# Development of frequency dependent squeezing and future plans at NAOJ

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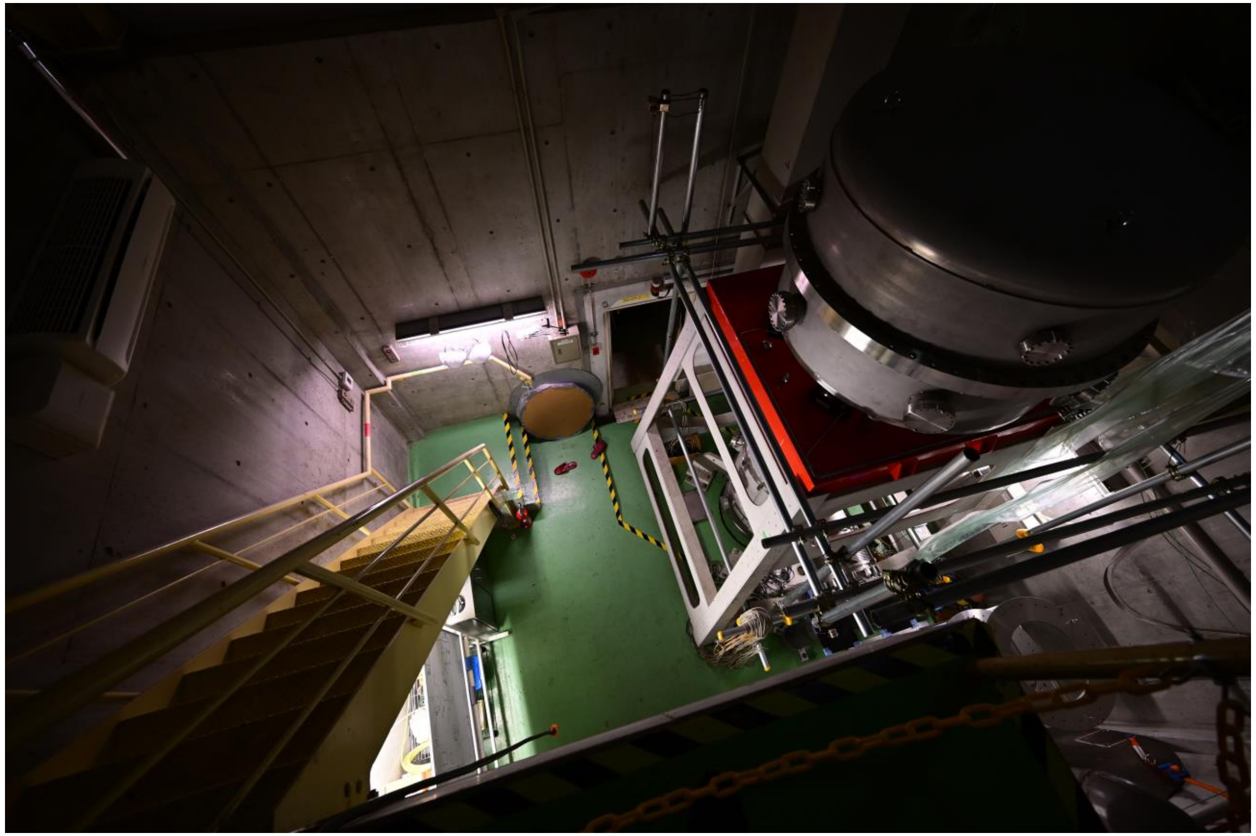
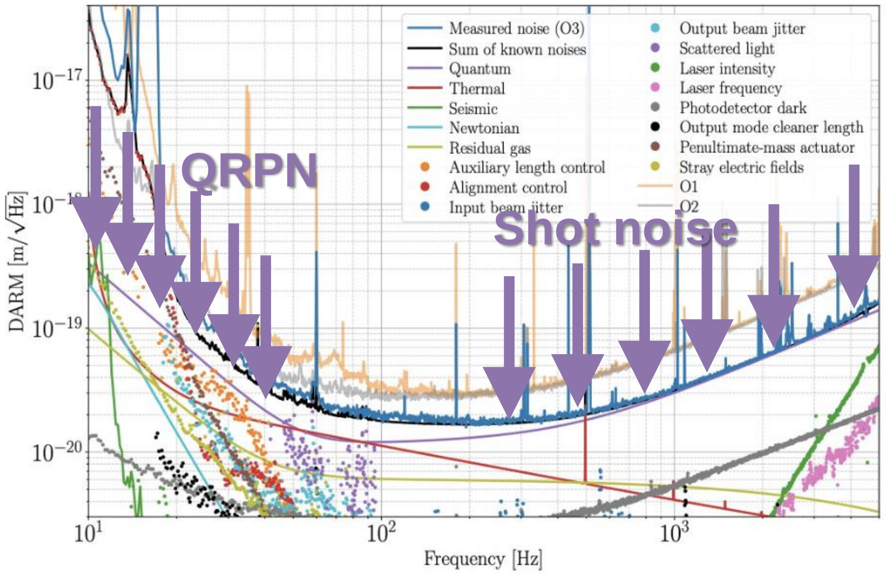
# Overview

- Status of frequency dependent squeezing at TAMA 300, NAOJ Mitaka campus
- Status of frequency dependent squeezing for KAGRA
- Facilities available at NAOJ
- Future strategy in quantum optics

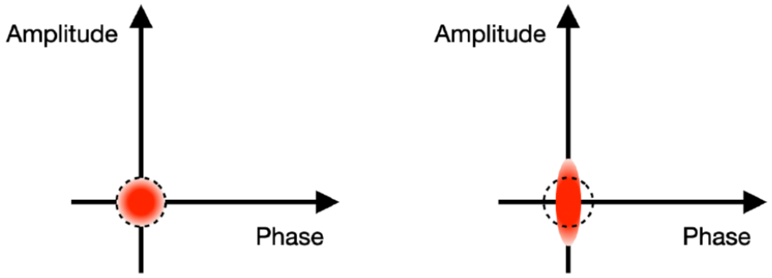


# Quantum noise and squeezed light

- Sensitivity of advanced GW detectors in principle limited by quantum noise
- High frequency sensitivity is limited by quantum fluctuation of phase, photon arrival time
- Low frequency sensitivity should be limited by quantum fluctuation of amplitude (radiation pressure noise)
- We can create squeezed vacuum using an optical parametric oscillator OPO, and typically we squeeze phase fluctuations

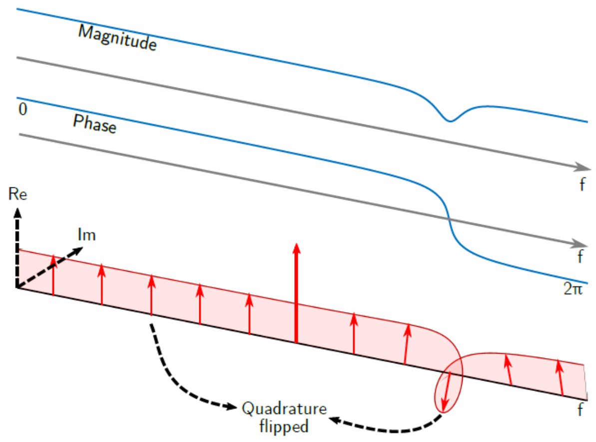



A. Buikema *et al.* Sensitivity and Performance of the Advanced LIGO Detectors in the Third Observing Run, Phys. Rev. D 102, 062003 (2020)

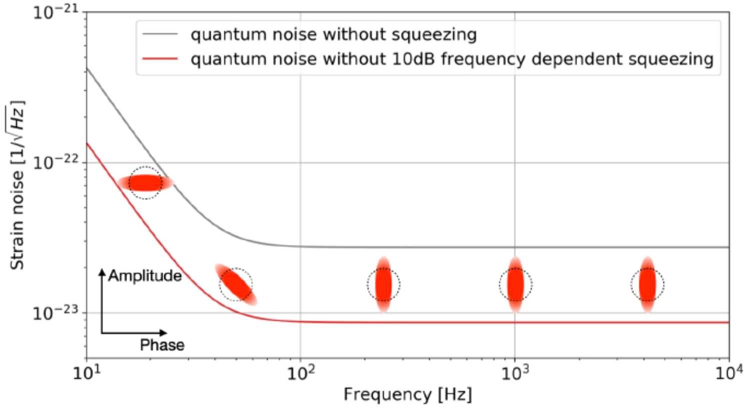


# Frequency dependent squeezing

- We can send the frequency independent squeezed light to a detuned filter cavity
- High frequency components are just reflected
- Lower frequency components are stored and acquire a phase delay
- Rotation of the squeezed ellipse – we squeeze dominant noise quadratures in each band.



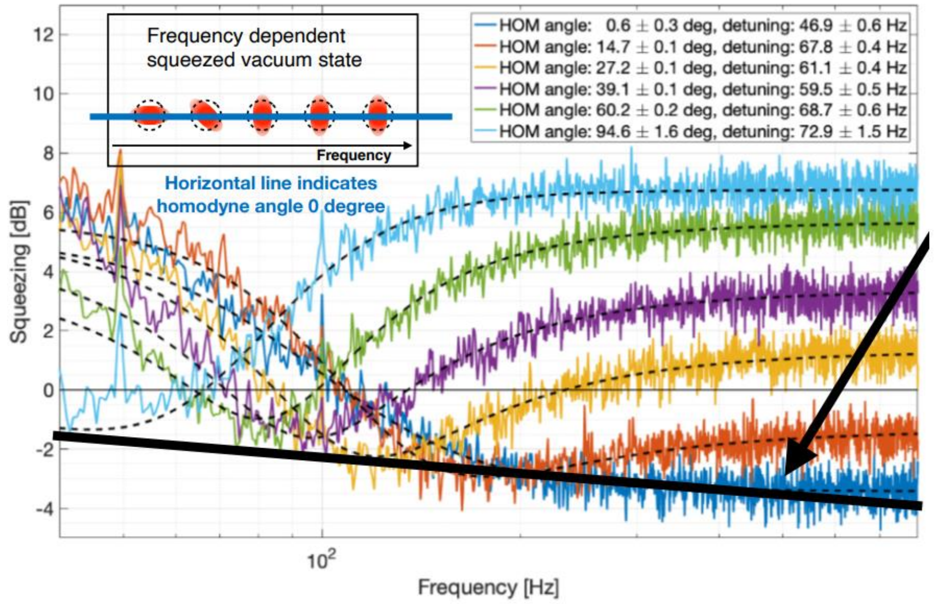

Min Jet Yap PhD thesis “Quantum noise reduction for gravitational wave interferometers with non-classical states”



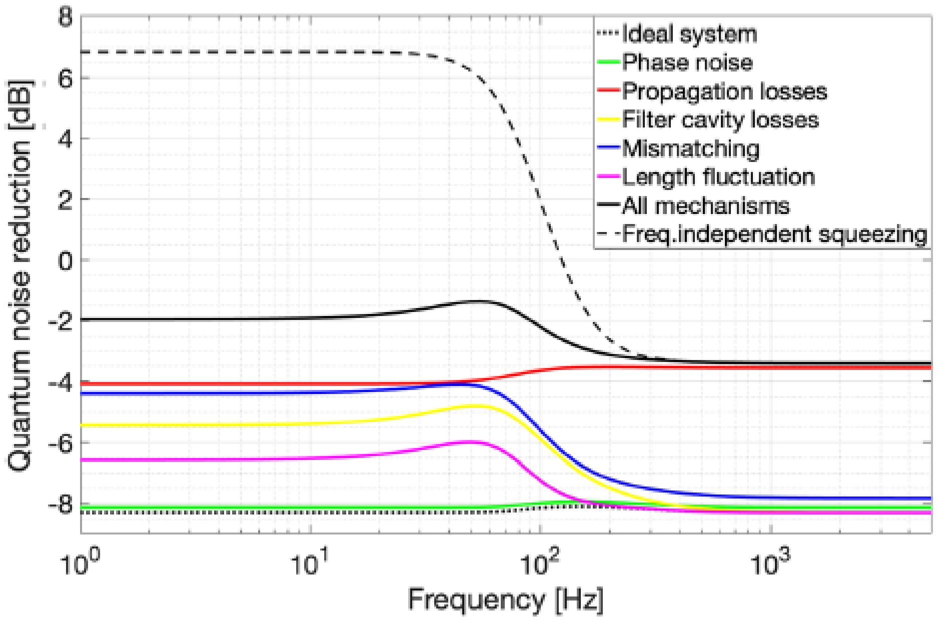

Yuhang Zhao PhD thesis

# TAMA300 experiment

- Frequency dependent squeezing of a suspended interferometer was demonstrated in 2020 at NAOJ
- Squeeze level – 8.3 dB produced, 3.4 dB observed (max)
- Rotation frequency about 90 Hz
- Dominant sources of loss are optical loss and mode mismatch
- Backscatter becomes prominent below 50 Hz




Y. Zhao *et al.* PRL **124** 171101 (2020)



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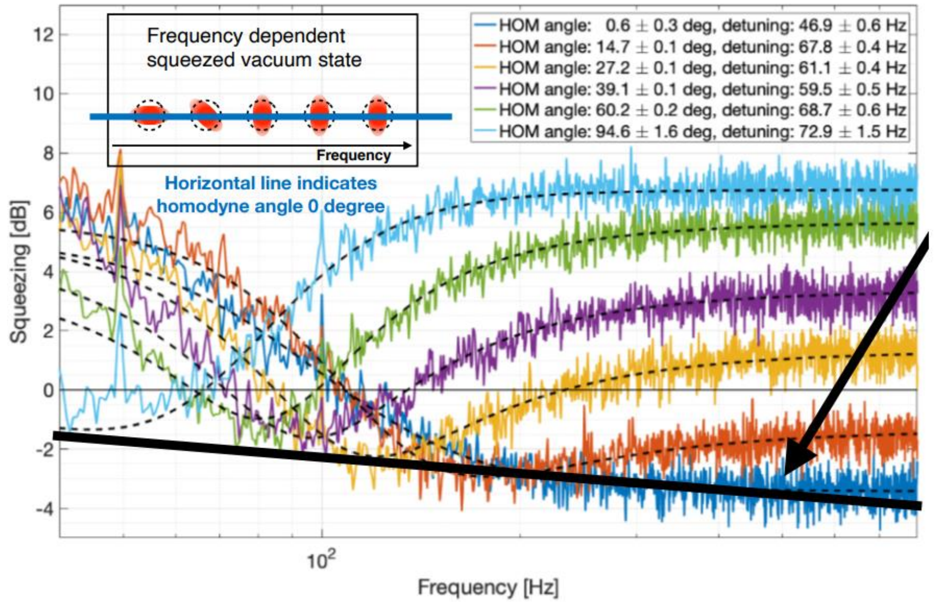
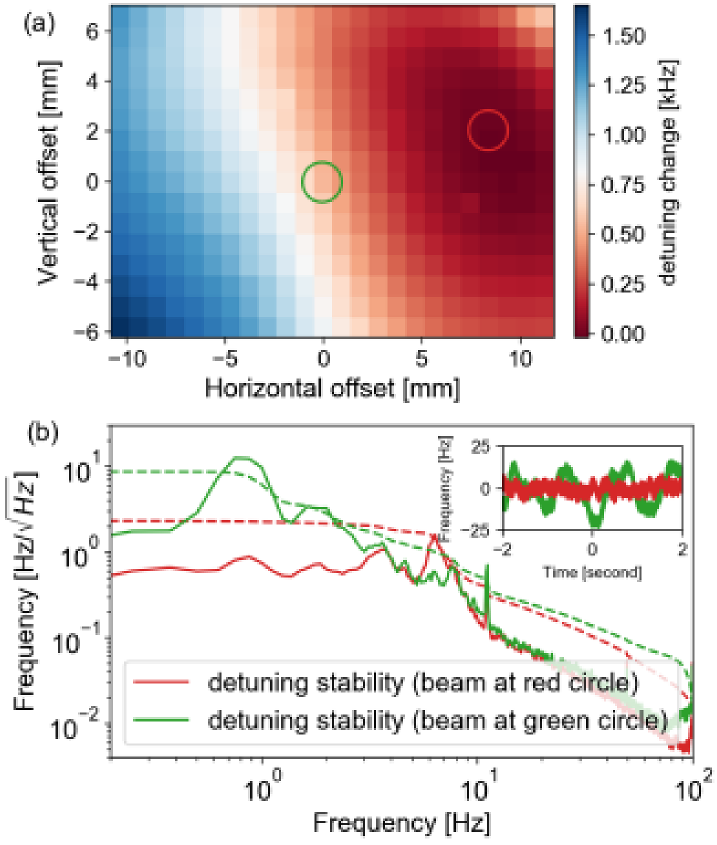



Y. Zhao *et al.* PRL **124** 171101 (2020)

| Generated squeezing | 8.3 dB |
| --- | --- |
| Injection losses | 24% |
| Readout losses | 7% |
| Phase noise | 30 mrad |
| FC round-trip losses | 120 ppm |
| FC locking accuracy | 6 pm |
| Mode-matching squeezing / FC | 94% |
| Mode-matching squeezing / Local Oscillator | 98% |
| FC length | 300 m |

# Recent publications

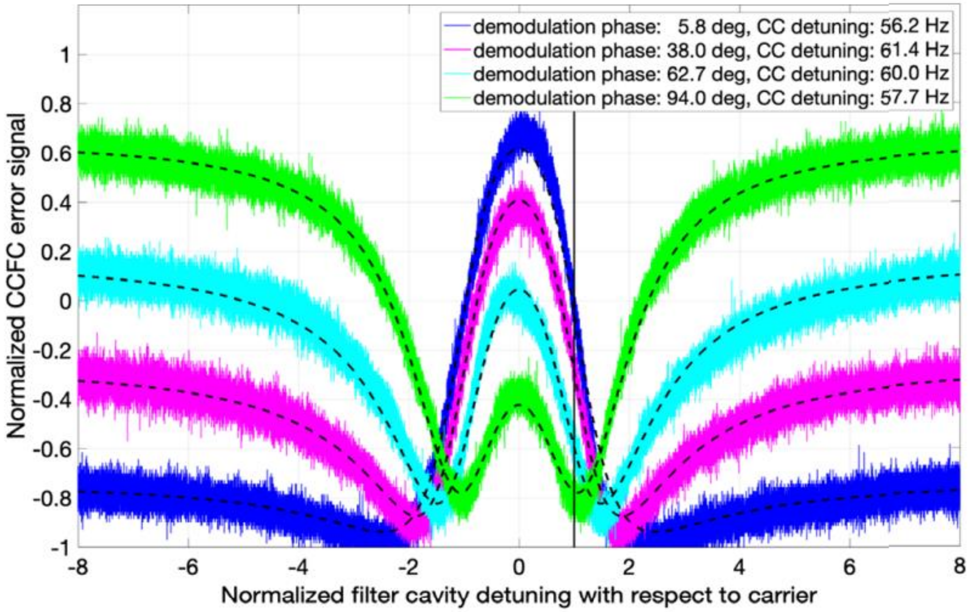
- Bichromatic control of filter cavity
- Some research into the behaviour of relative detuning between the green and infrared beams
- We managed to mitigate these detuning instabilities and improve the overall lock accuracy by ~ 4x
- Possibility of just controlling FC with green, previously thought to be too noisy for GW detector



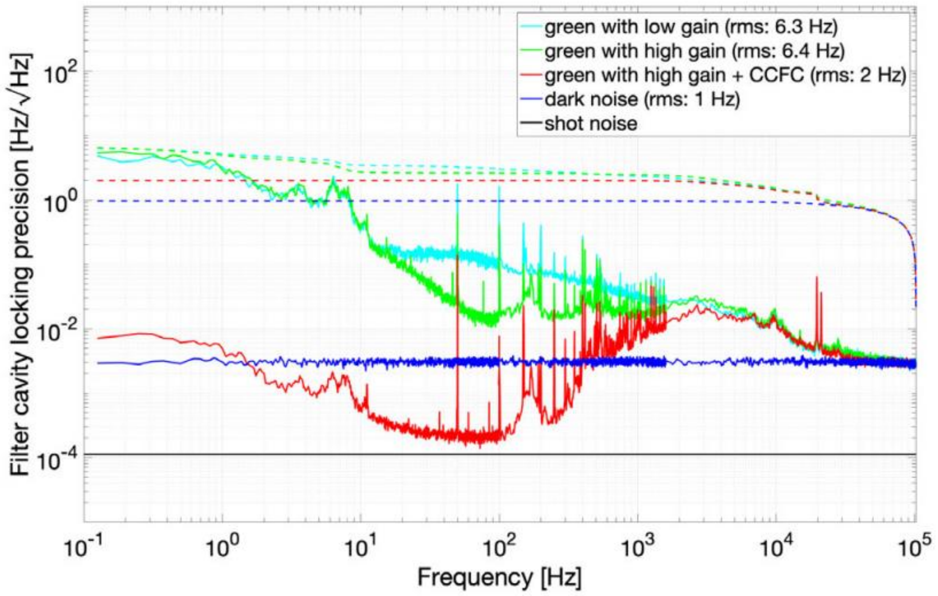

Y. Zhao et al. PRD **105** 082003 (2022)

# Recent publications

- Demonstration of filter cavity control with coherent IR sidebands
- Length control ideally should be performed with a beam co-propagating with the squeezed field.
- We managed to show this principle with a suspended filter cavity, as well as the improvement compared to green lock

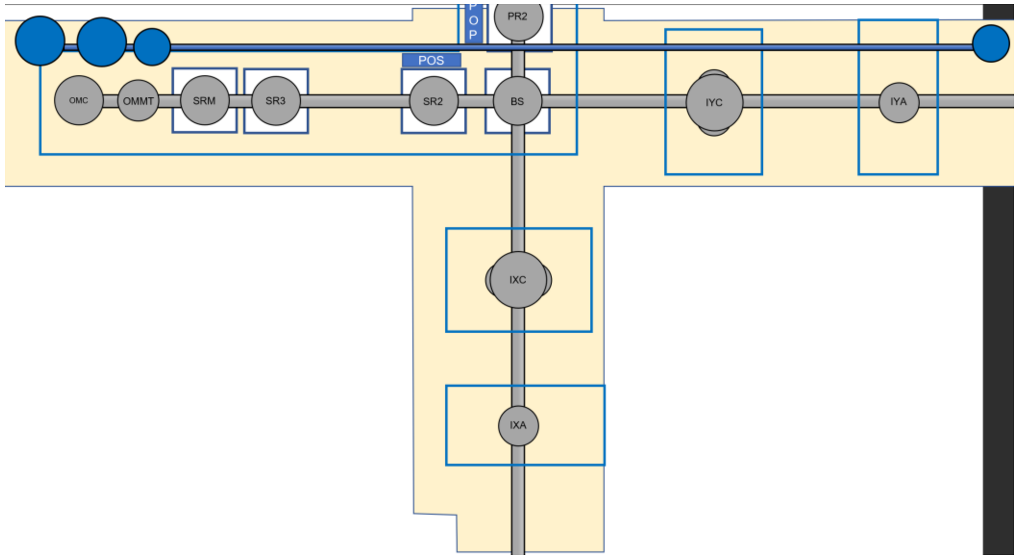



N. Aritomi et al. PRD **106** 102003 (2022)



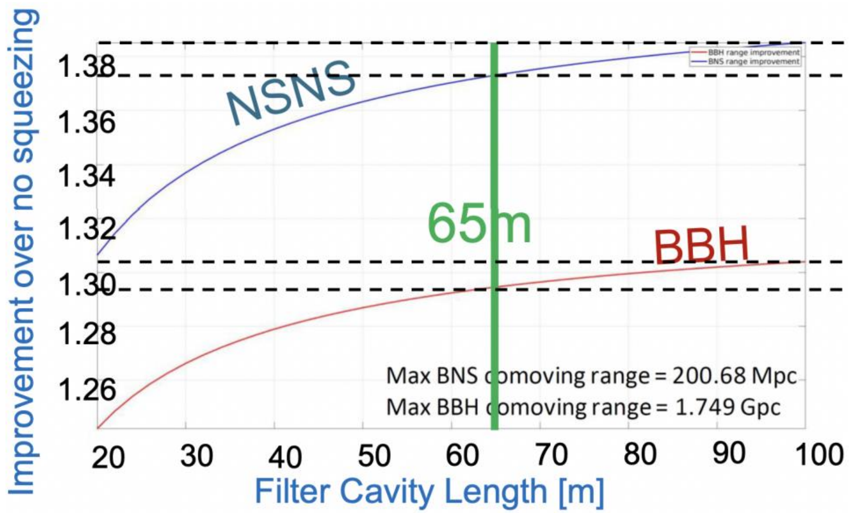
# Status of FDS at KAGRA

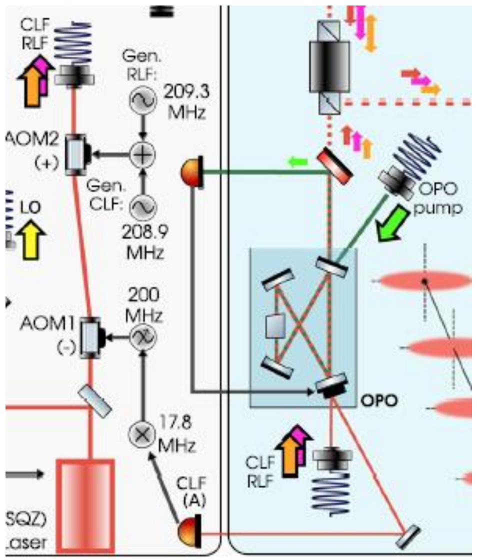
- Development of FDS at KAGRA is scheduled for O5 (tight timing for mirror fabrication though…).
- Largely managed at NAOJ Mitaka, with inputs NTHU and KASI.
- A lot of baseline design work has already been done by our predecessors
- Still, KAGRA has some unique conditions – better seismic noise, but also less space

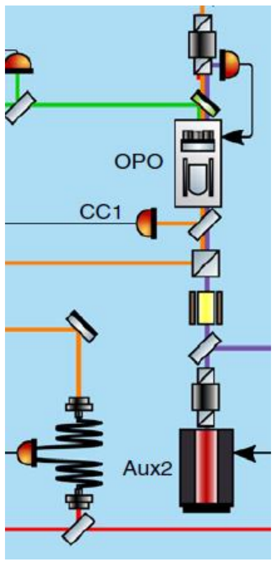


# KAGRA specific FDS tasks

- Available FC space was determined to be 85 m (initially 65m) vs ideal 300 m. Optical loss increase is manageable
- Mode matching setup in the confined space to be determined
- We should investigate different control schemes (A+ RLF, V+ subcarrier, TAMA CCFC) – fundamental difference is in the generation of the length control beam



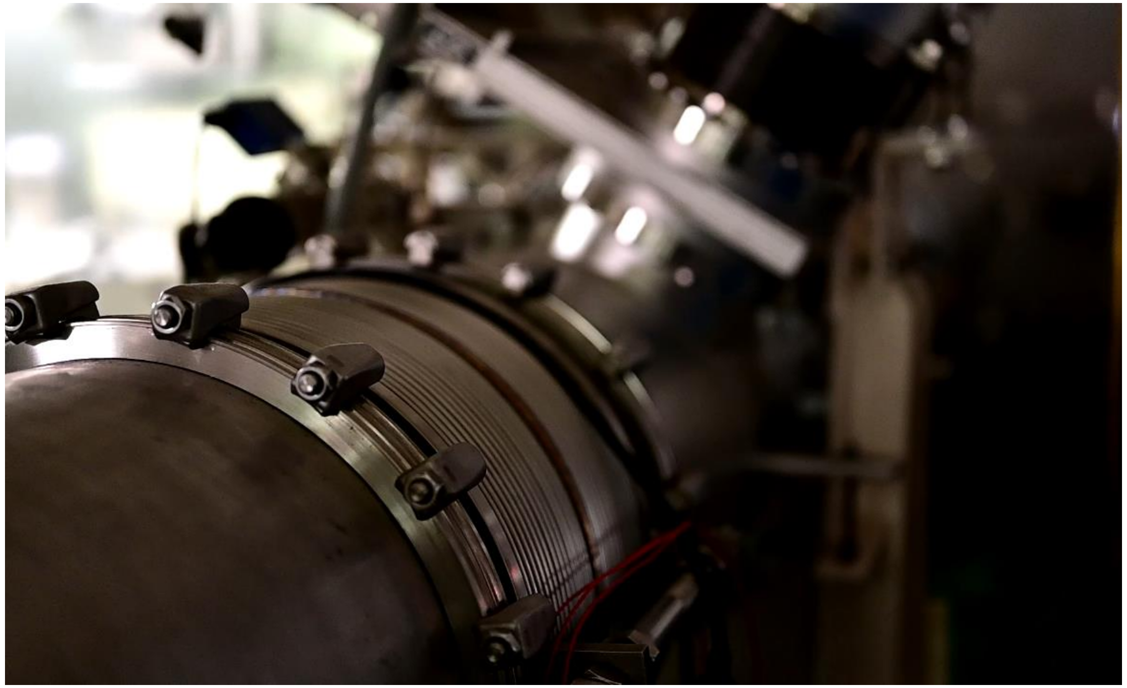

NAOJ Future Strategy for TAMA300

# Future strategy

- Fundamental proof-of-concept is “done”
- We have plenty of resources and expertise
- We are busy evaluating what to do with the TAMA300 interferometer as well as future developments in gravitational wave detection.

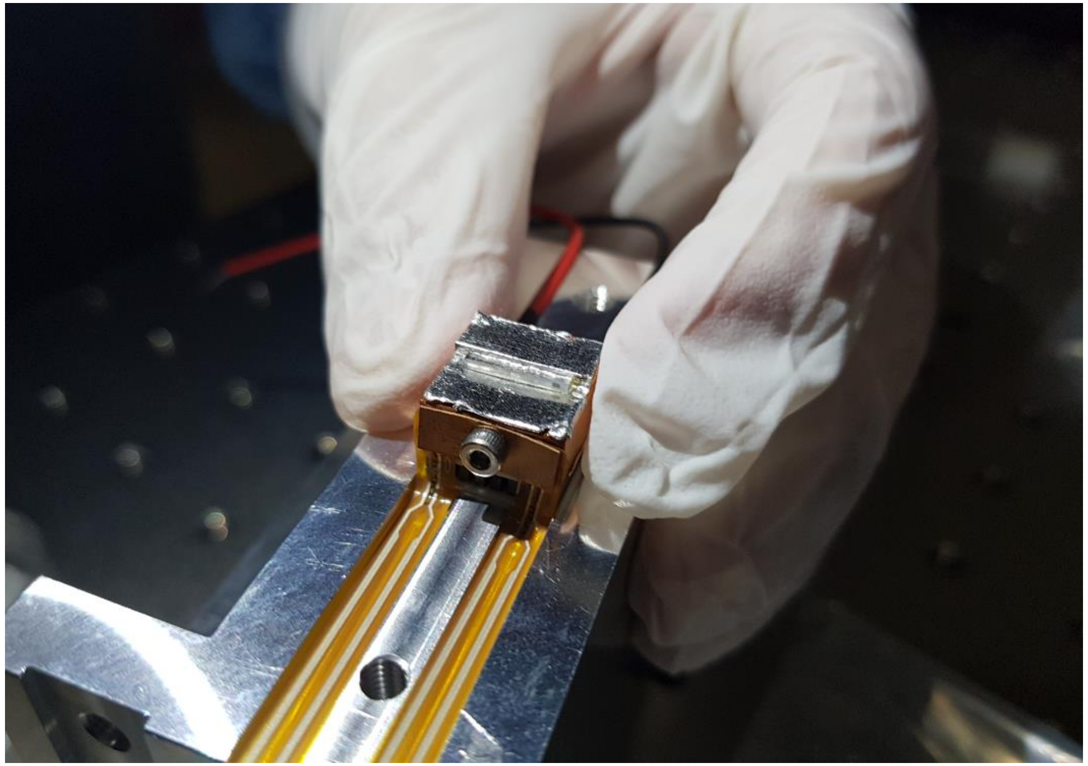
# Resources

- 300 m interferometer vacuum arms, as well as former IMC vacuum tank pair ~ 10m
- Squeezer table, many optics, lasers and equipment for 532, 1064, 1550.
- Full loadout of GW interferometer oriented CDS timing system hardware for synchronised signal acquisition, storage, remote and automated control
- KOACH filter cleanroom in ATC building



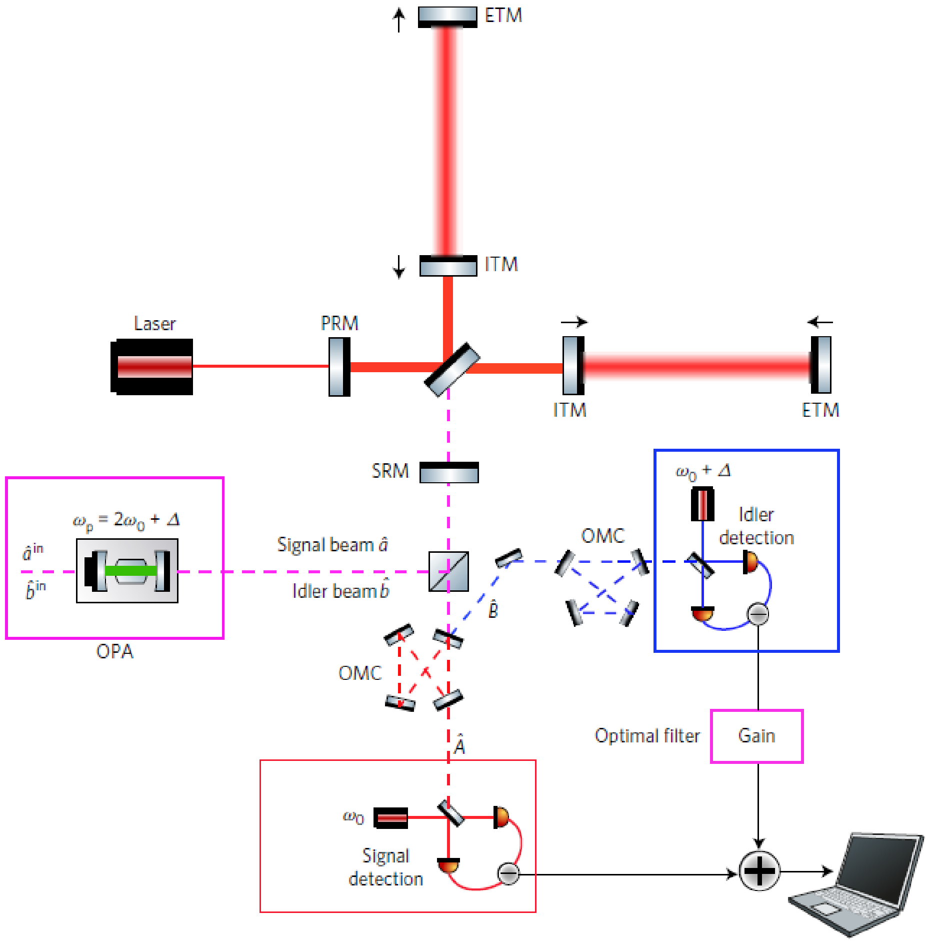
# Resources

- Spare cryostats – one in ATC building, others belonging to Tomaru-san at KEK (Mitaka to Ibaraki commute though -_-)
- 2 spare PPKTP crystals and experience in full characterization and assembly of OPO cavity
- Experience in other fields
- Money (Matteo Leonardi Quantum Enhancement Kiban-A)



# EPR squeezing

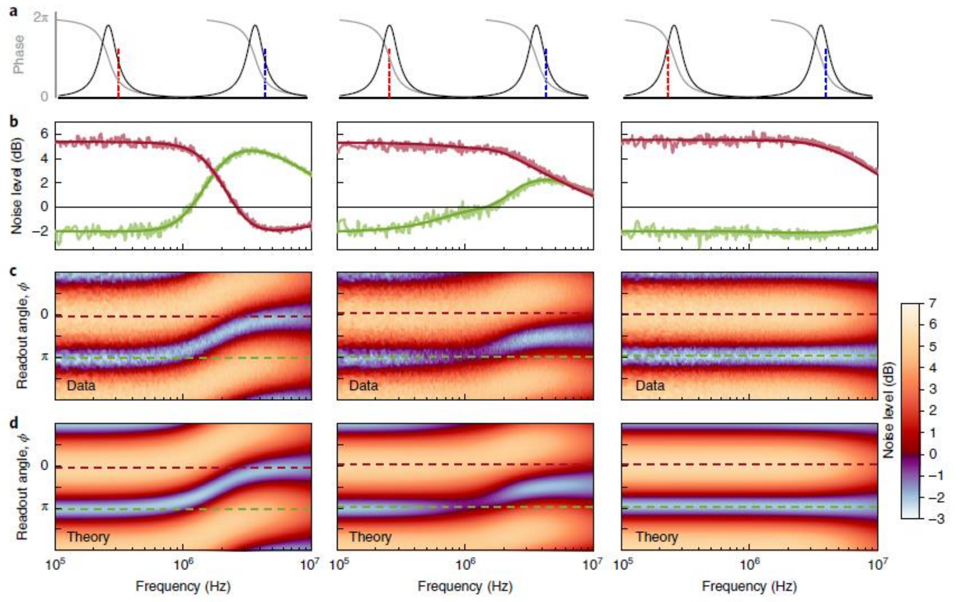
- There are two correlated FIS beams generated from the OPO
- The signal beam is resonant inside the interferometer and acquires the gravitational wave signal.
- The idler beam is detuned from the interferometer. It sees the interferometer as a filter cavity and acquires frequency dependent squeezing
- By the properties of quantum mechanics, simultaneous measurement of the signal and idler will project frequency dependent squeezing onto the signal



Min Jet Yap PhD thesis “Quantum noise reduction for gravitational wave interferometers with non-classical states”

# EPR squeezing

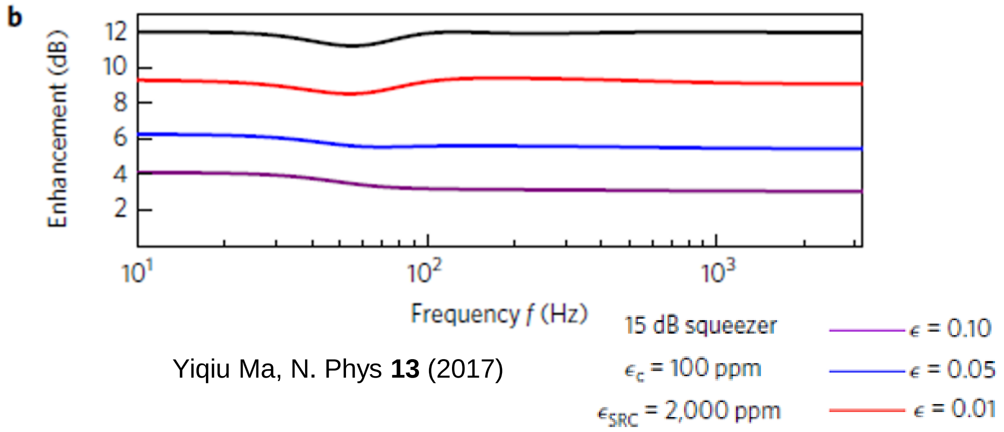
- Seems like a natural option for TAMA – already demonstrated on tabletop, immediately relevant to GW detection, we have spare OPOs as well as experience in using them.
- However, there is a fundamental 3 dB penalty due to the two beams – optical loss is sensed twice. This penalty and strict optical loss limits make us question the worth for GW detection




QRPN reduction

Two mode FDS (Yiqiu Ma N Phys)

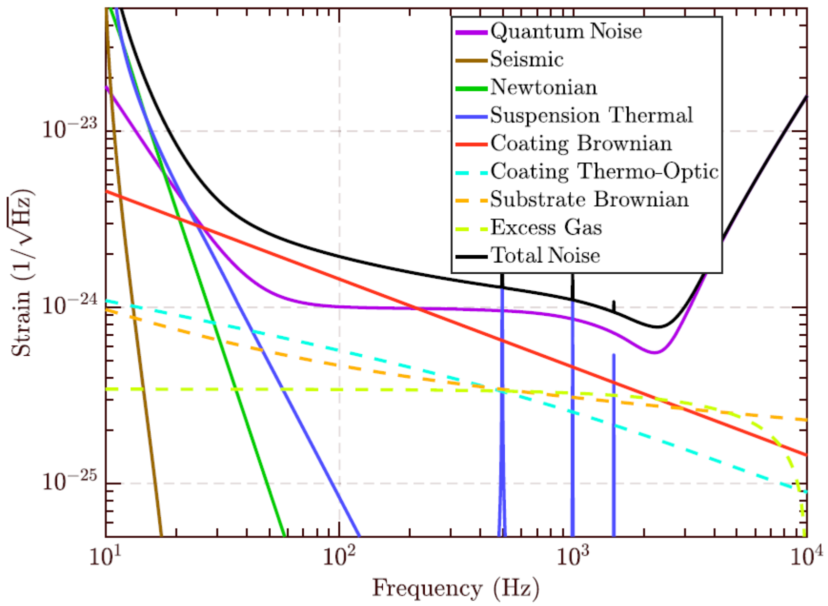
Detuned interferometer compensation

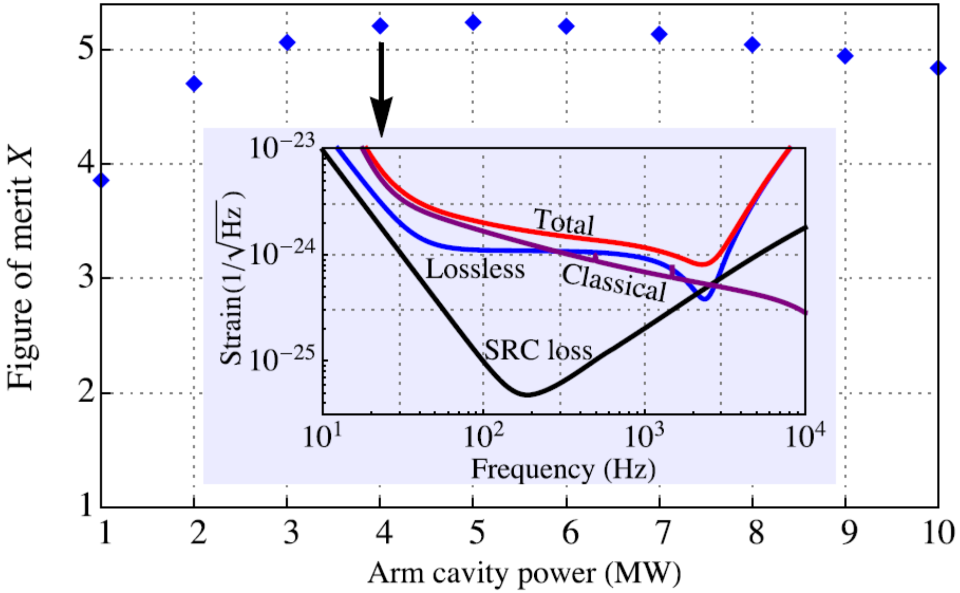



Yiqiu Ma, N. Phys **13** (2017)

# Long SRC

- When the SRC approaches the length of the interferometer, the storage time in the SRC becomes significant
- Optical coupling resonance between the SRC and arm cavities -> in the 1-5 kHz range for GW detector with ~ 300m long SRC
- Limited by optical loss from wavefront distortion in the SRM/ITM cavity

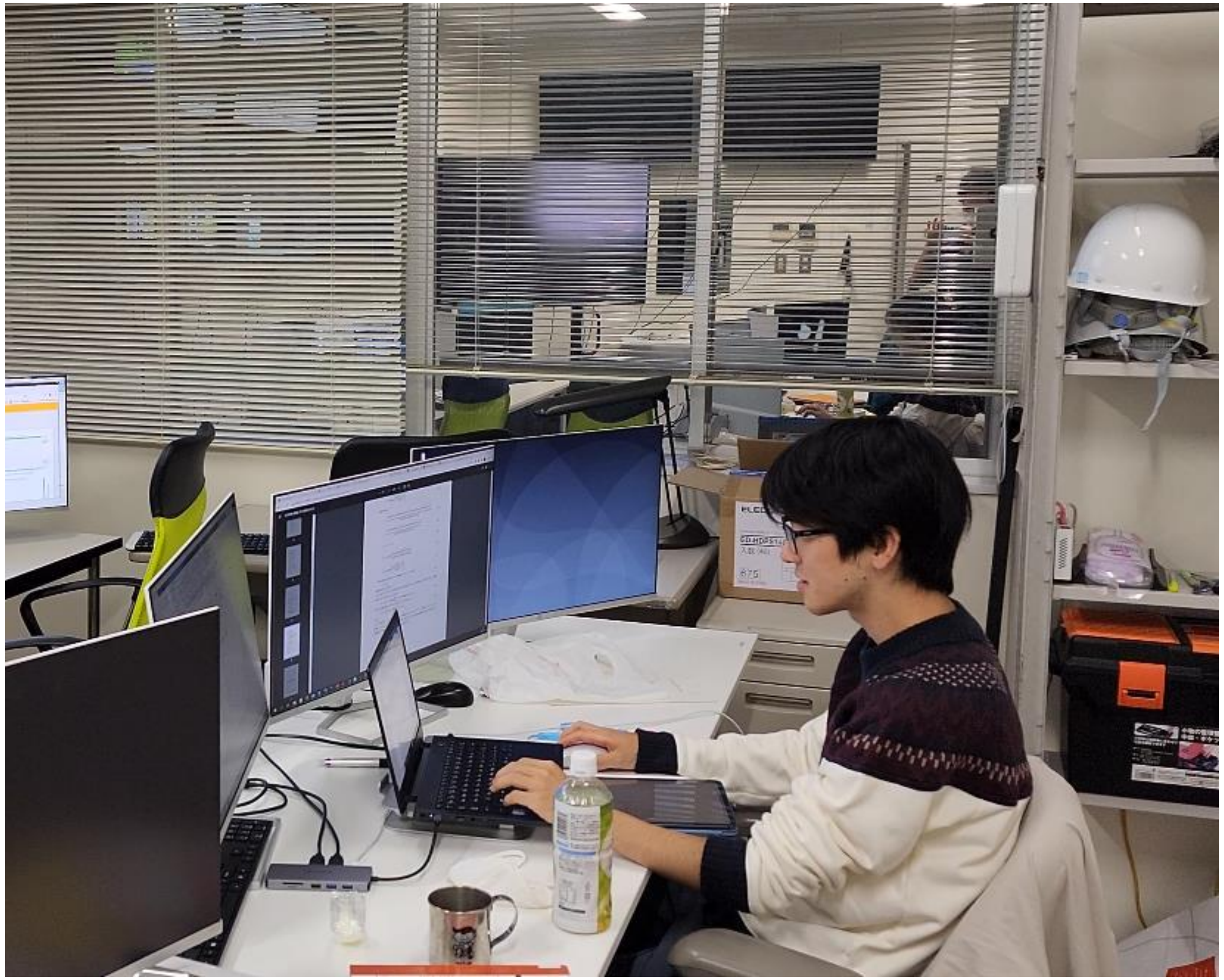



Denis Martynov PRD **99** 102004 (2019)

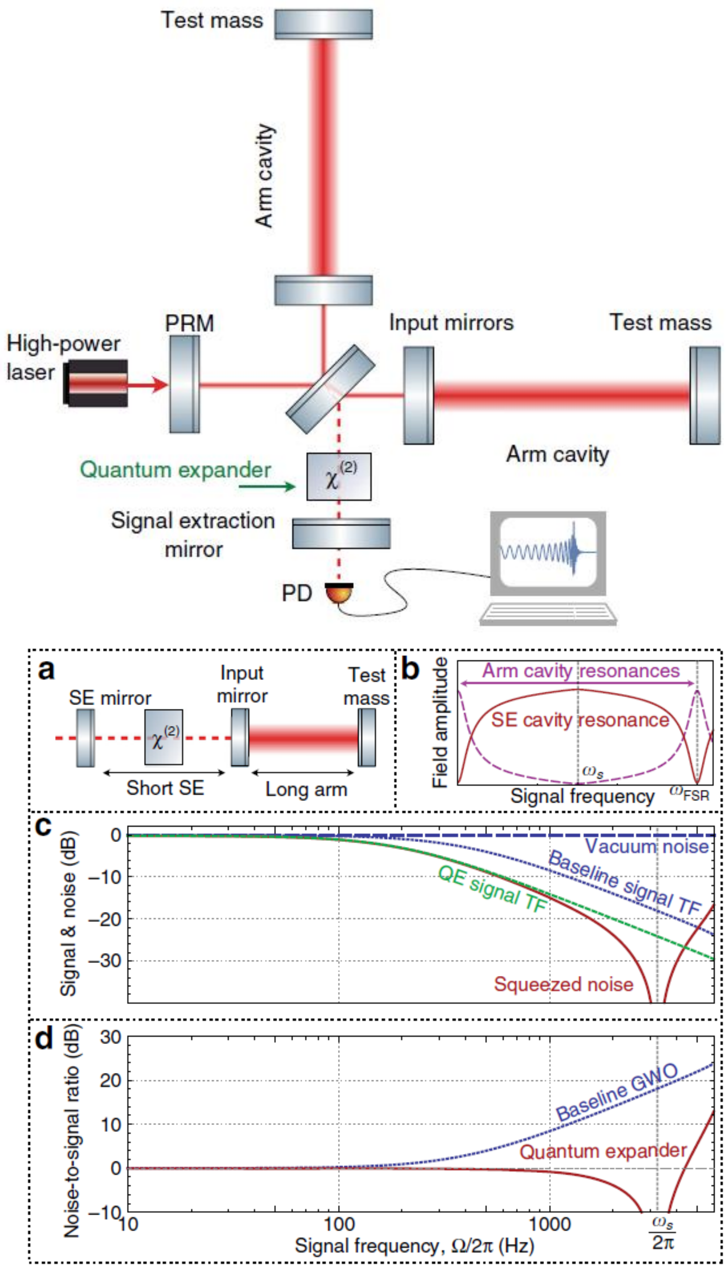
# Speed meter

- This talk is getting a bit long so thankfully Yohei Nishino has that covered ☺



# Internal squeezing

- OPO in the signal recycling cavity
- Creates squeezing of the shot noise, however, low frequency noise is unaffected
- Optical loss, of course (as for all nonclassical light manipulation)
- Technical issues – clipping by OPO, delivering green pump inside SRC, effect of auxiliary sidebands on OPO process…




Mikhail Korobko Light Sci App **8**:118 (2019)

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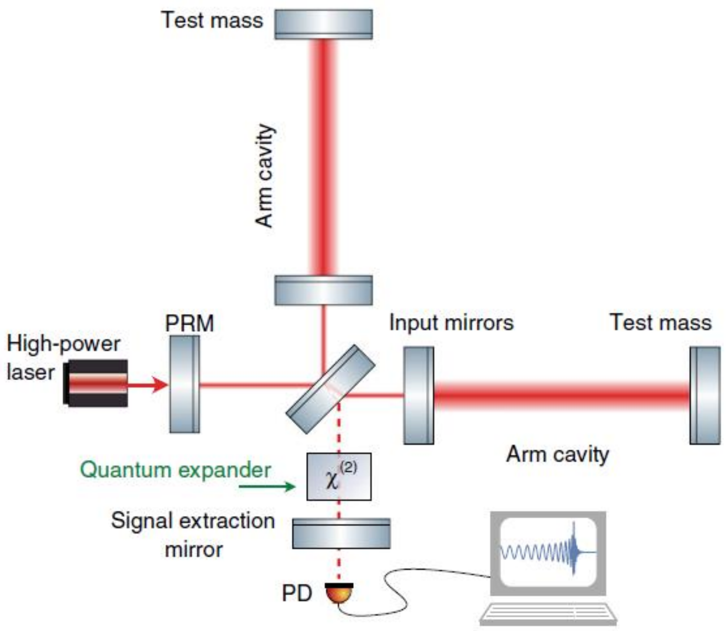


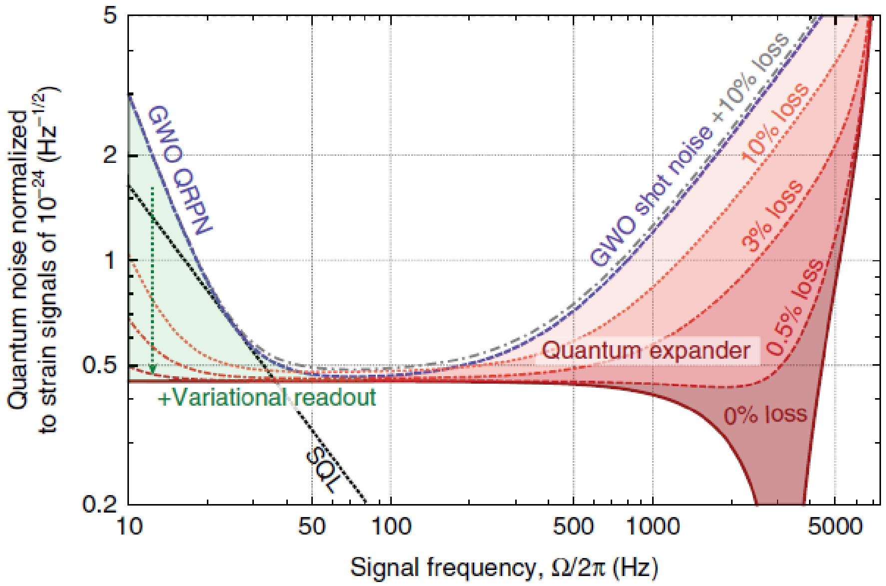


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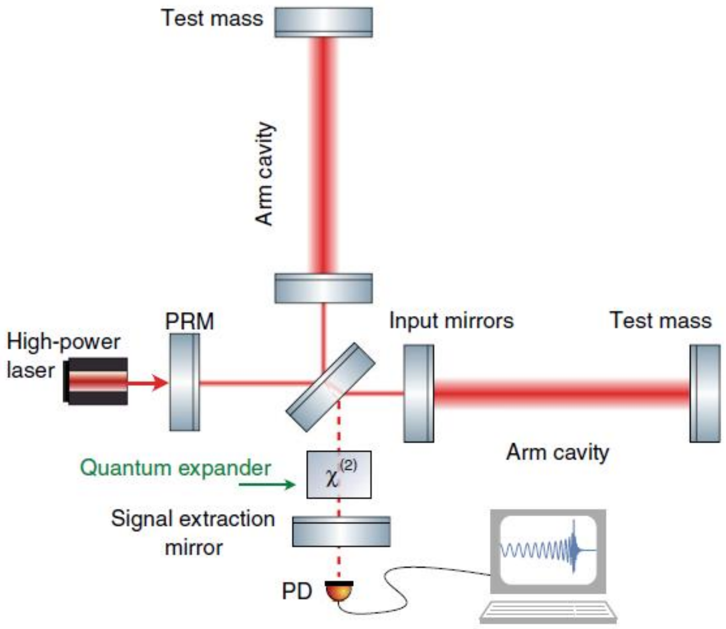
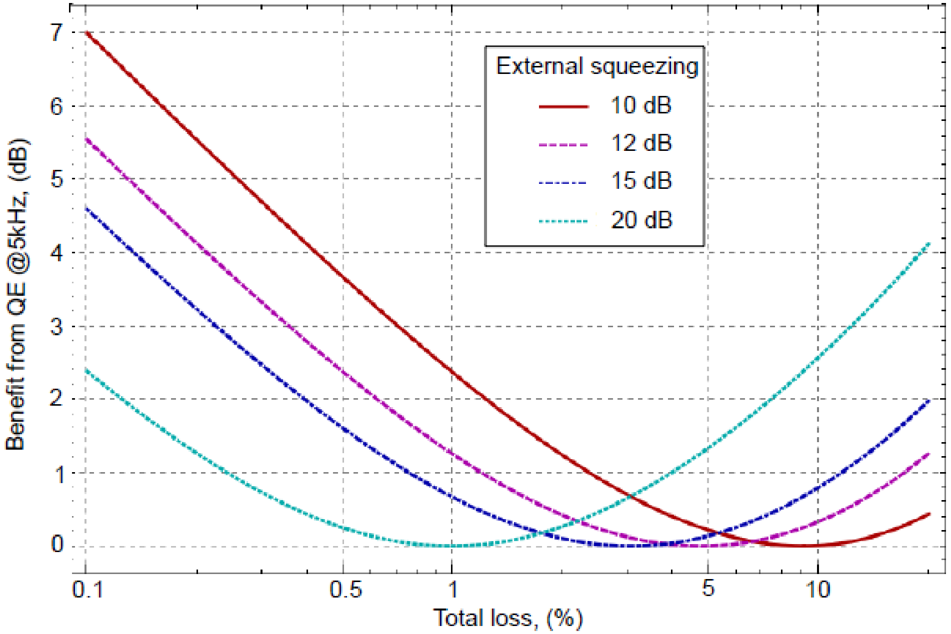
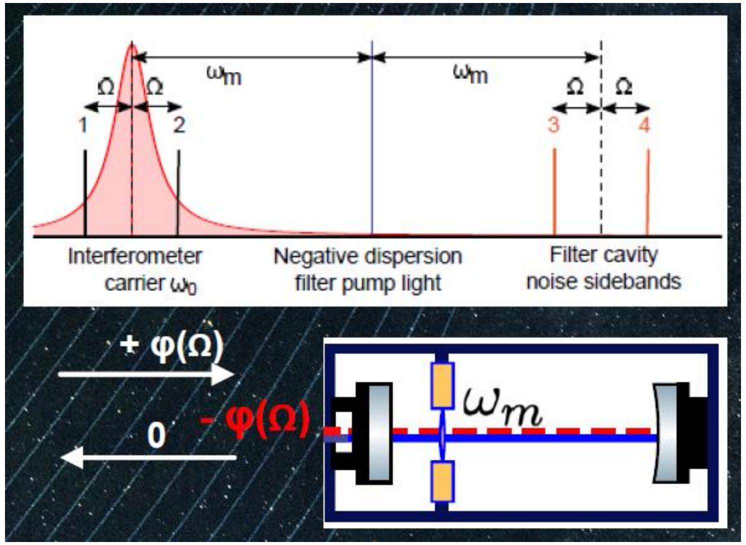



Mikhail Korobko Light Sci App **8**:118 (2019)

# PT symmetric white light cavity

- GW signals travel a long distance.
- High frequency signals are detuned and acquire a phase delay
- An optomechanical filter – an optical cavity with a moving mechanical oscillator coupled to the light field – can provide a compensating phase delay.
- Can make a broader range of frequencies resonant (hence the term “white light”)
- But mechanical resonator introduces thermal noise

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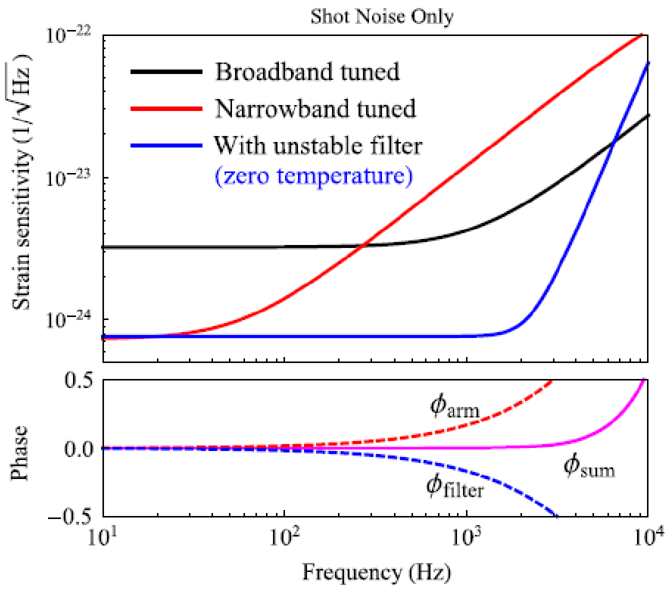
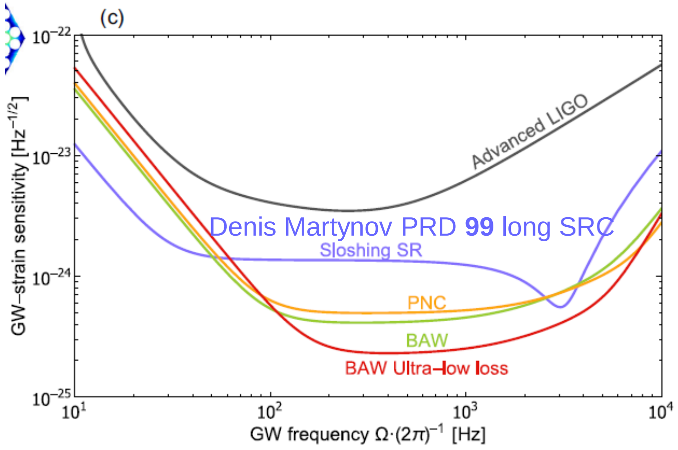


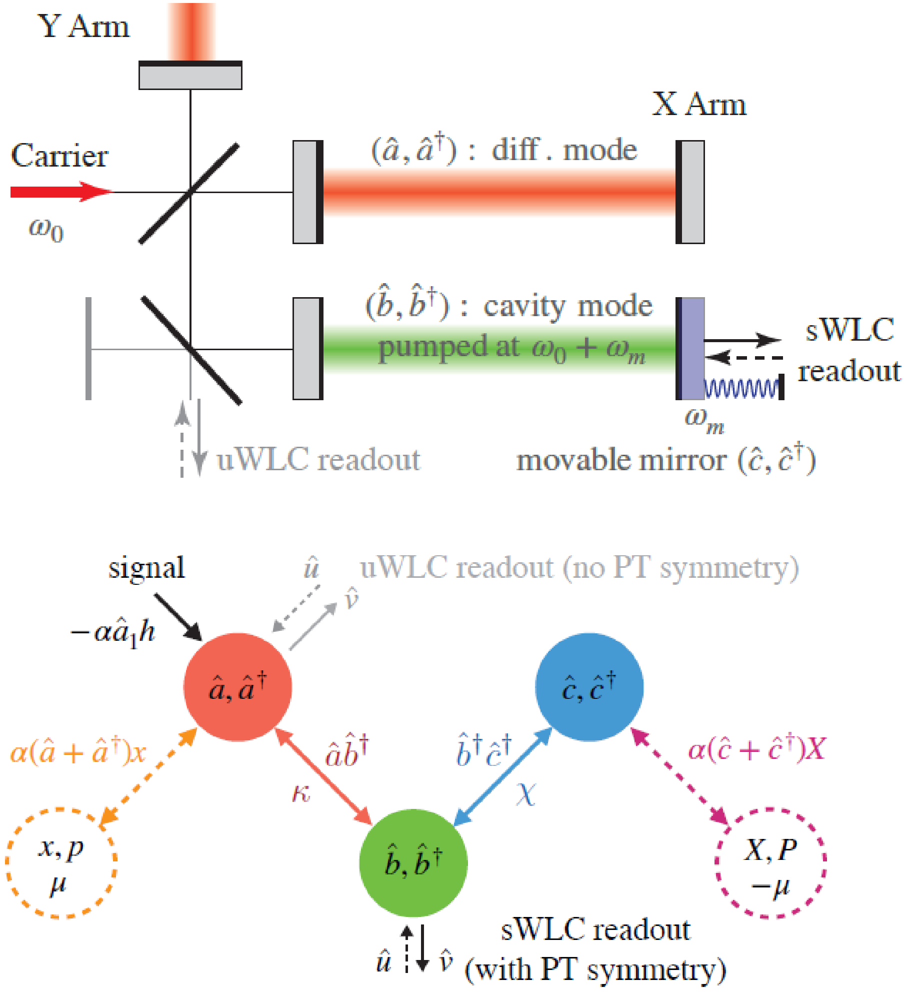

Haixing Miao PRL **115** 211104 (2015)




Michael Page Comms Phys **4**: 27(2021)

# PT symmetric white light cavity

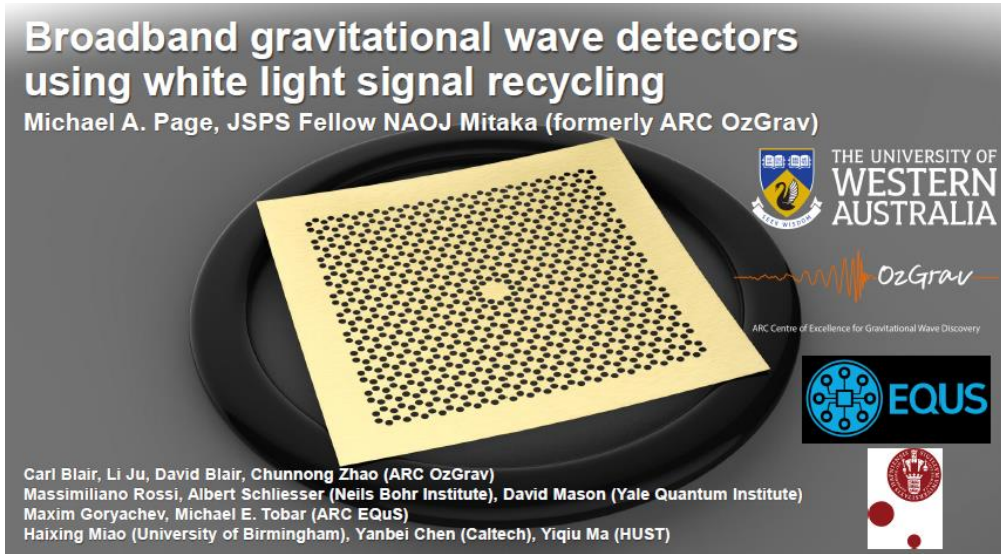
- Initial propositions of this scheme had an unstable optomechanical filter - by design the pump and signal beams are detuned by ωm, but this also causes instability
- PT symmetry refers to the mode configuration and readout – conversion from unstable to stable system by counterbalance of flow rates χ and κ

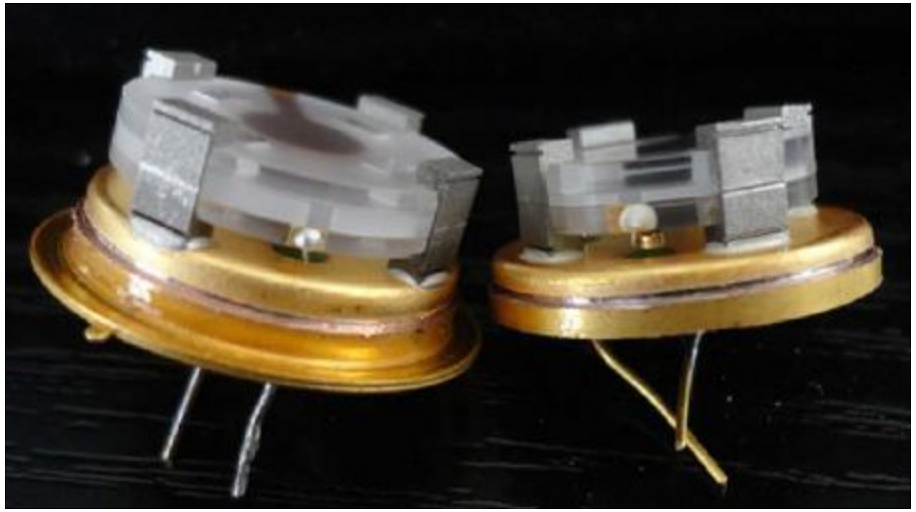



Xiang Li arXiv:2012.00836v1

# PT symmetric white light cavity

- The mechanical resonator problem was what I worked on before coming to Japan
- The optomechanical filter cavity contains two beams and a mechanical resonance
- Mechanical resonators with low thermal noise have inefficient transfer of energy from pump to GW signal, and vice versa (not a fundamental property, just current state-of-the-art).
- Also in many cases they are really small



# Brainstorming

- Detect conventional GW TAMA
- Detect MHz GW at TAMA
- Negative mass spin EPR
- Dark matter
- Optomechanical FDS filter cavity
- Topological energy transfer and exceptional points (one layer of abstraction above PT symmetry)

# Conclusion

- Frequency dependent squeezing proof of concept is finished
- Currently investigating integration of FDS into KAGRA
- Also looking at future prospects for the many resources at NAOJ
- There is still a lot of investigation of prospects for enhancing current GW detectors, investigating more esoteric quantum optics, or going to other astronomy entirely