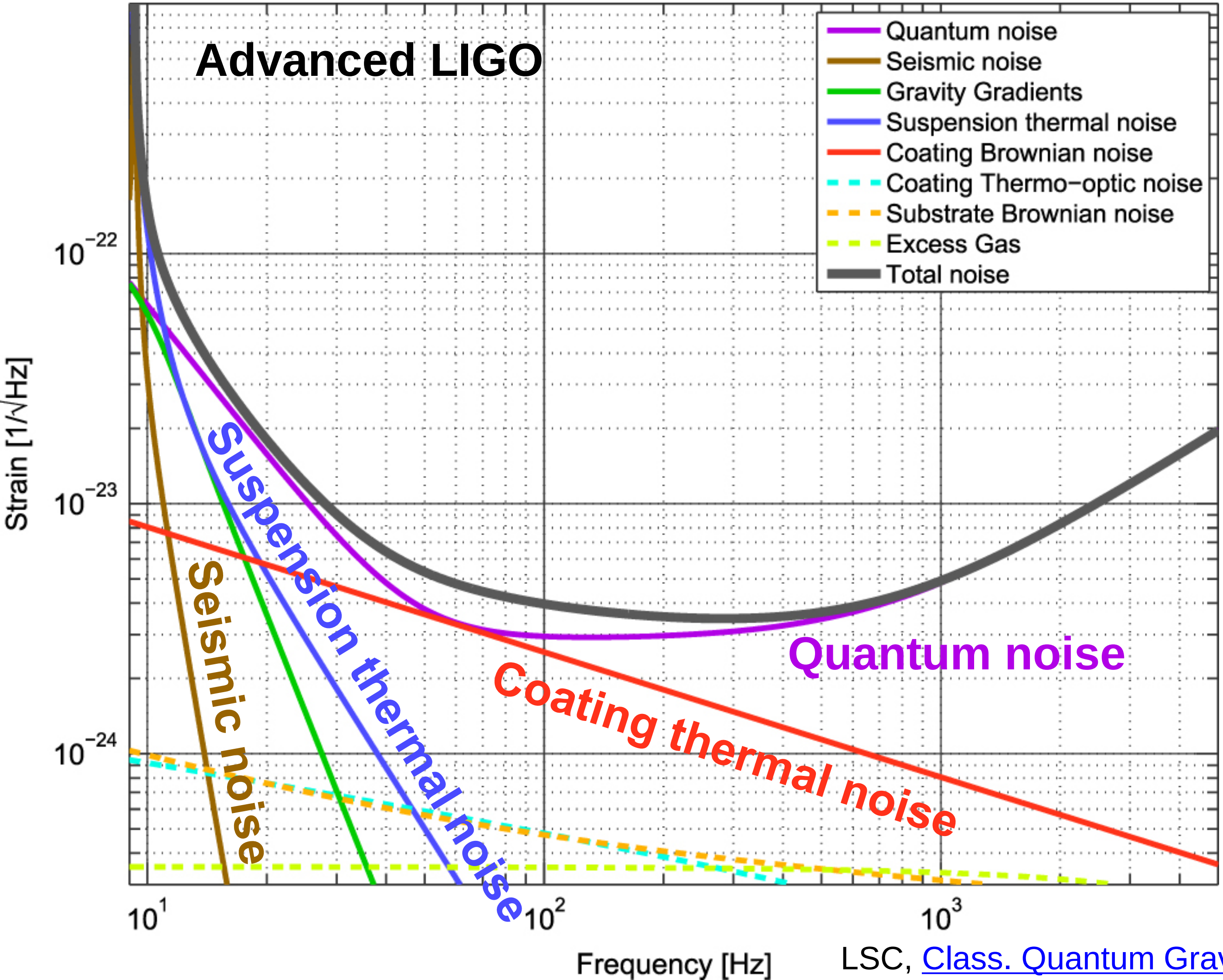
Compared with LIGO and Virgo, suspension thermal noise is higher due to thick and short suspension to extract heat



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

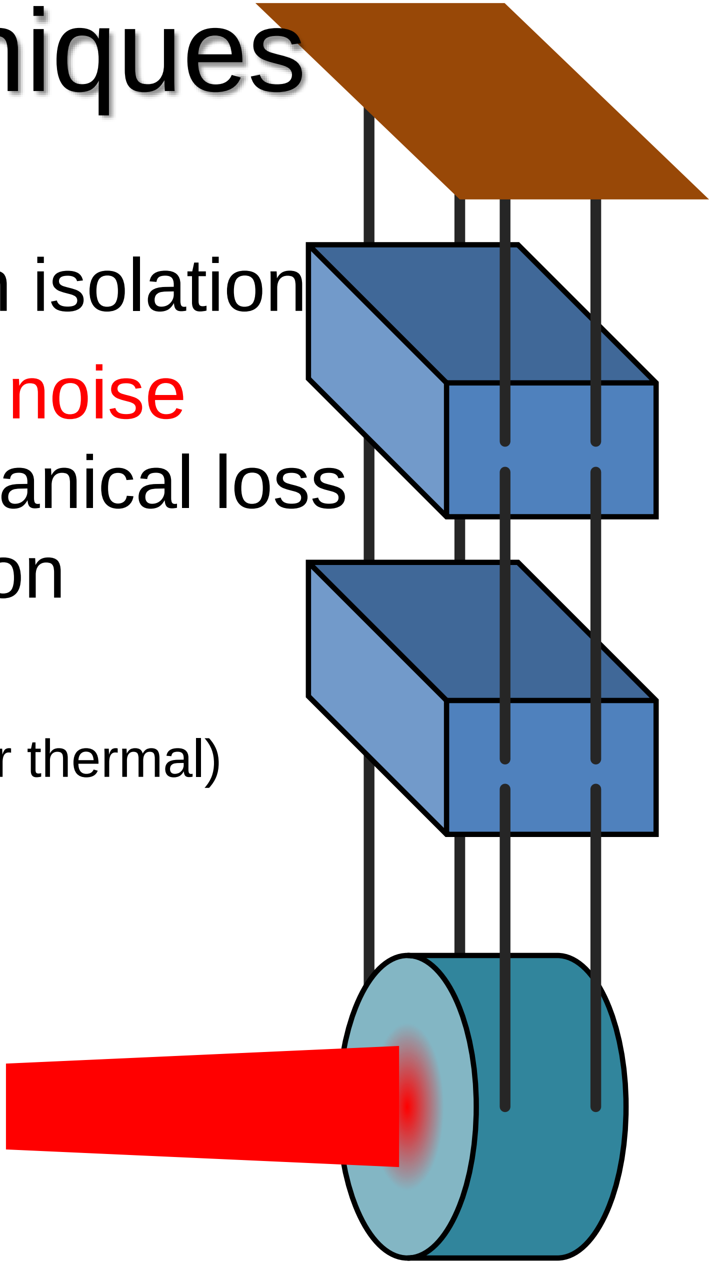
Noise Sources

- Similar for aLIGO designed sensitivity



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

Noise Reduction Techniques

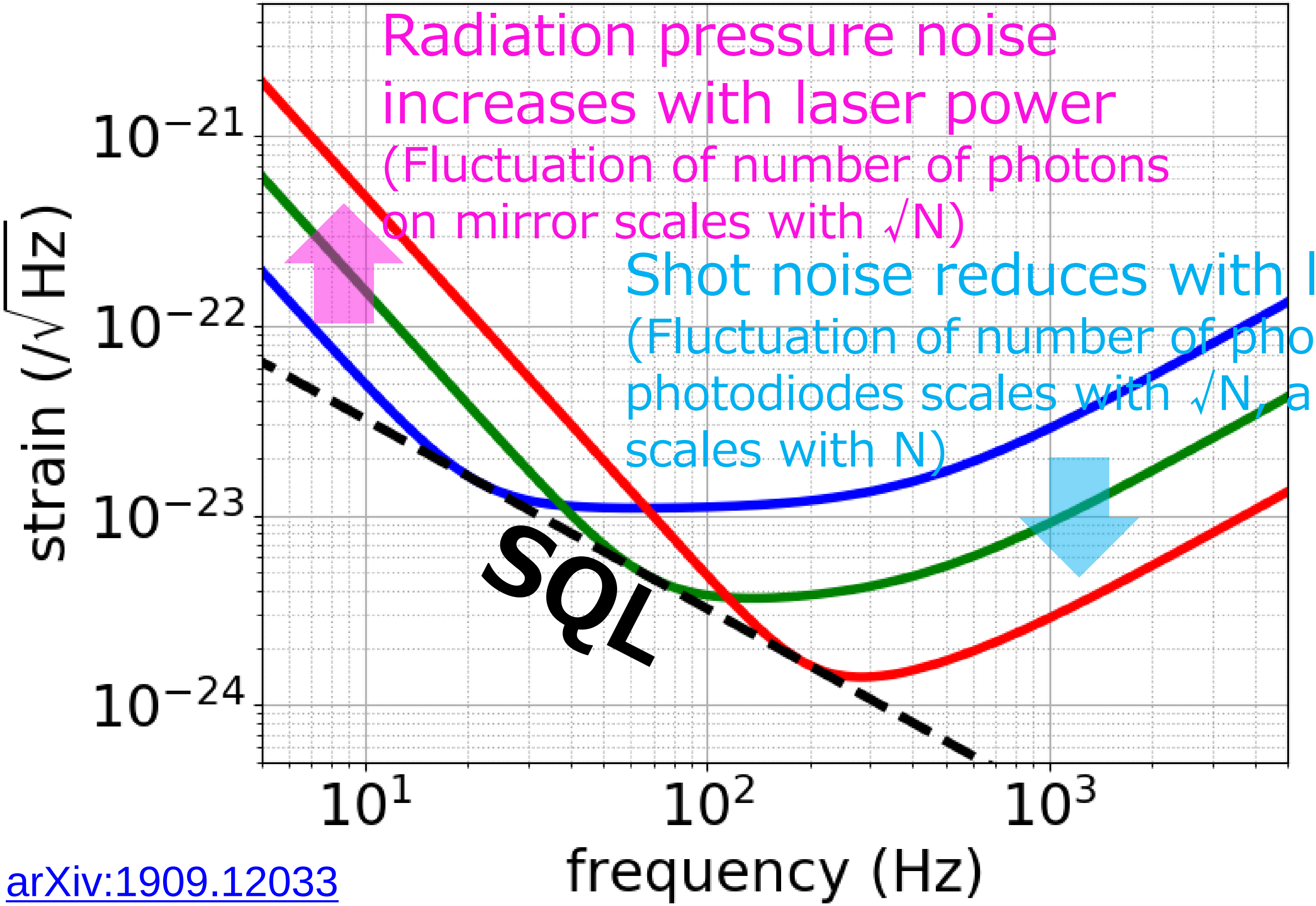


- Seismic noise
  - suspend mirrors for vibration isolation
- Mirror and suspension thermal noise
  - use materials with low mechanical loss
  - thinner and longer suspension
  - cryogenic cooling
  - use larger beam size (for mirror thermal)
- Quantum noise
  - optimize laser power
  - interferometer 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



Radiation pressure noise increases with laser power

(Fluctuation of number of photons on mirror scales with √N)

Shot noise reduces with laser power

(Fluctuation of number of photons on photodiodes scales with √N, and signal scales with N)

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

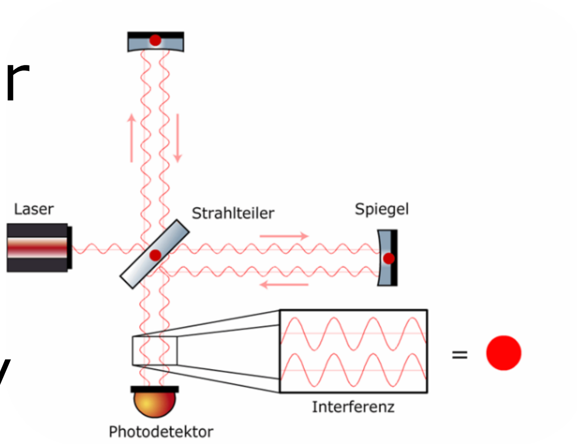
$$\mathcal{K} = \frac{8\omega_0 I_0}{mL^2\omega^2(\gamma^2 + \omega^2)}$$

Mirror
mass

Arm
length

Cavity
linewidth

GW frequency



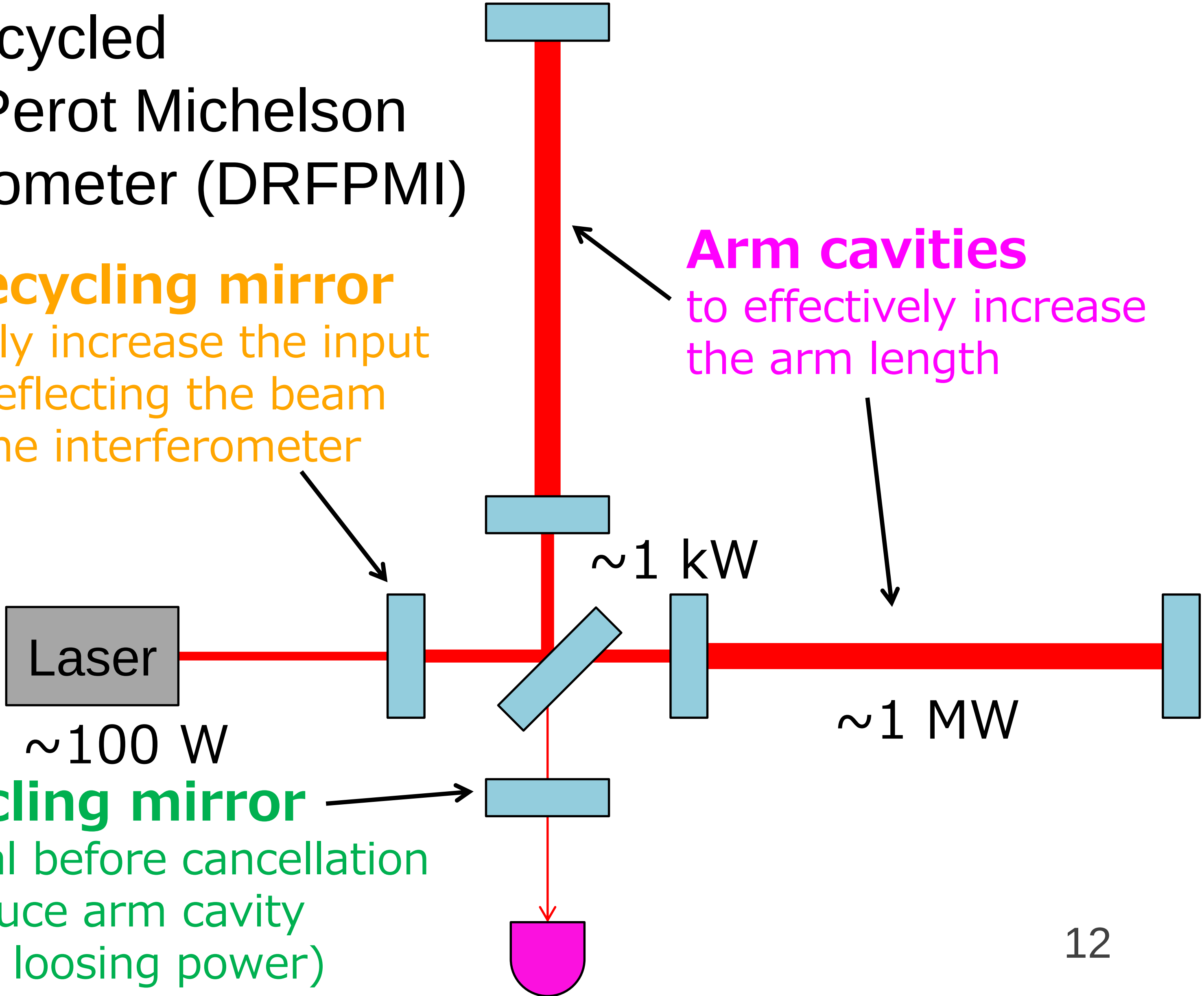
- SQL

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

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

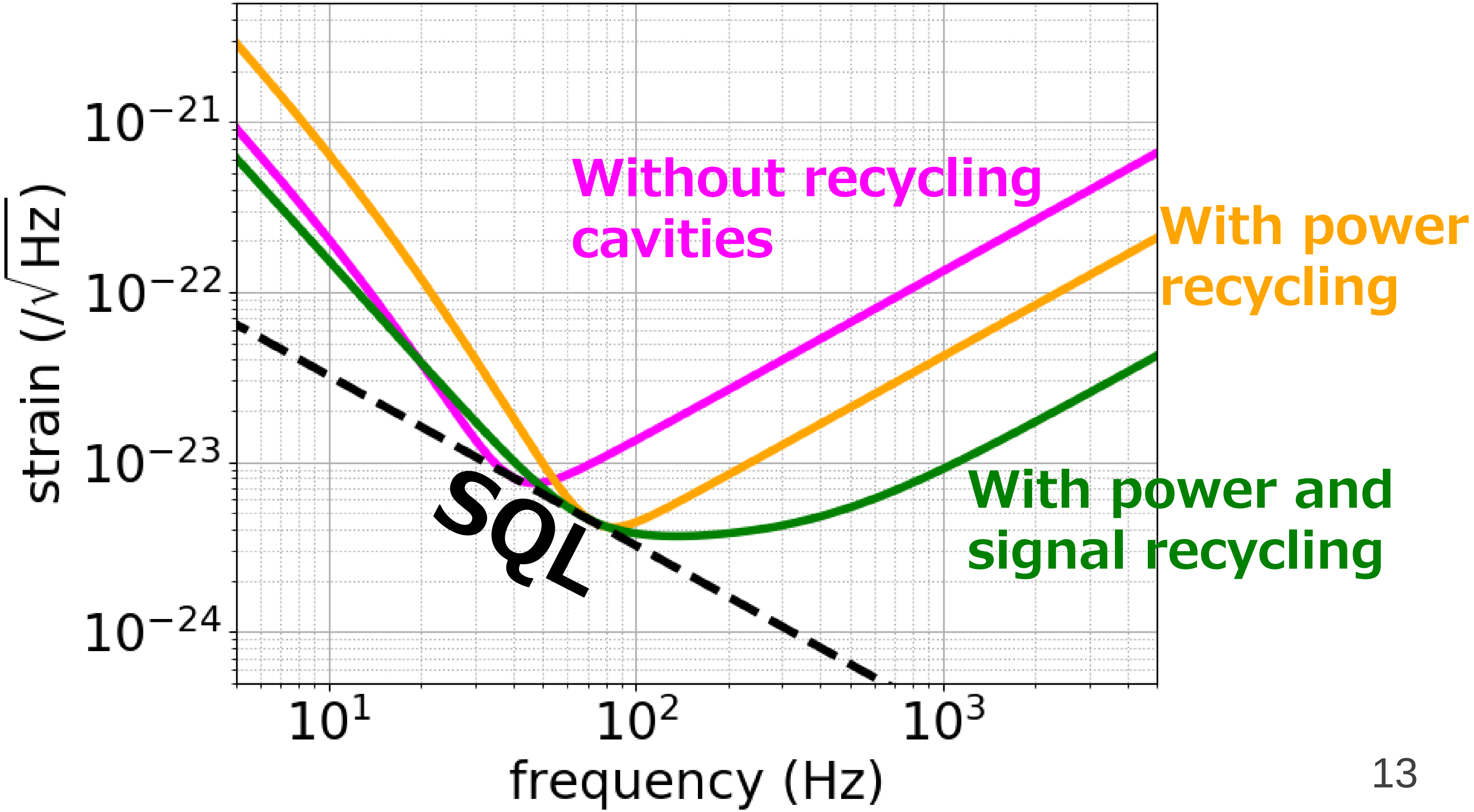
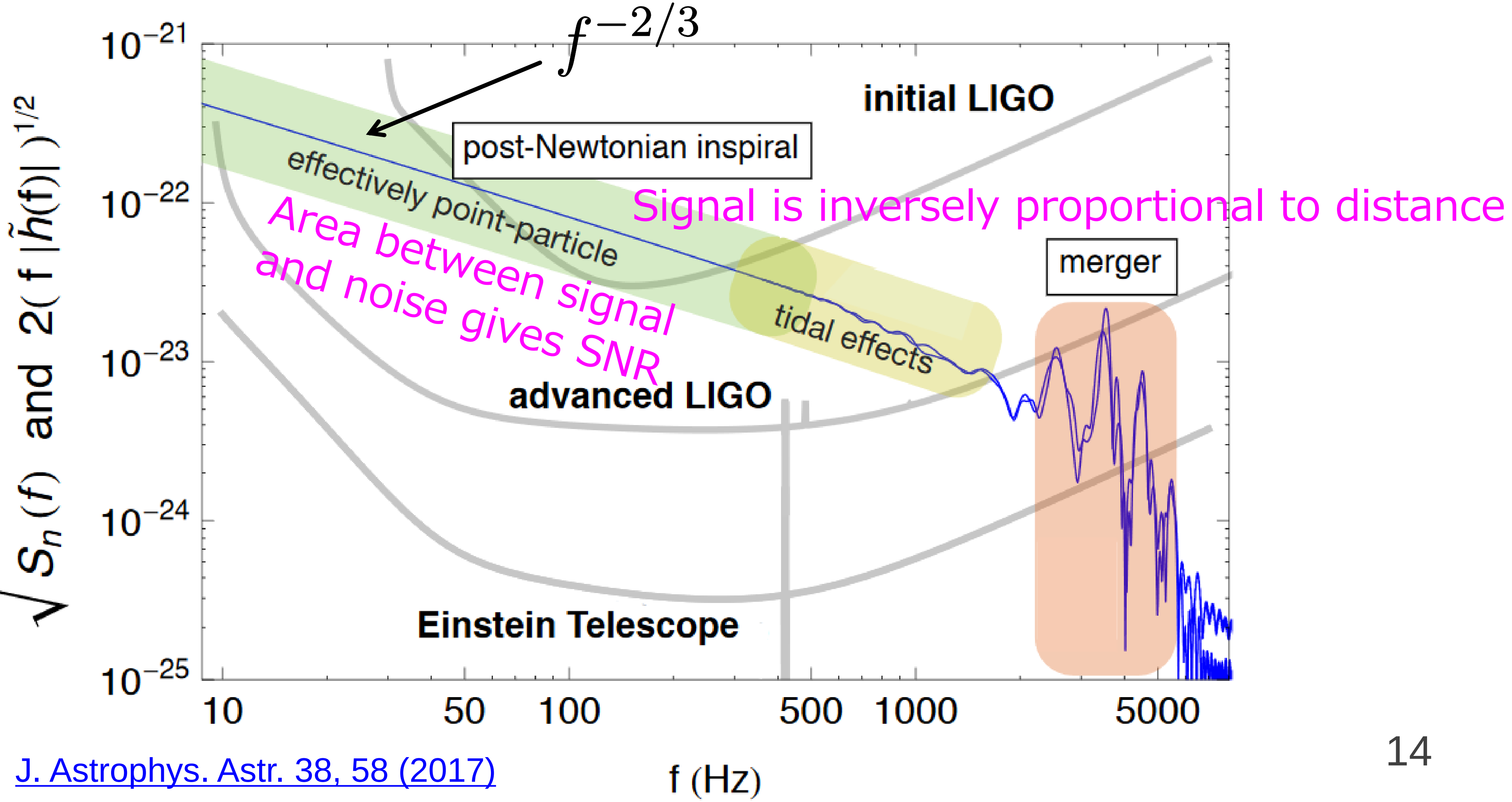


Figure of Merit for Sensitivity

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



$f^{-2/3}$

Signal is inversely proportional to distance

Area between signal and noise gives SNR

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

Inspiral Range

- Detectable distance using inspiral signal

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

Sky average for source location and polarization angle

SNR threshold (usually 8)

Detector noise

Frequency dependence of inspiral signal in characteristic strain

Chirp mass (detector frame)

- ISCO frequency

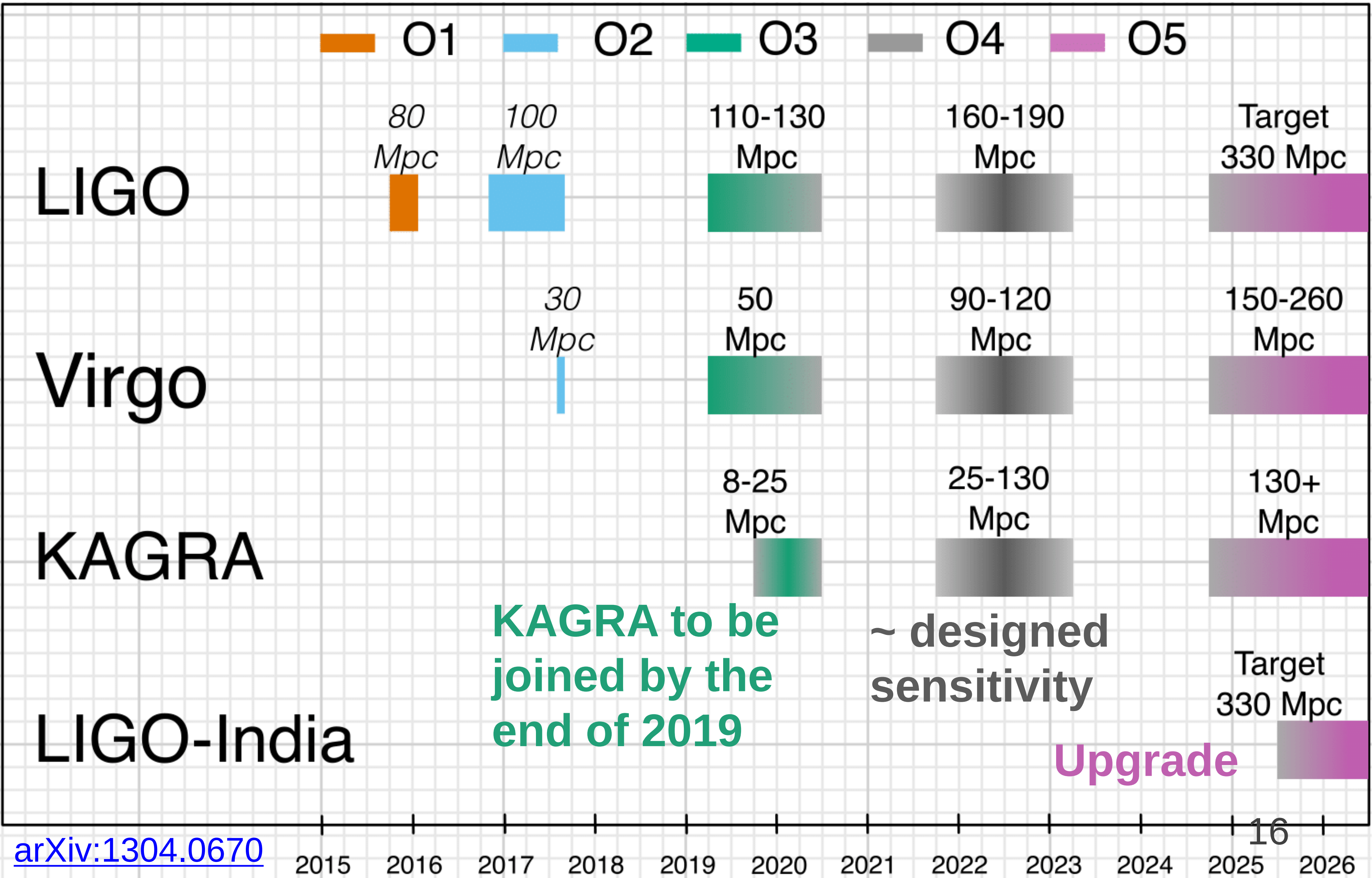
$$f_{\mathrm{max}} = \frac{c^3}{6^{3/2}\pi G M_{\mathrm{tot}}}$$

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

- Heavier objects marge at lower frequencies, with larger GW amplitude

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

Observing Scenario of LVK



KAGRA to be joined by the end of 2019

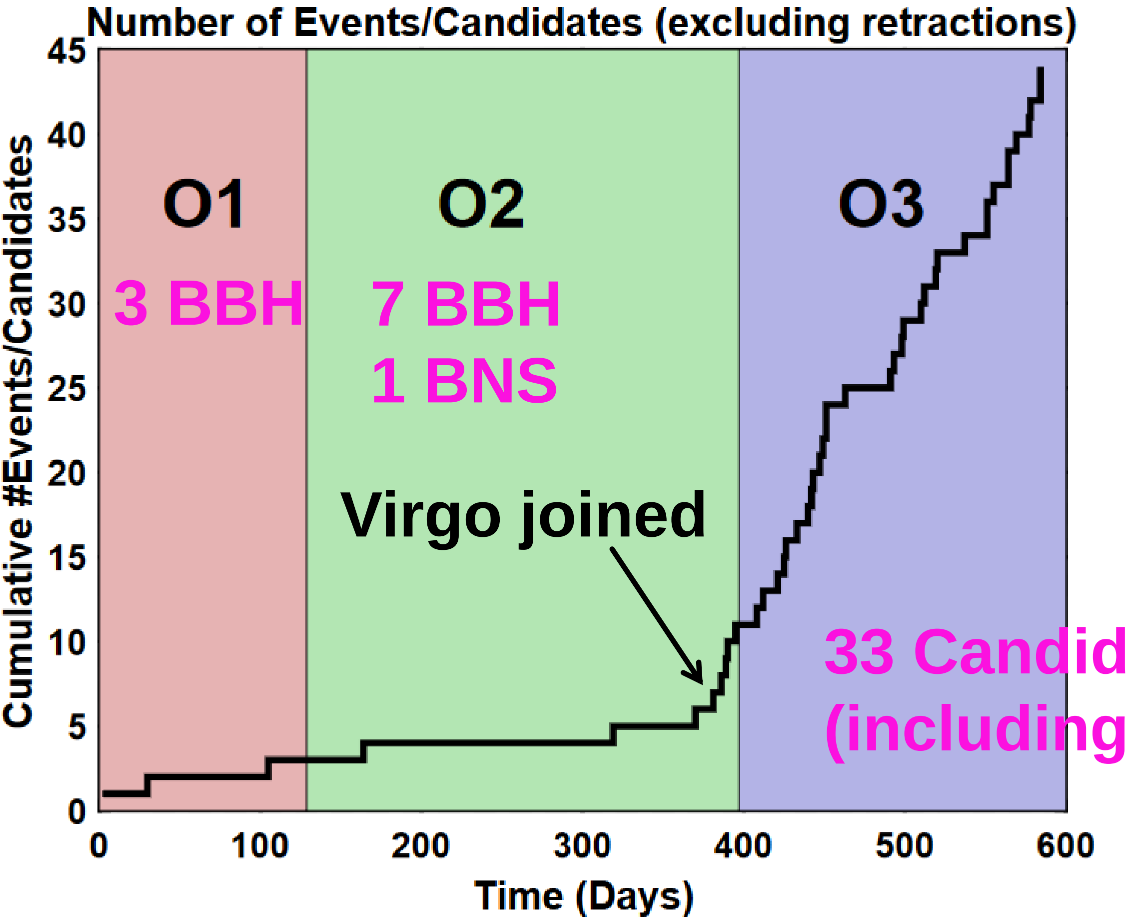
~ designed sensitivity

Upgrade

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



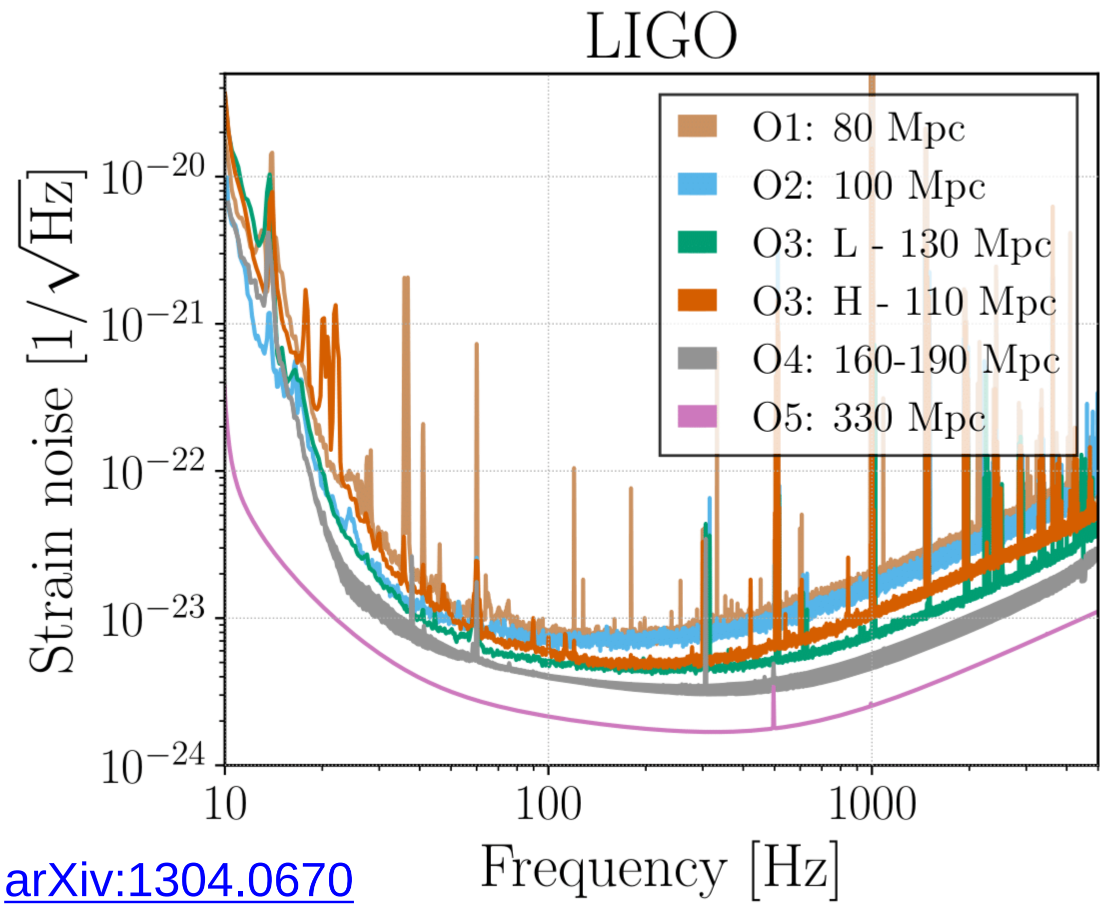
Details can be found below
https://gracedb.ligo.org/superevents/public/O3/

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

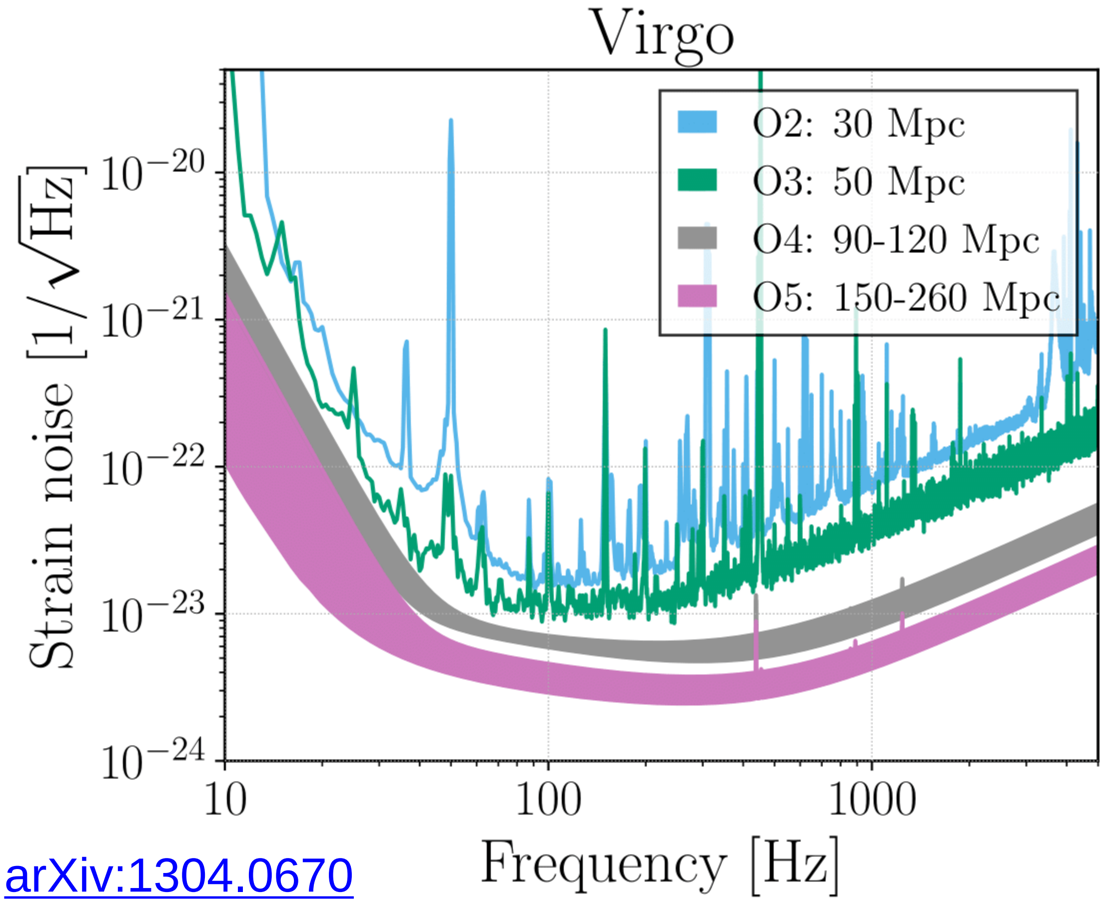
+ Australia

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.

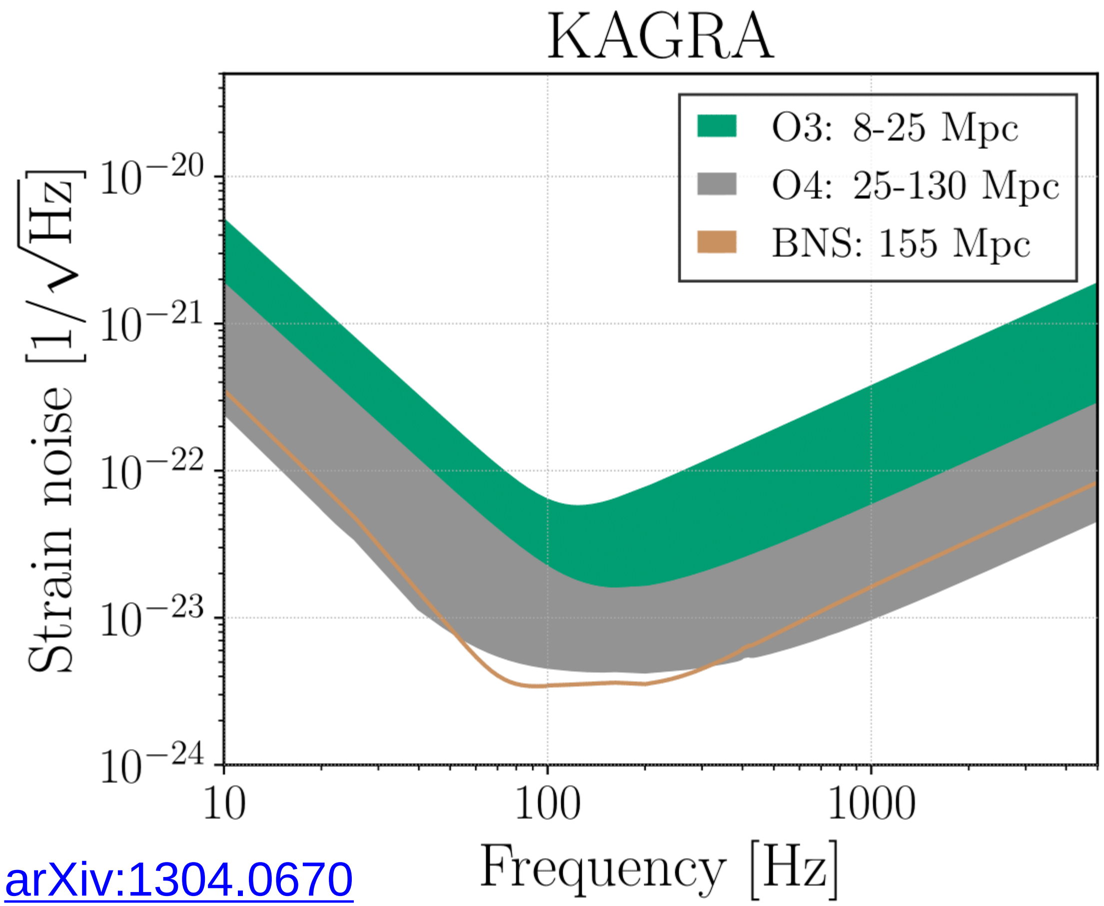


Not good at high frequencies since signal recycling is not done yet

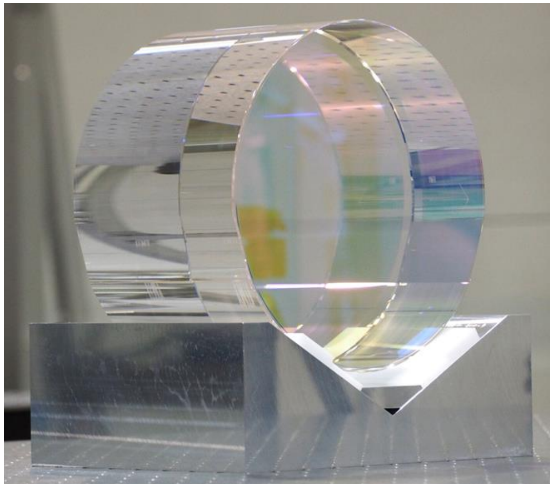
arXiv:1304.0670

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.

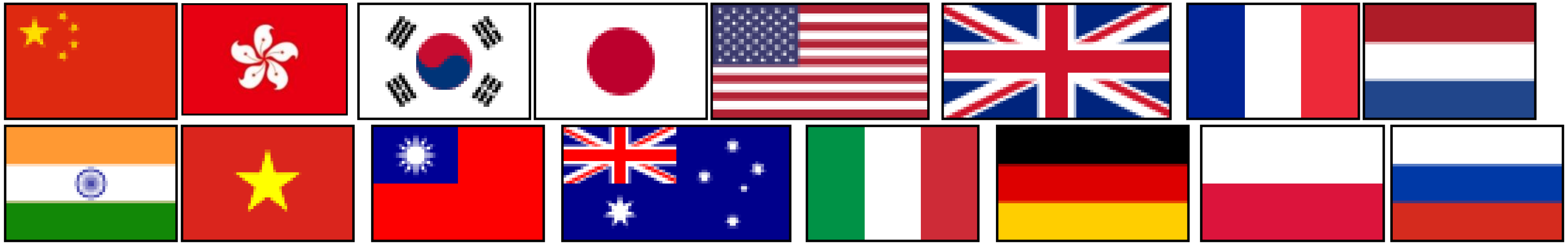


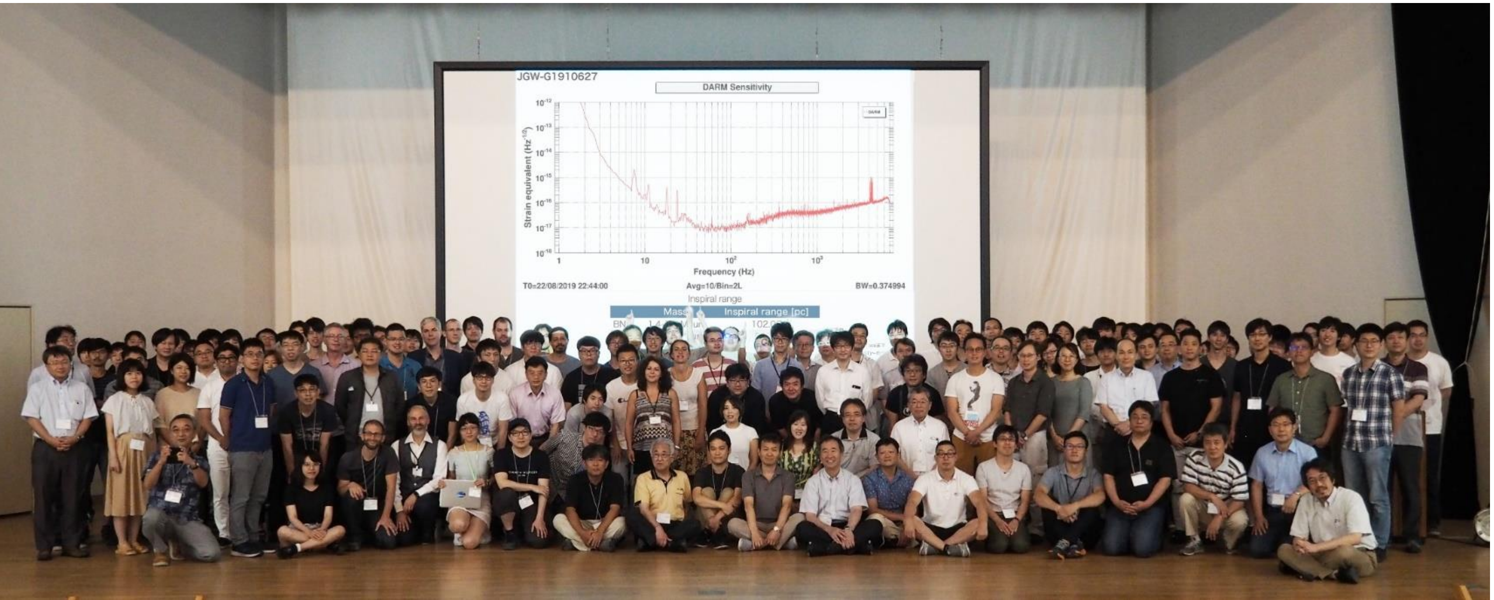
arXiv:1304.0670

KAGRA Project

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

Join us!

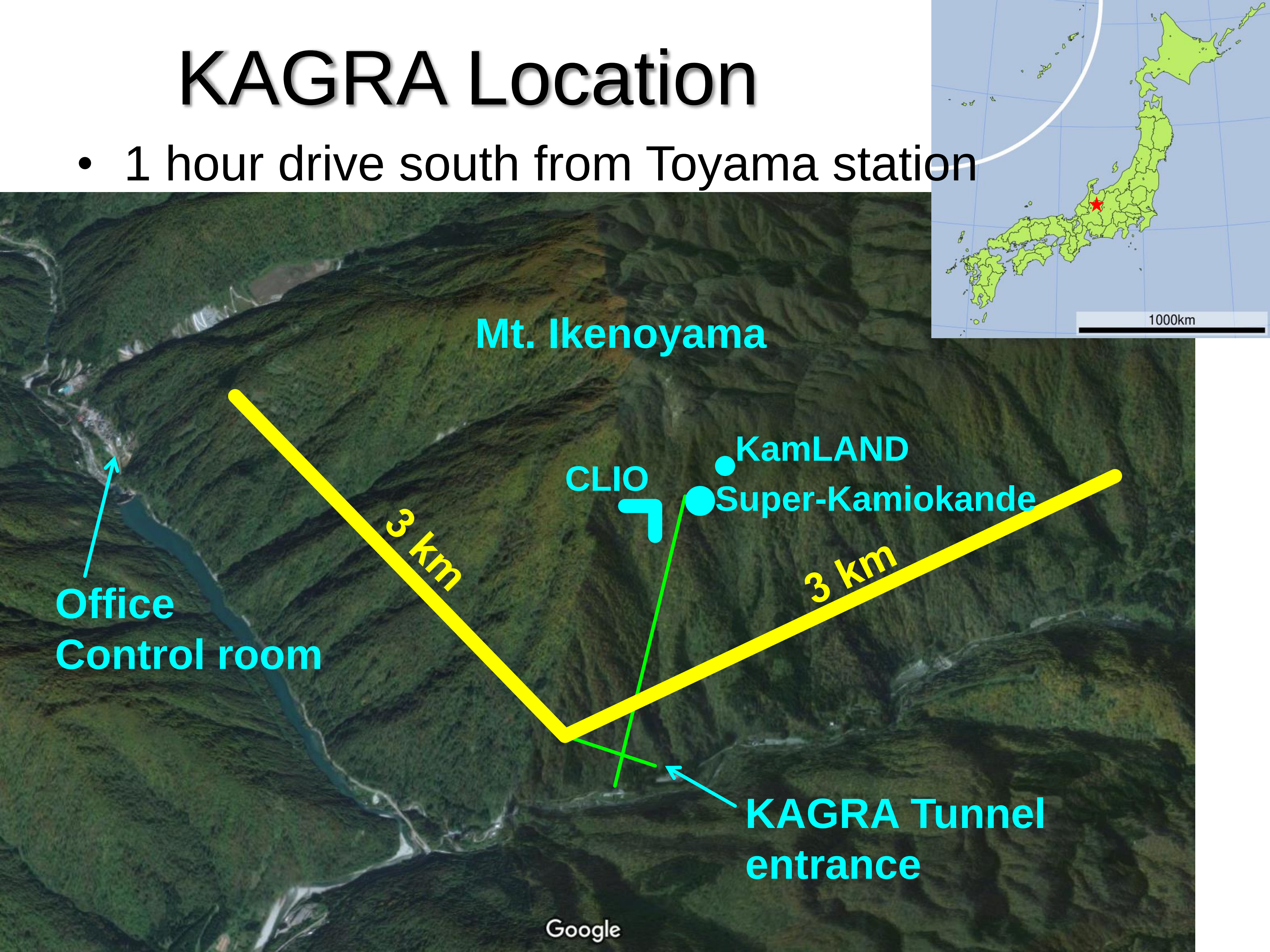




Aug 2019
F2F meeting
@ Toyama

KAGRA Location

- 1 hour drive south from Toyama station

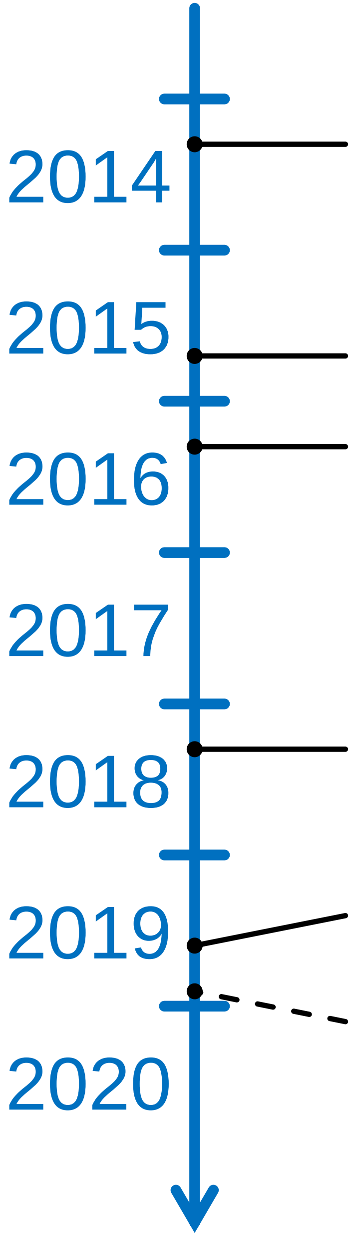


KAGRA Tunnel

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

Entrance
(2016.2.8)

KAGRA Timeline



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

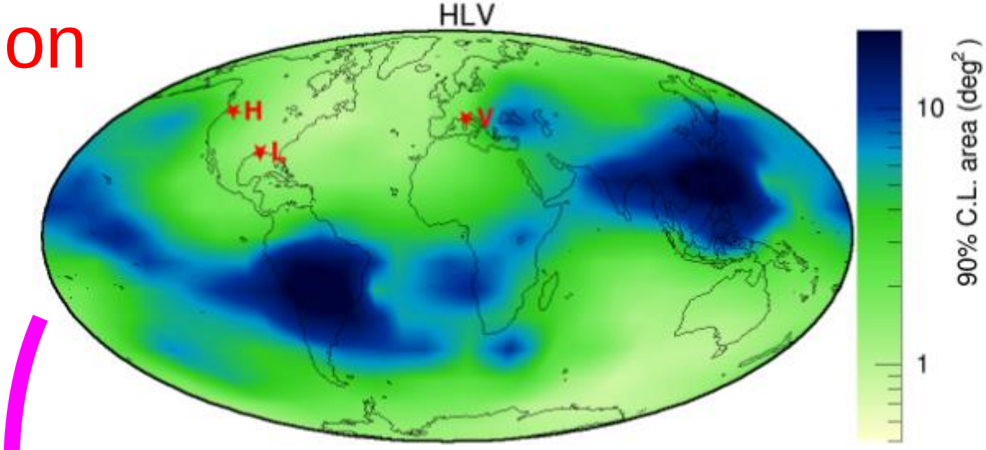
Completion Ceremony on Oct 4

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

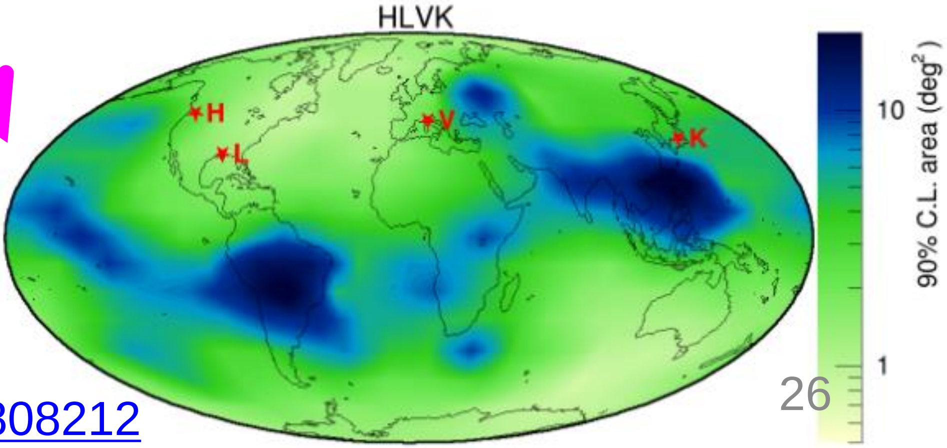
https://www.u-tokyo.ac.jp/focus/ja/articles/z0508_10010.html

KAGRA Joining Observation

- Improves 3+ detector duty factor
  LHV 34 % → LHVK 65 %
  (assuming 70 % duty factor for single detector)
- Improves sky localization
  1.5-1.25 Msun BNS at 40 Mpc
  LH: 120 Mpc
  V: 60 Mpc
  K: 10 Mpc



With KAGRA



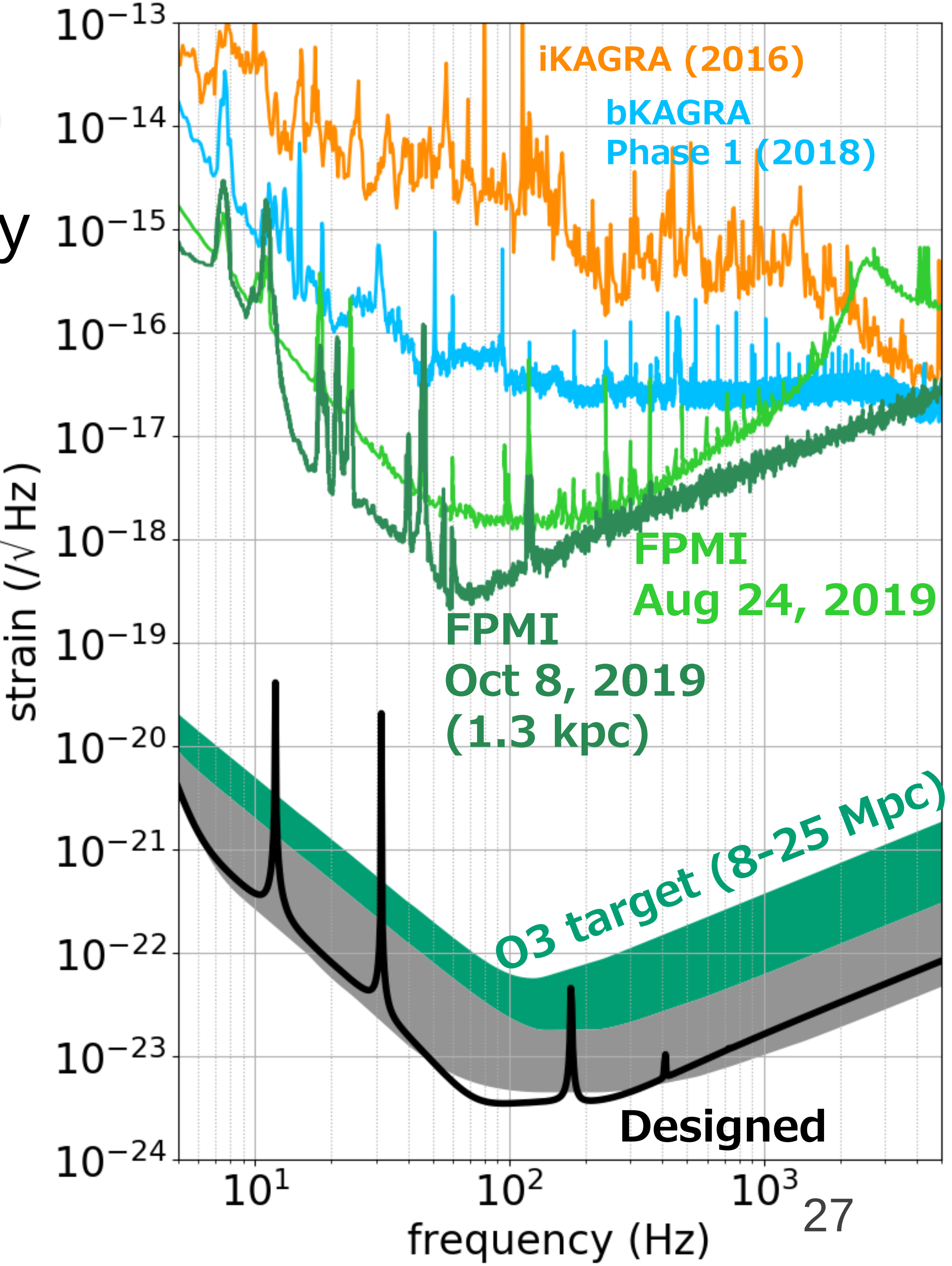
- Enables better GW polarization measurements
  H. Takeda+,
  PRD 98, 022008 (2018)

S. Haino,
JGW-G1808212

KAGRA Status

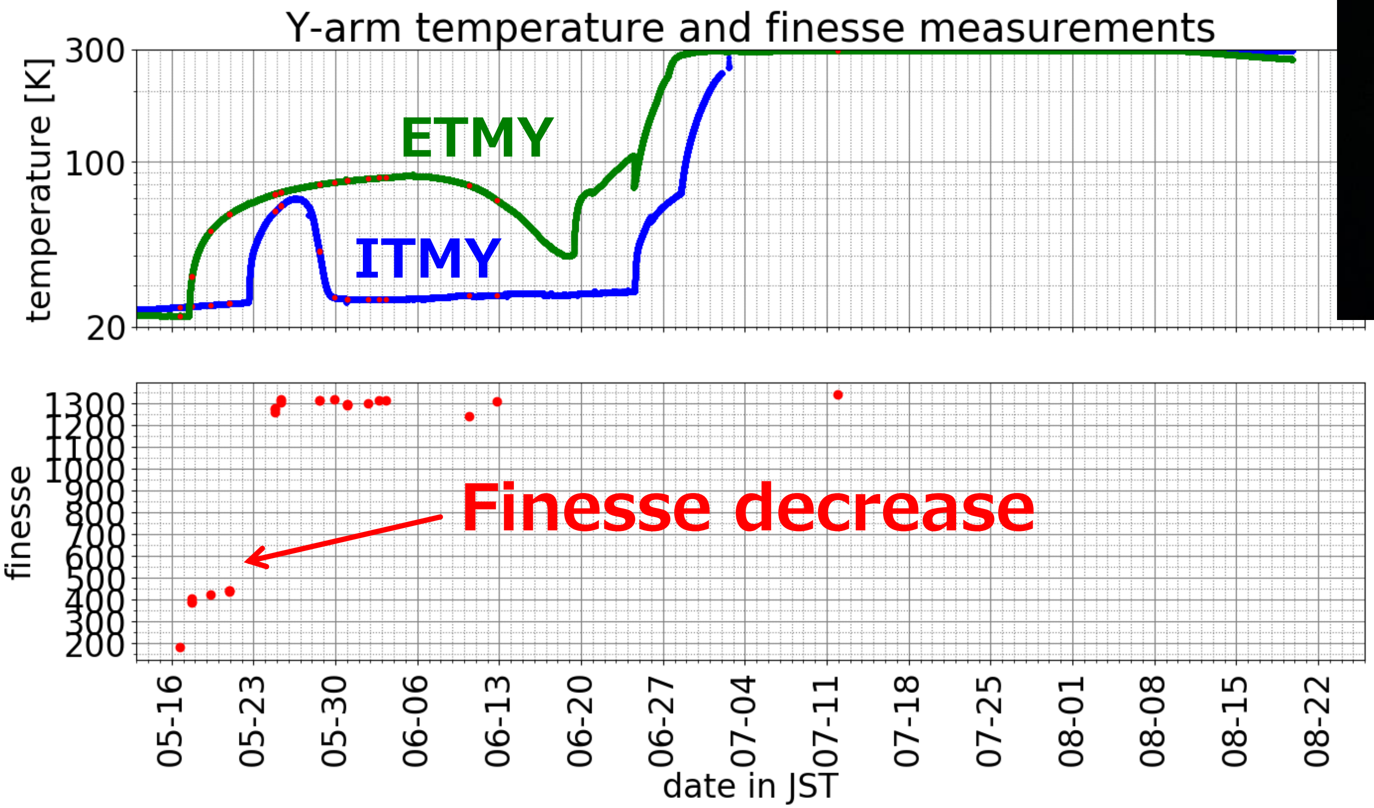
- First FPMI sensitivity on August
- Now around 1 kpc
- Two big problem found in May-June:
  - Frosting
  - Birefringence

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



Effect of Frosting

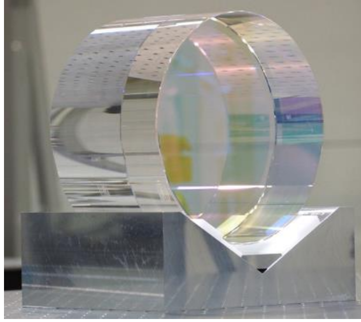
- Finesse decreases at cryogenic temperatures (below ~30 K)
- Frosting from residual gas adsorption on mirrors, probably due to vacuum leakage



Frosted mirror seen with green laser

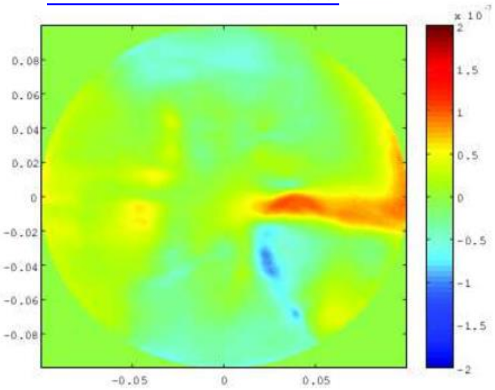
Y. Enomoto+, klog #9861

Effect from Birefringence

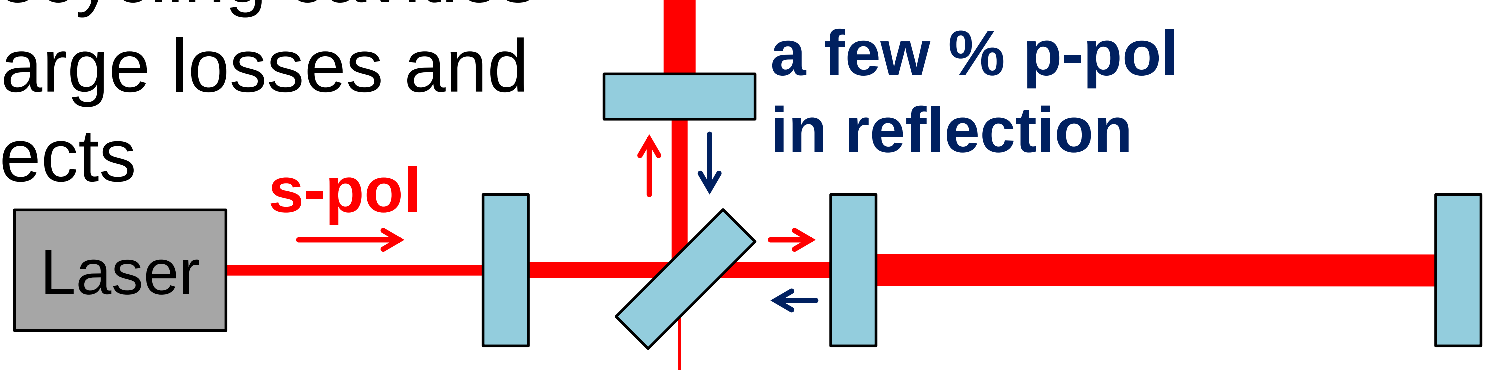


- Sapphire crystal axis and beam axis was not aligned well enough, and there's also inhomogeneity
- Hard to lock power and signal recycling cavities due to large losses and dirty effects

K. Somiya+, arXiv:1907.12785

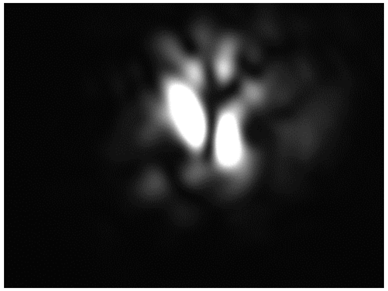


a few % p-pol in reflection



Power and signal recycling cavities contaminated by p-pol

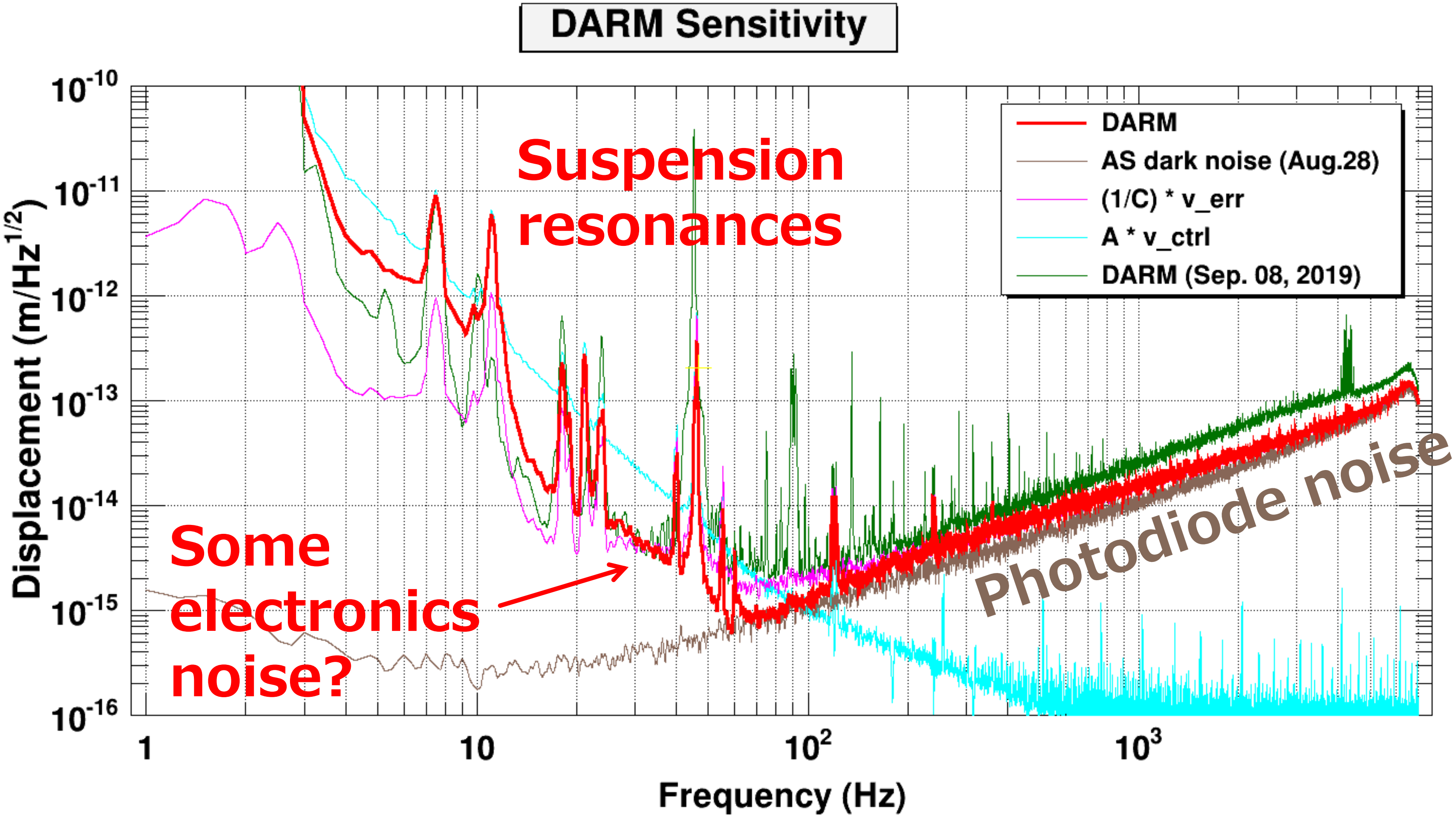
p-pol beam shape from ITM reflection



K. Kokeyama+, klog #9495

Current Sensitivity

- Limited by technical noises and can be reduced



Suspension resonances

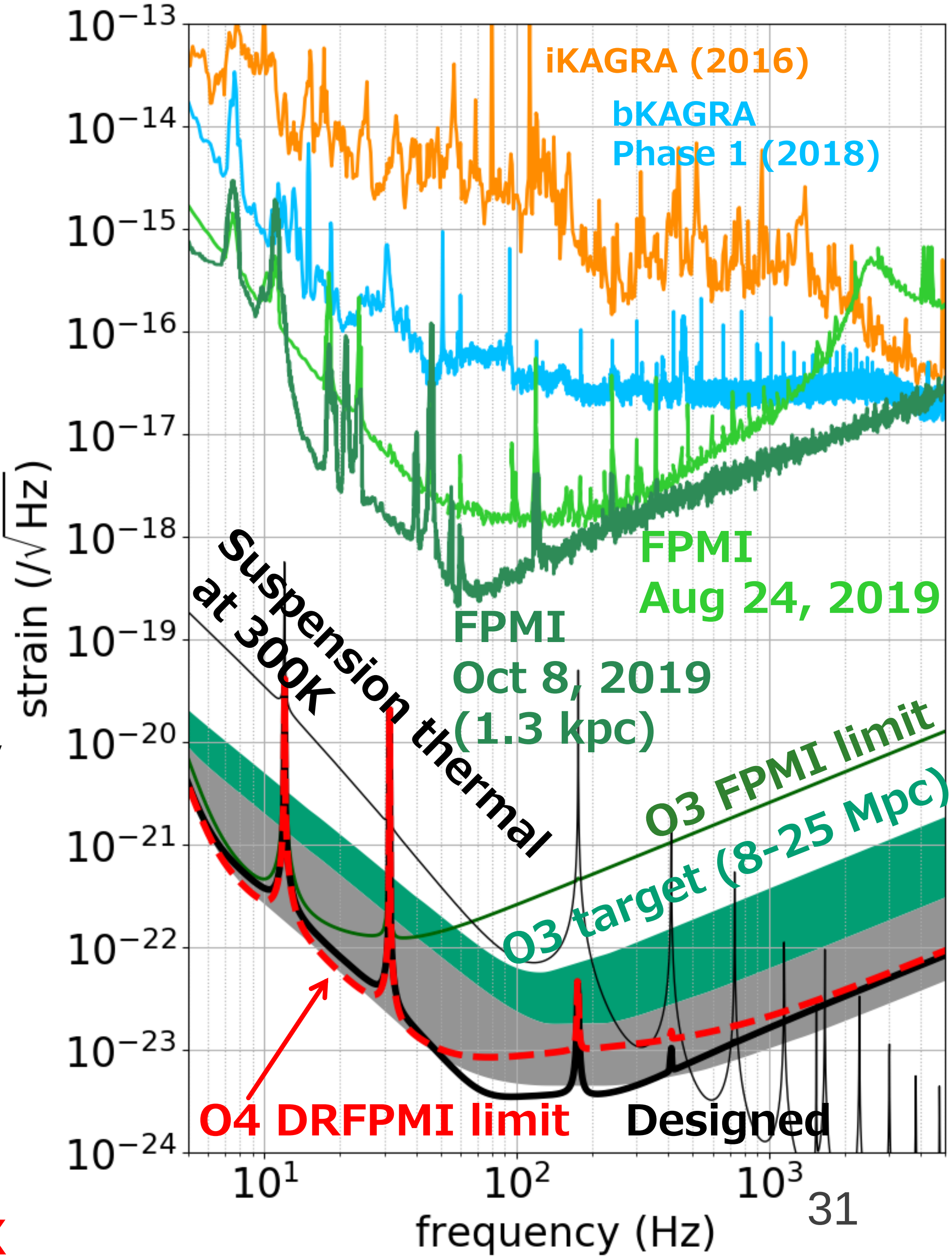
Some electronics noise?

Photodiode noise

M. Nakano+, klog #10869

O3 and O4 Prospects

- Probably no recycling cavities for O3, possibly at room temperature
  → a few Mpc at max
- Reduced sensitivity due to large losses for O4, even if unwanted polarization is removed
  → ~80 Mpc at max

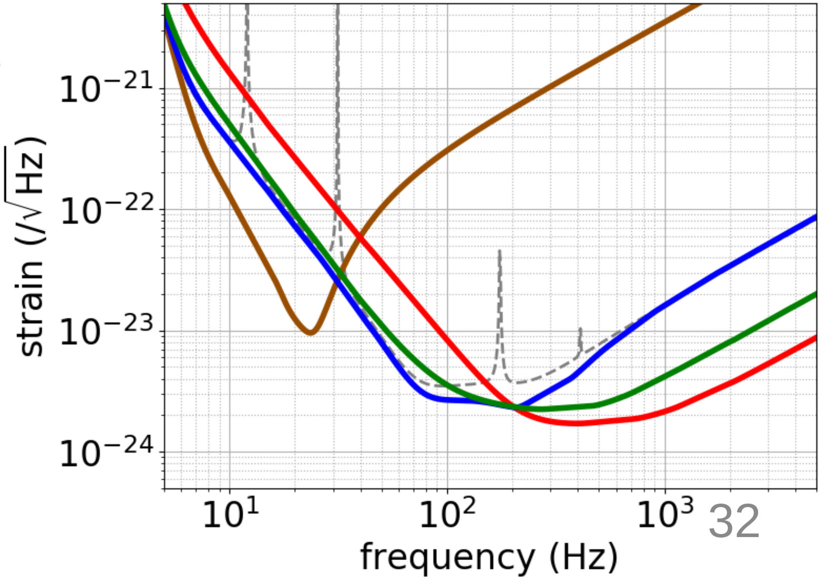


Future Plan for O5?

- 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

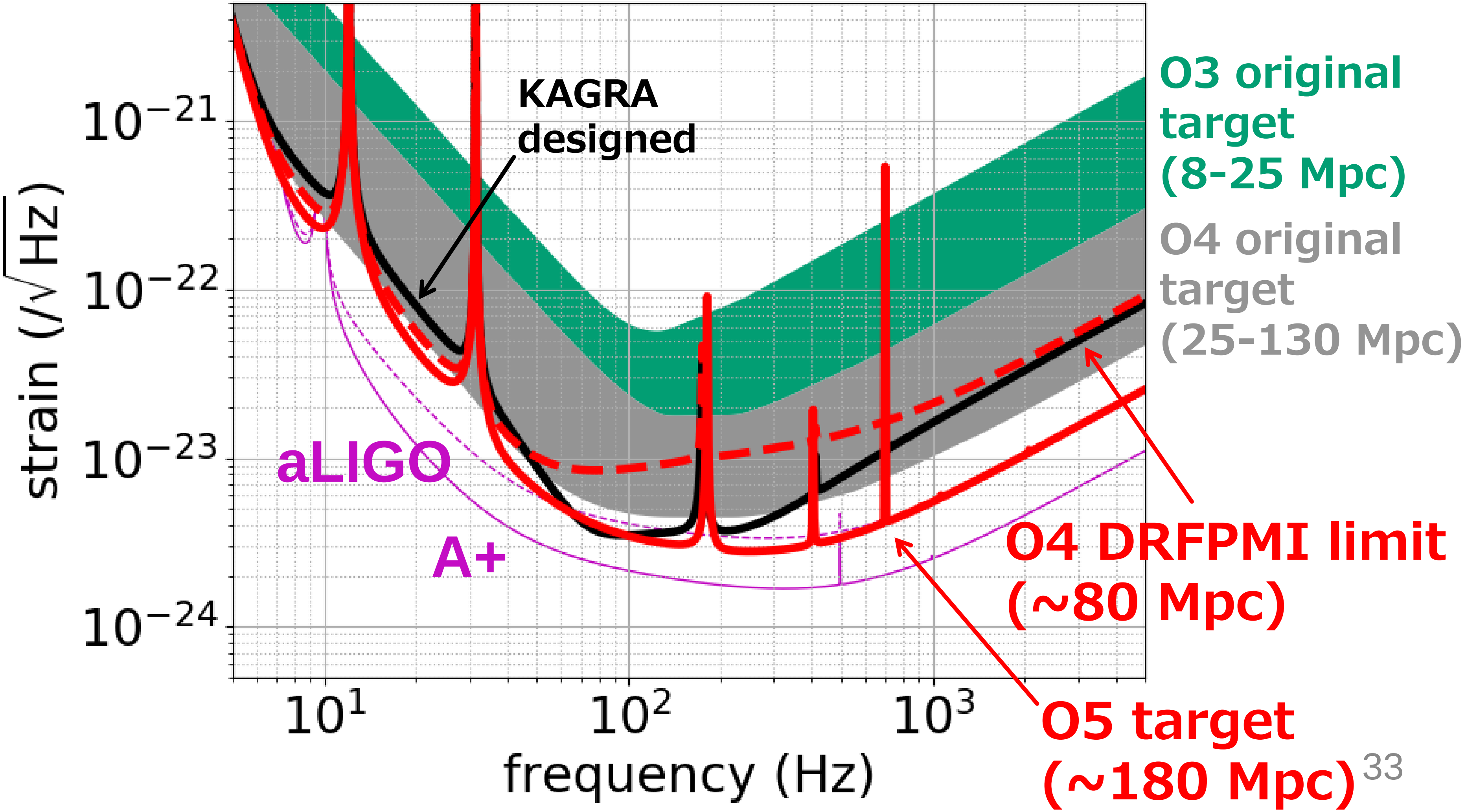
YM+, arXiv:1906.02866

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



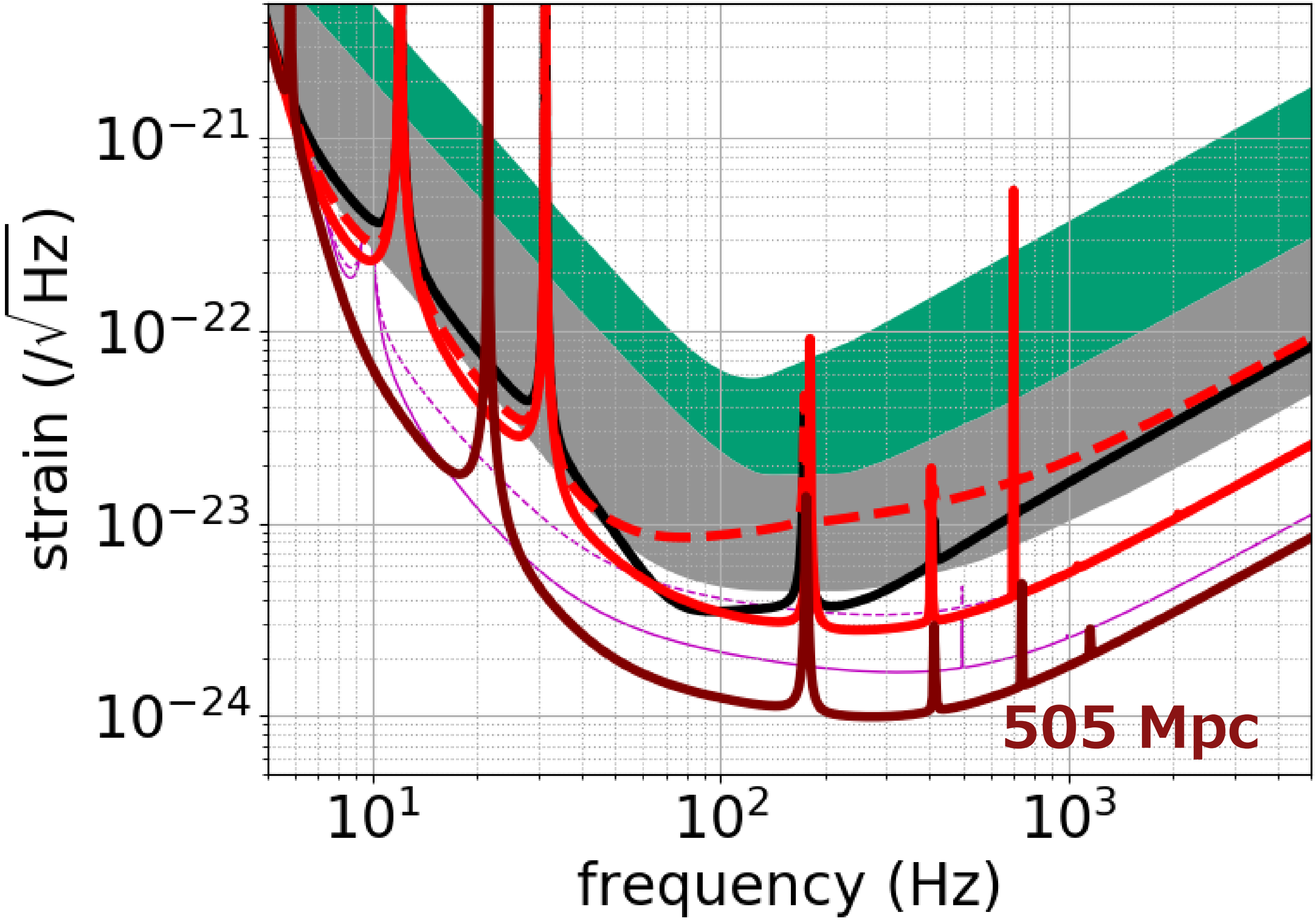
O5 Prospects

- 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

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 ma

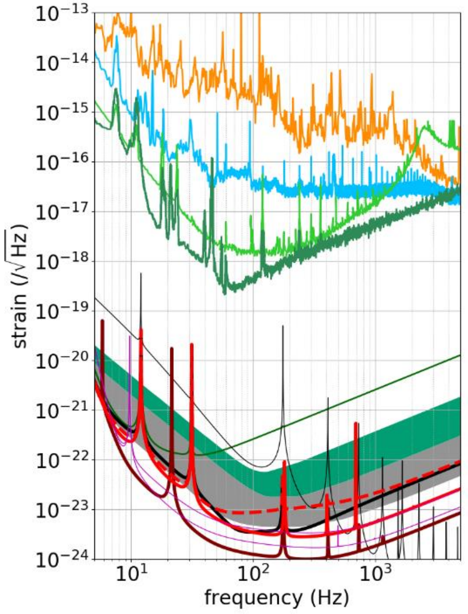
  O4 (2021-2023): ~80 Mpc at max

  Improved mirrors, squeezing

  O5 (2024-): ~180 Mpc

  200 kg mirrors, squeezing etc.

  Ultimately 500 Mpc?



- Many orders of magnitude ahead. Stay tuned!