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Improving the sensitivity of KAGRA gravitational wave detector

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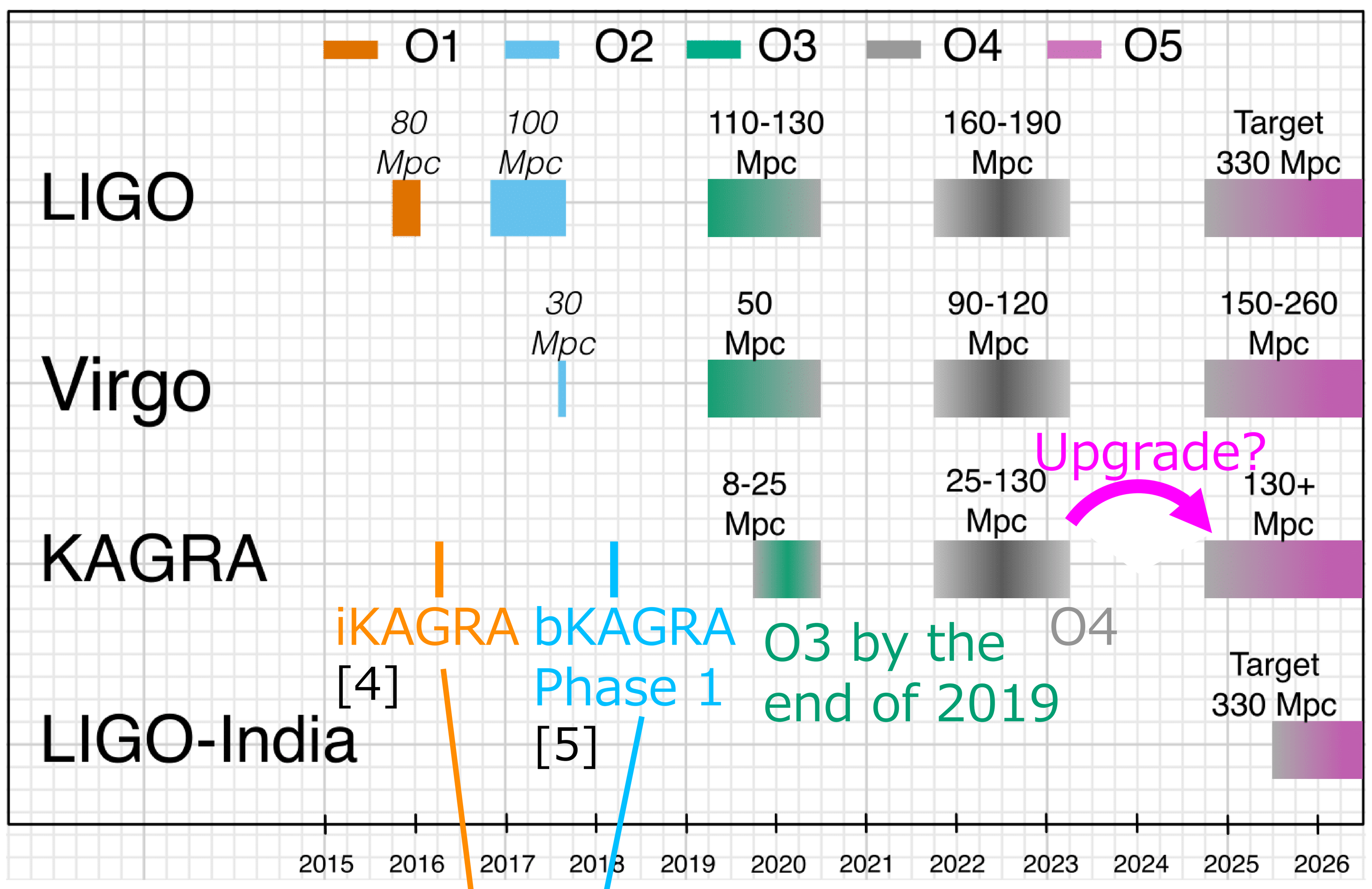
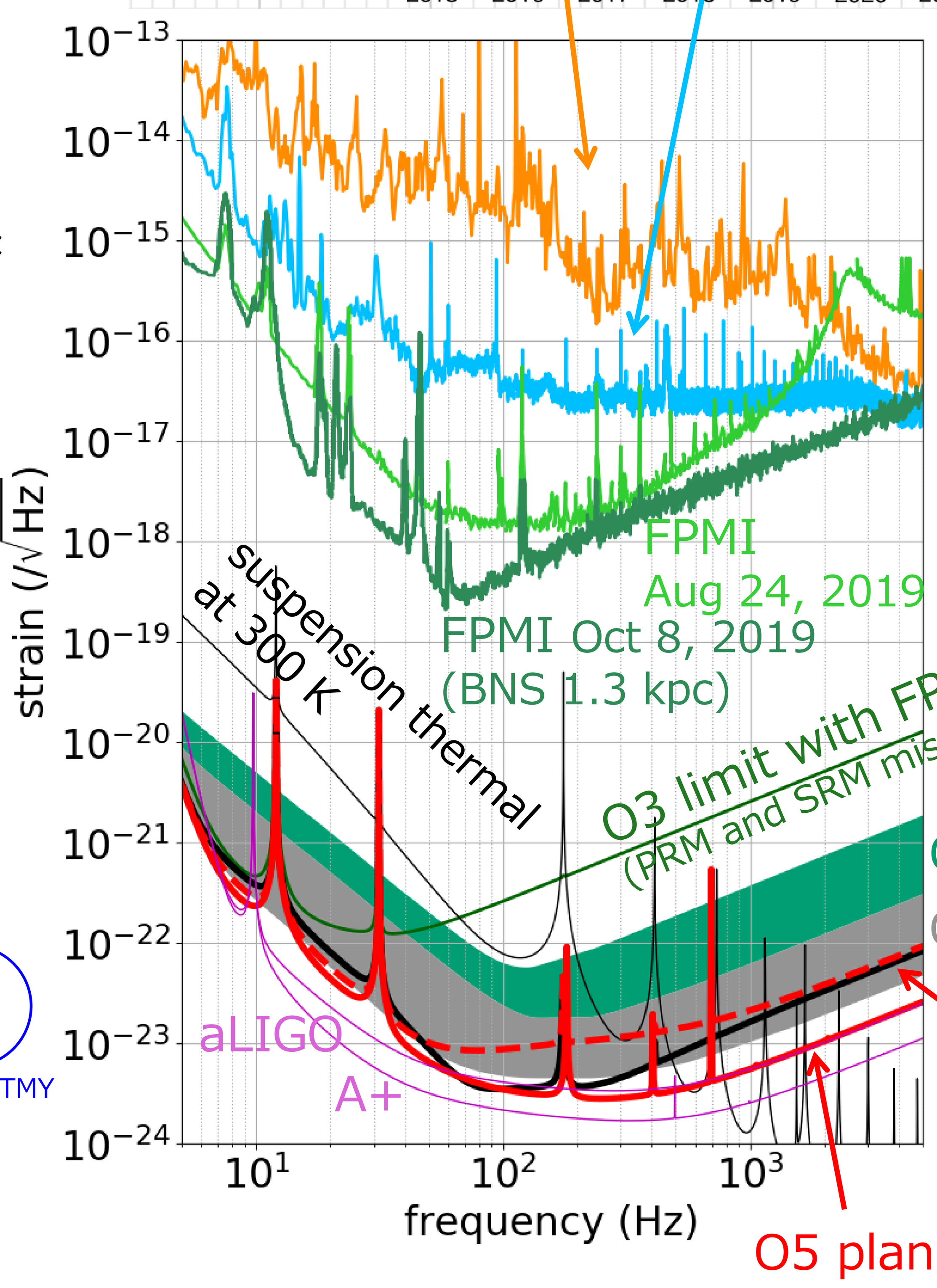
Cryogenic cooling of test mass mirrors adds more complexity to the sensitivity design of interferometric gravitational wave detectors. This is because the heat extraction design affects both suspension thermal noise and quantum noise [1]. Here, we present the prospects for improving the sensitivity of KAGRA from O3 to O5. We show that it is likely that binary neutron star range of KAGRA will be only **a few Mpc in O3** and **about 80 Mpc in O4 at most** optimistic cases, with current birefringent sapphire input test masses. We also show that the sensitivity can be improved **upto 180 Mpc in O5**, with improved test masses and frequency dependent squeezing, without increasing the inout laser power from the originally designed value. Detector parameters critical for the sensitivity calculation are also explained.

Observing Scenario

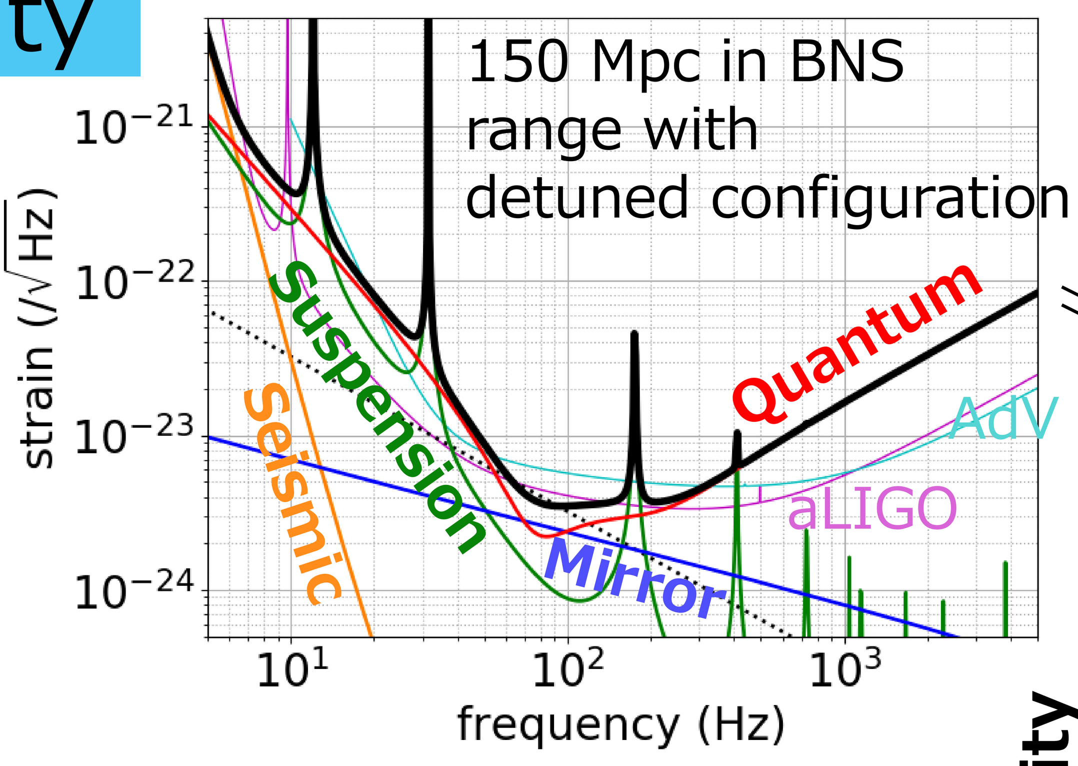




Joining O3 by the end of 2019 is considered to be a **must** even if the sensitivity is not as good. Current KAGRA sensitivity is 4-5 orders of magnitude worse than that of LIGO and Virgo

Designed Sensitivity

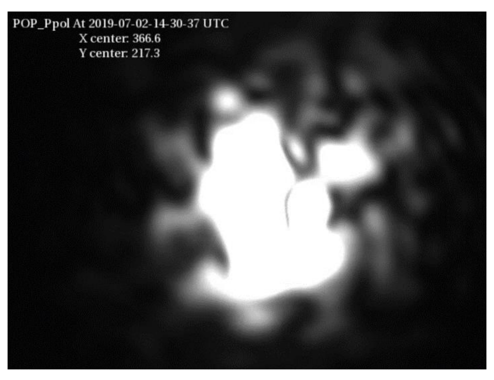
KAGRA has smaller coating thermal noise than other detectors owing to cryogenic cooling, but has larger suspension thermal noise due to **thick and short suspension fibers** to extract heat from test mass mirrors. Reducing or increasing the input laser power improves the sensitivity in low or high frequency bands [2].



Arm cavity parameters gives bandwidth of quantum noise
- ITM transmission: 0.4 %
- Finesse: 1530

Mirror Birefringence

Unexpectedly **large and inhomogeneous birefringence** of sapphire input test masses (ITMs) was found. Birefringence creates unwanted polarization in the reflection of ITMs. The **optical losses** are as high as several %, and power and signal recycling cavities **cannot be locked** stably until now.



Shape of unwanted polarization component of reflected beam from X-arm

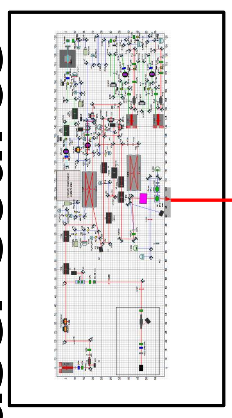
Further Reading

[1] Y. Michimura+, PRD 97, 122003 (2018)
[2] Y. Michimura+, arXiv:1906.02866
[3] KAGRA Collab., PTEP 2018, 013F01 (2018)
[4] KAGRA Collab., CQG 36, 165008 (2019)
[5] K. Somiya, arXiv:1909.12033
[6] K. Komori, PRD 97, 102001 (2018)
[7] E. Capocasa+, PRD 93, 082004 (2016)

Y-arm cavity

TRY, TMSY, ETMY, ITMY, IMC TRANS, MCe, MCi, MCo, IMMT1, IFI, IMMT1, PRM, PR3, PR2, POP, BS, ITMX, X-arm cavity, IMC REFL, REFL, SR2, POS, SR3, SRM, OMMT2, OMMT1, OFI, OSTM, AS, OMC

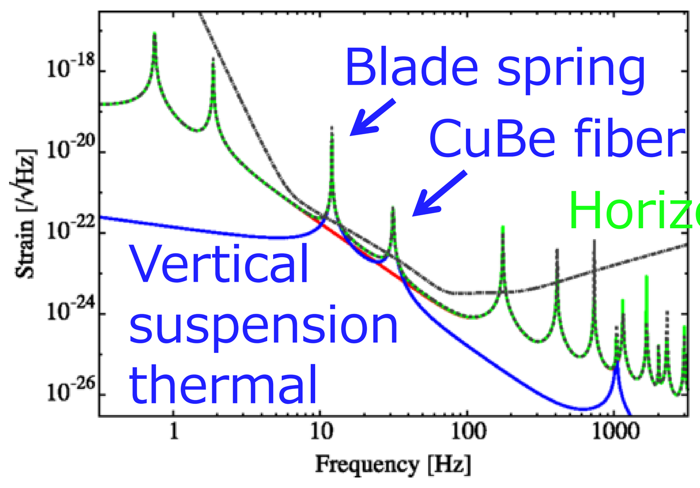
Pre-stabilized laser source



Power recycling cavity

Signal recycling cavity

Significant vertical thermal noise comes from blade springs and CuBe fibers suspending the intermediate mass (IM)
- Blade spring resonance:
  14.5 Hz vertical
  2 kHz horizontal
  (lower the better)
- Blade spring loss angle: 7e-7
- CuBe fiber loss angle: 5e-6
- IM temperature: 16 K



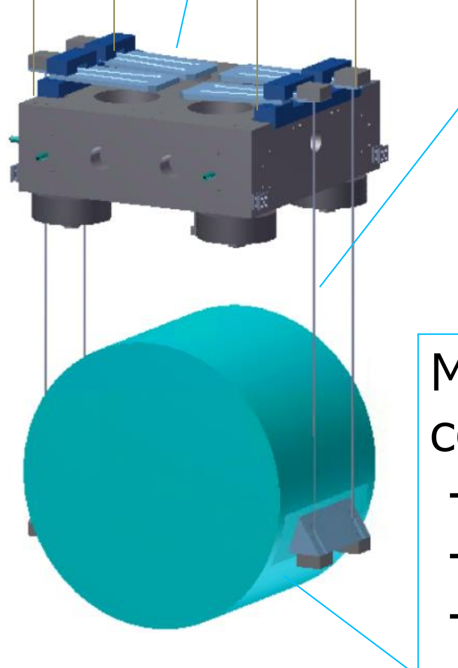
Ref. [6]

Increasing input laser power reduces quantum noise at high frequencies but increases at low frequencies.
- Power at BS:
  1 W for O3 due to no power recycling?
  200 W for O4 due to reduced recycling gain from birefringence?
  673 W for O5?

Signal recycling cavity parameters changes the shape of quantum noise
- SRM transmission:
  30% for O3
  15 % for O4-O5?
- Detuning angle:
  0 deg for O3-O5?
  3.5 deg in design

Frequency dependent squeezing will be injected from here to reduce quantum noise in broad band [7]
- Filter cavity length: 60 m in O5?
- Injected squeezing: 10 dB

Readout quadrature changes the shape of the quantum noise
- Homodyne angle:
  90 deg for O3-O5?
  135.1 deg in design



Parameters for sapphire fibers suspending the test mass is critical for suspension thermal noise and heat extraction calculations.
- length: 35 cm
- diameter:
  1.6 mm in design, 1.4 mm for O5??
- loss angle: 2e-7
- thermal conductivity: 5800 W/m/K

Mirror parameters are critical for calculating coating and substrate thermal noises
- size: 22 cm dia. 15 cm thick
- mass: 22.8 kg
- temperature: 22 K
- loss angle: 1e-8
- substrate absorption:
  50 ppm/cm in design
  25 ppm/cm for O5??
- coating loss angle: 3e-4 / 5e-4
- coating absorption: 0.5 ppm