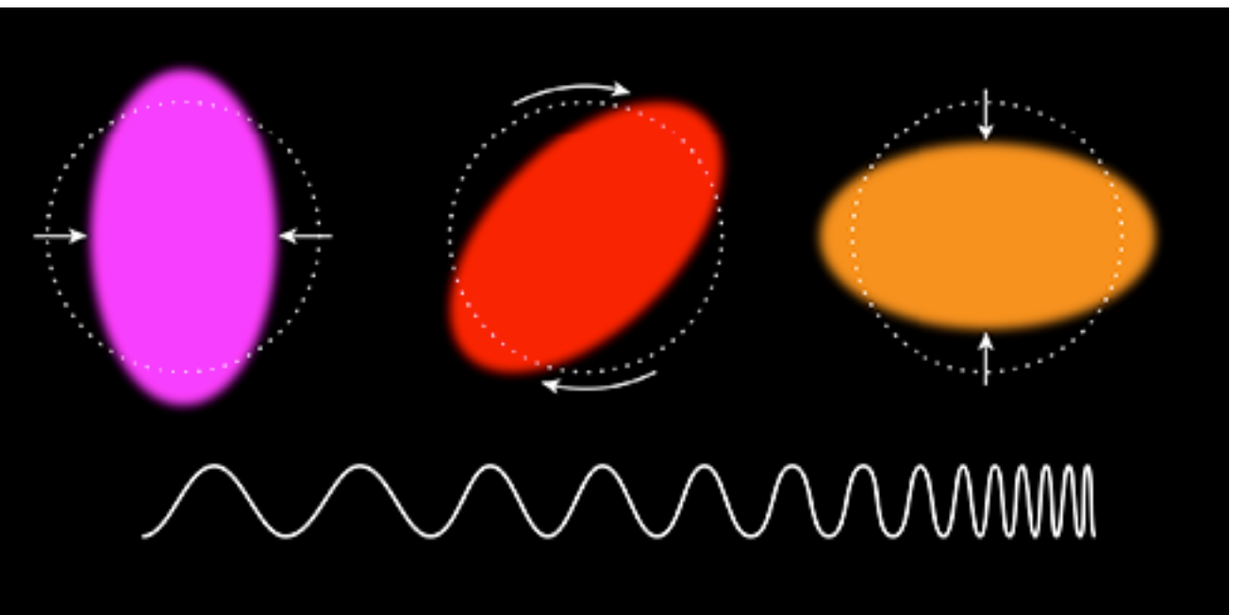
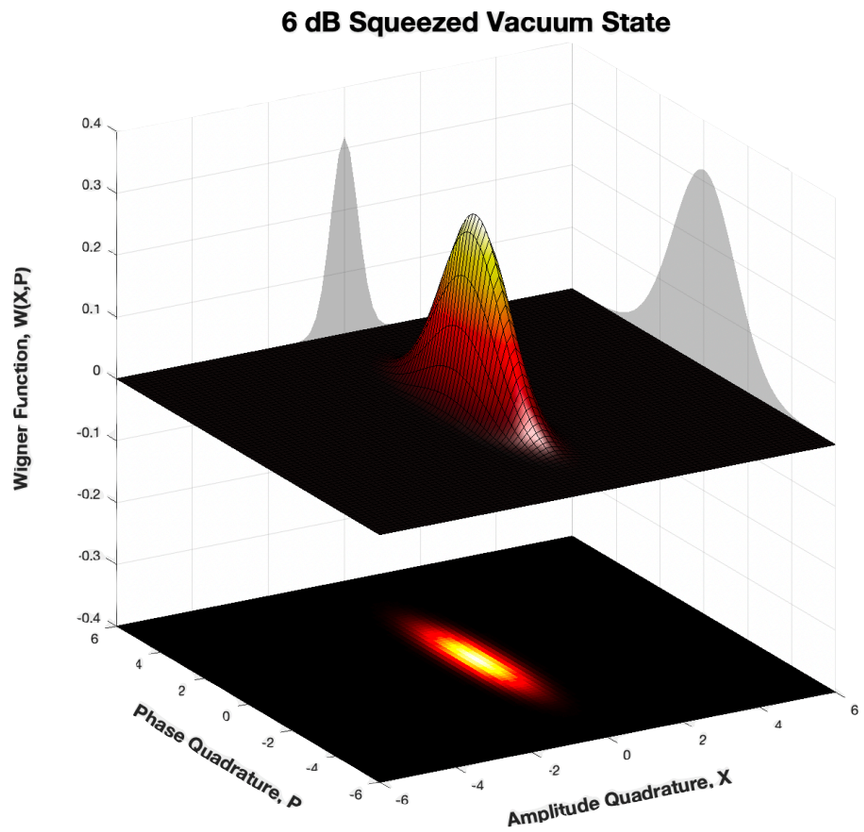
Squeezed Light Applications:

in Gravitational Wave and Quantum State Tomography

Yao-Chin Huang

Supervisor: Ray-Kuang Lee

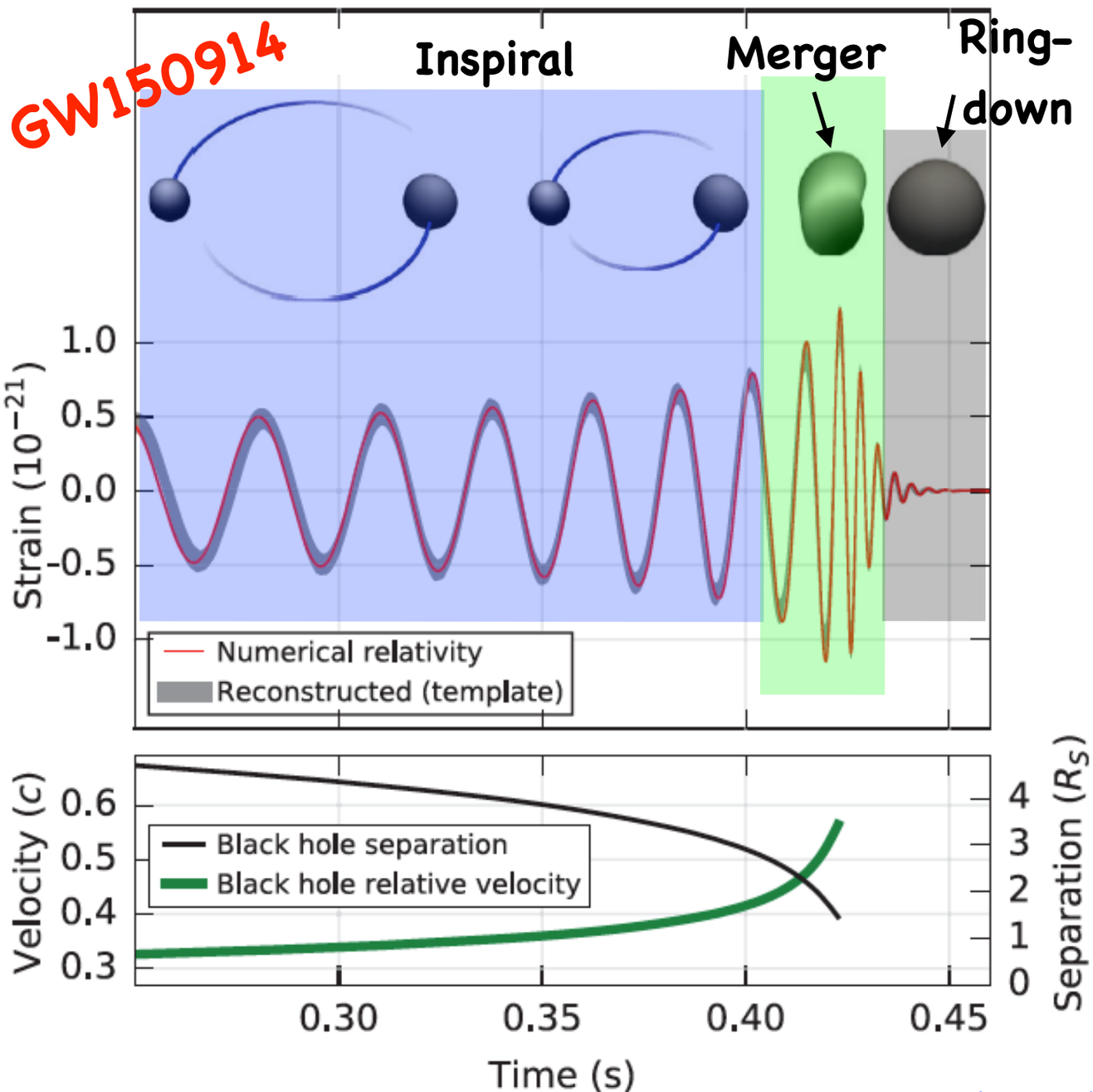




Part I : Gravitational Wave Detector

- First Detection Event:
  - Binary Black Hole
    (2015, GW150914)
  - Binary Neutron Star
    (2017, GW170817)

- 2017 Nobel Prize in Physics:
  "for decisive contributions to the LIGO detector and the observation of gravitational waves."



PRL, **116** 061102(2016)

Global Network of GW Telescopes

- Ground-based GW telescopes
- KAGRA join O3b in April 2020.

Japan

America

Germany

Italy

Adv. feature:

- Underground
- Cryogenic

Running

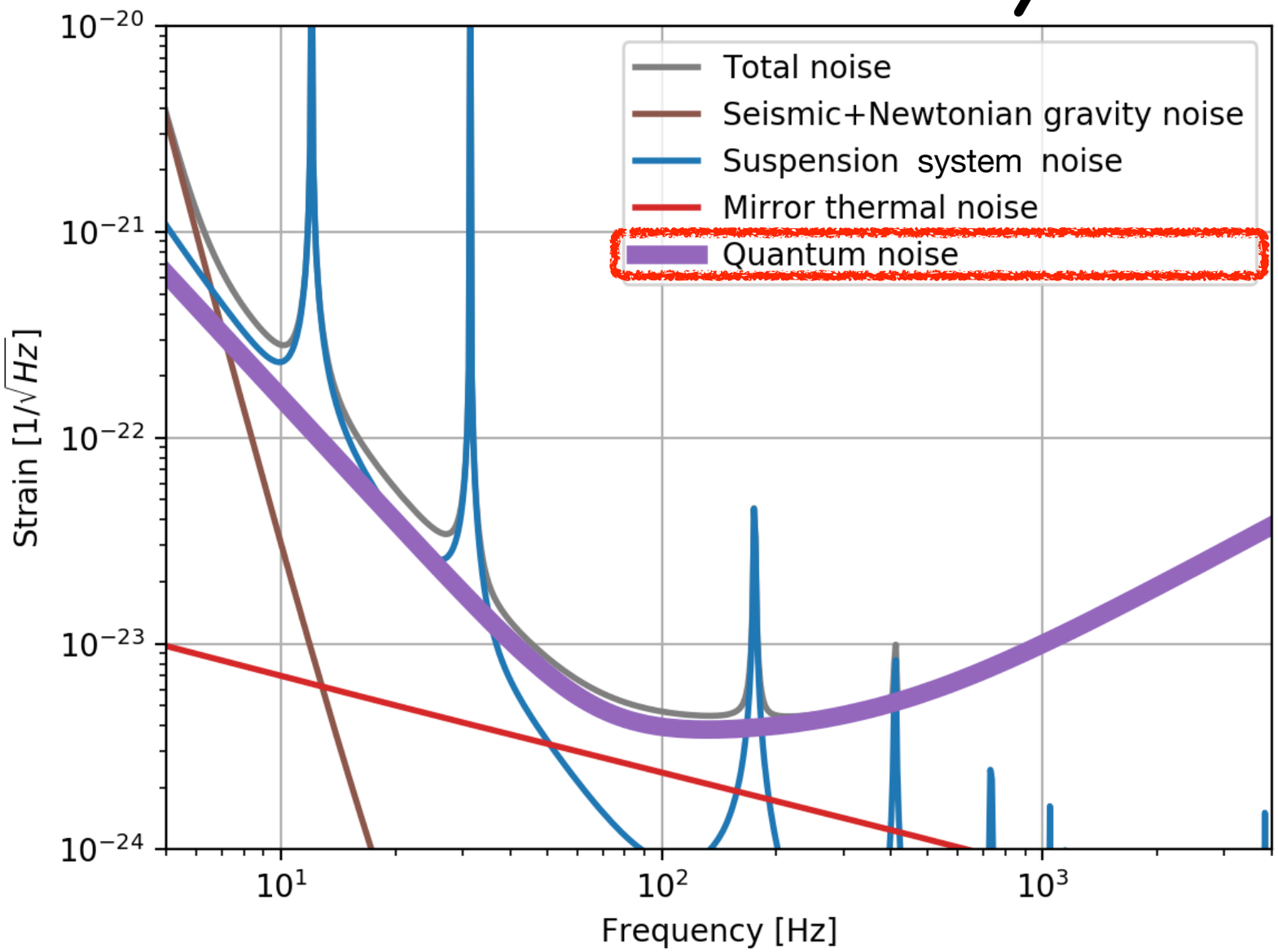
Planned

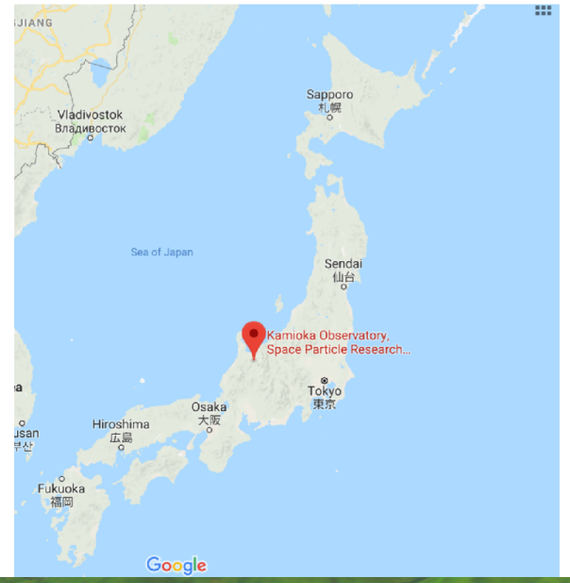
LIGO: https://www.ligo.caltech.edu/
Virgo: http://www.virgo-gw.eu/
KAGRA: https://gwcenter.icrr.u-tokyo.ac.jp/
IndIGO: http://www.gw-indigo.org/

KAGRA Introduction

- An underground GW detector in Kamioka, Japan.
- Prof. Lee group joined KAGRA as collaborator in 2018.
  R&D project: Quantum noise reduction with squeezed light

KAGRA Sensitivity



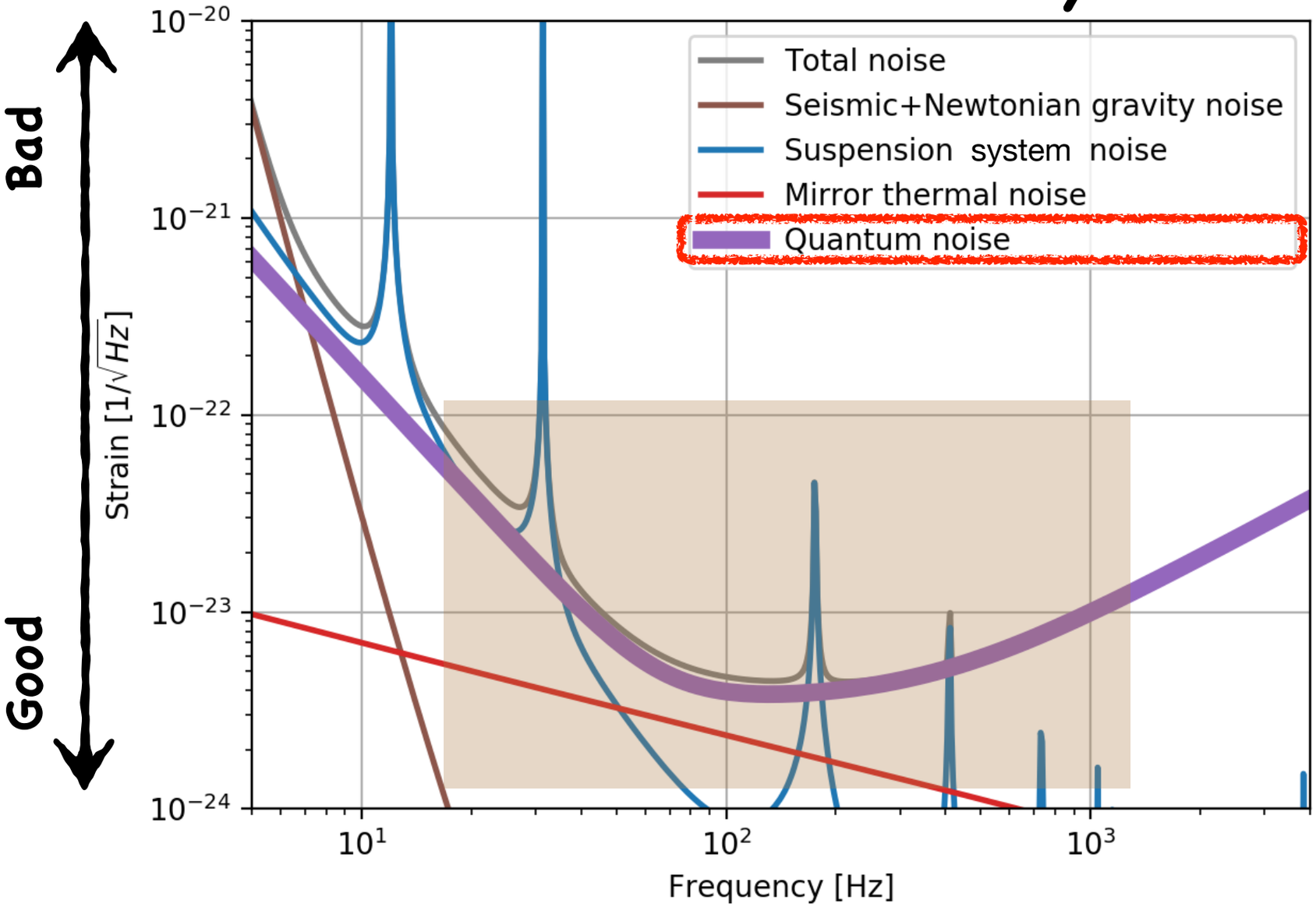


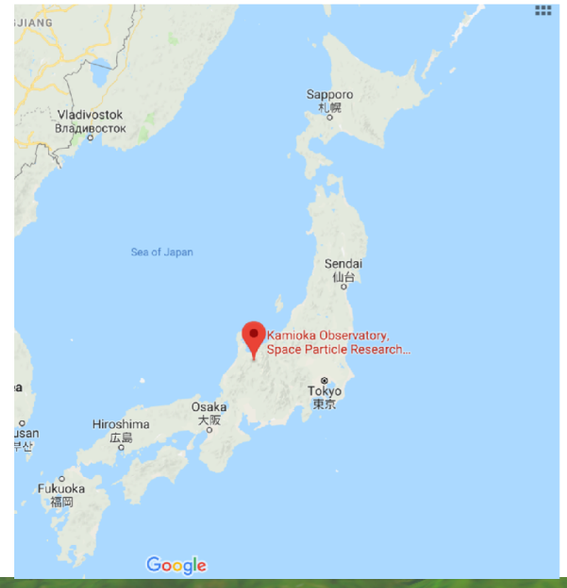
JGW-T1707038

KAGRA Introduction

- An underground GW detector in Kamioka, Japan.
- Prof. Lee group joined KAGRA as collaborator in 2018.
  R&D project: Quantum noise reduction with squeezed light

KAGRA Sensitivity



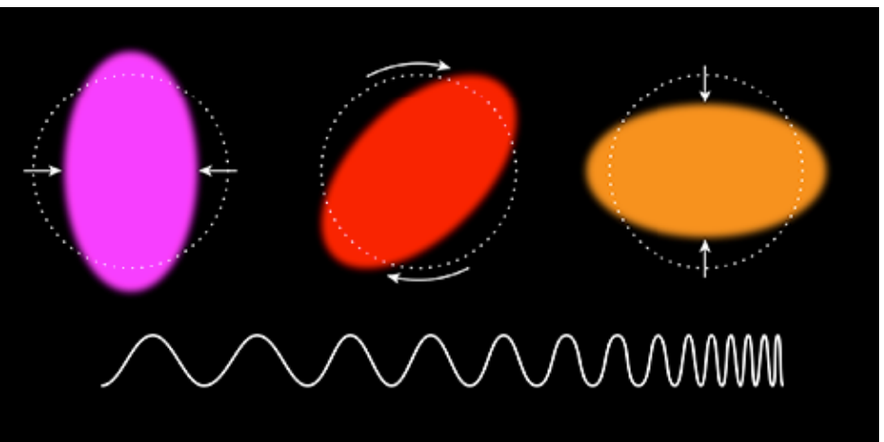


JGW-T1707038

Frequency-Dependent Squeezed Vacuum Source for Broadband Quantum Noise Reduction

- A broadband suppression of the quantum noise
- An improvement of the GW sensitivity

M. Leonardi, E. Capocase, Y. Zhao, N. Aritomi (NAOJ);
Chien-Ming Wu, Shu-Rong Wu, Yao-Chin Huang,
and Ray-Kuang Lee (NTHU)



Phys. Rev. Lett. **124**, 171101 (2020)

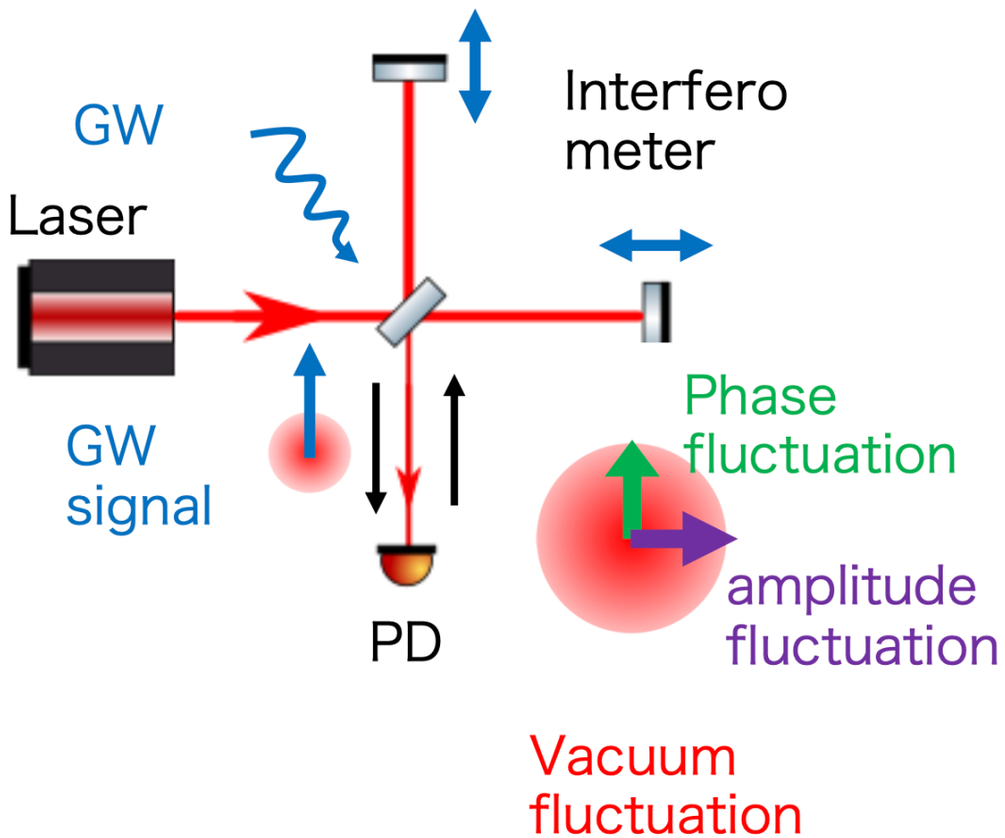
国立天文台
NAOJ
重力波プロジェクト推進室
Gravitational Wave Project Office

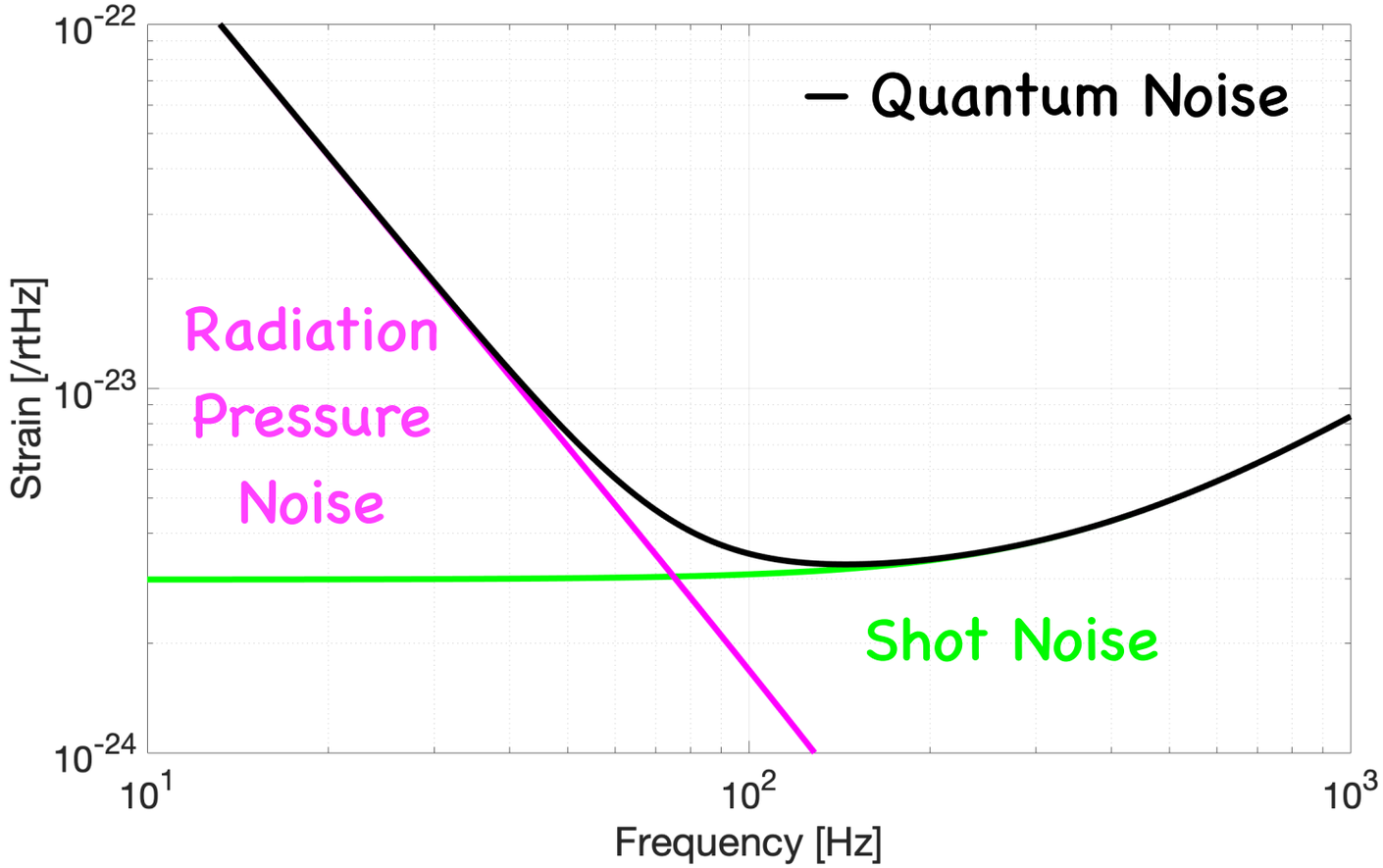
Quantum Noise

- Quantum noise originates from vacuum fluctuation.

$$h_{quantum} = \sqrt{h_{rad}{}^2 + h_{shot}{}^2}$$

- Amplitude fluctuation causes mirror fluctuation at low frequencies and becomes radiation pressure noise.
- Phase fluctuation of vacuum fluctuation becomes shot noise at high frequencies.

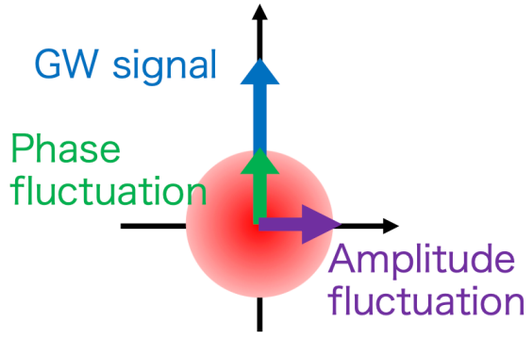


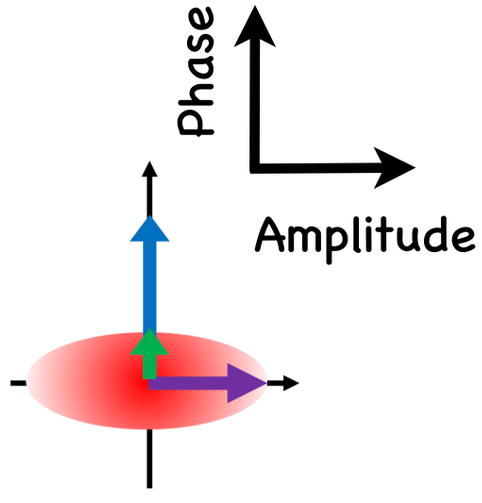


Phys. Rev. D. 23, 1693 (1981)

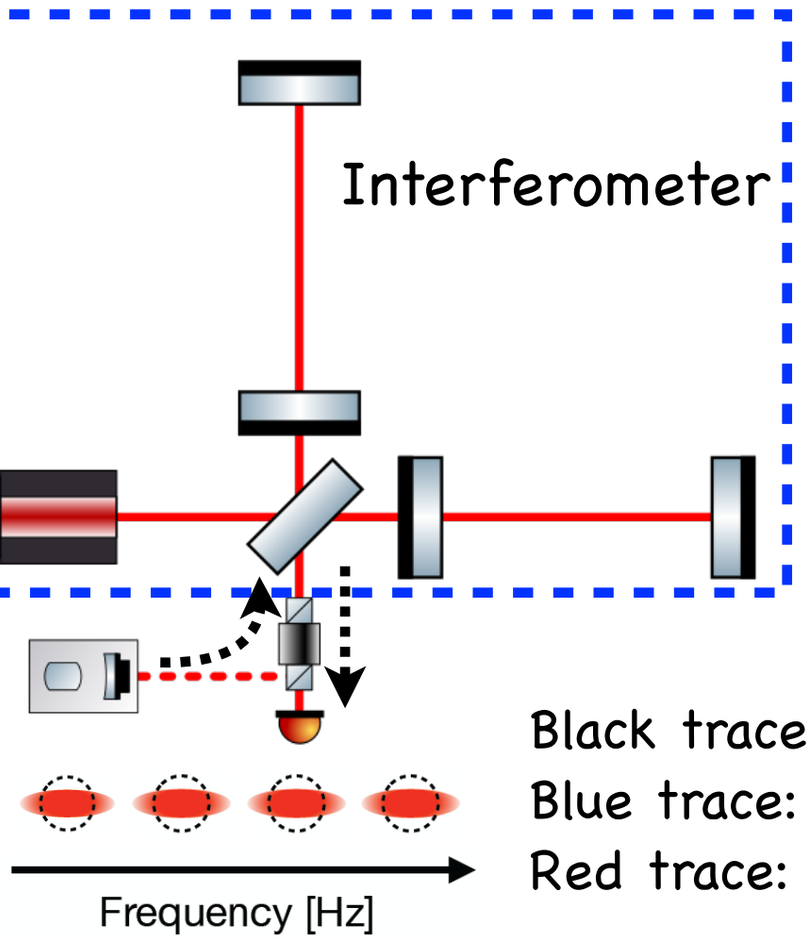
Squeezed Vacuum State

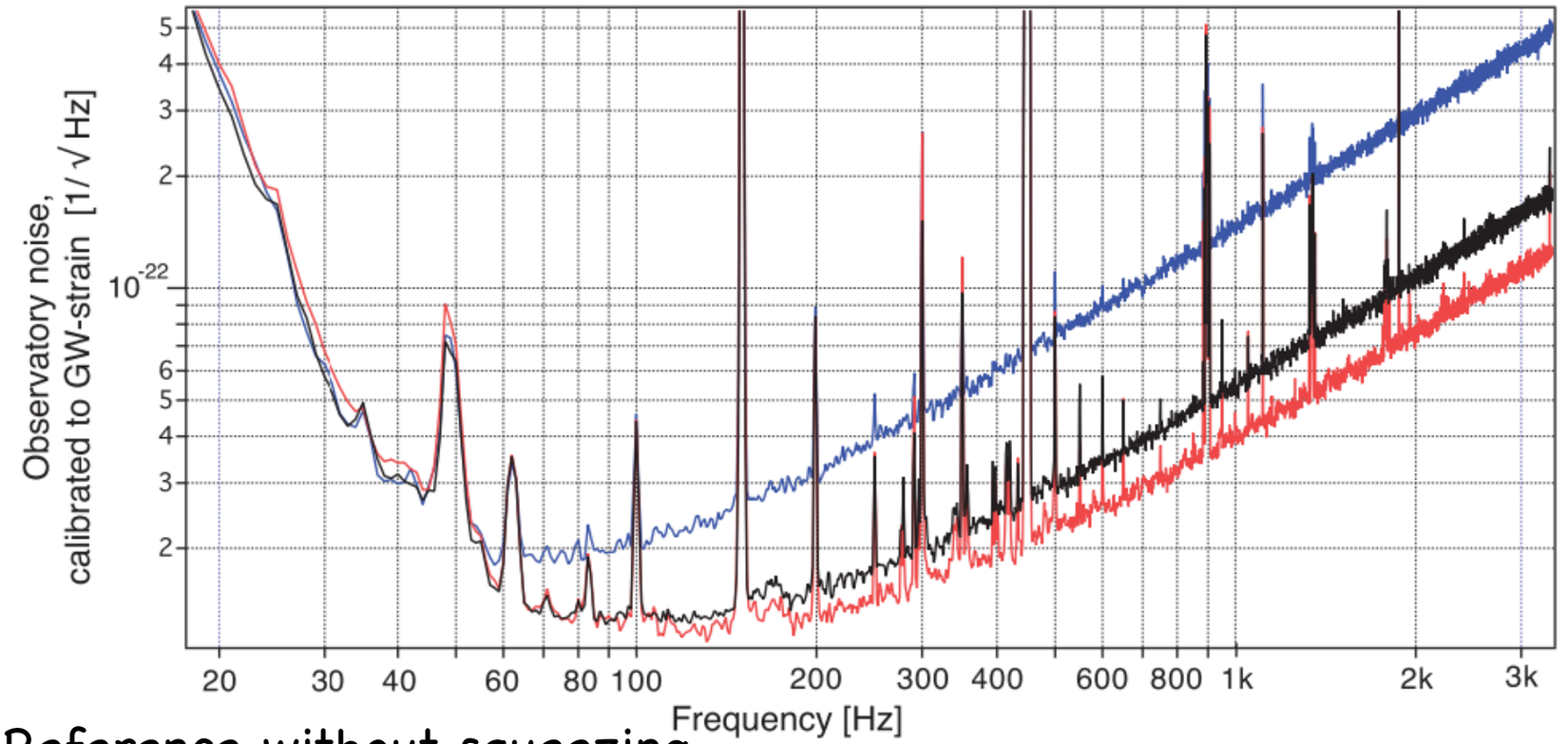
- Squeezed vacuum state used to reduce shot noise in phase direction.





- Shot noise reduction by squeezing injection is realized at LIGO and Virgo in 2019.
- Increase of radiation pressure noise is observed with Phase SQZ.



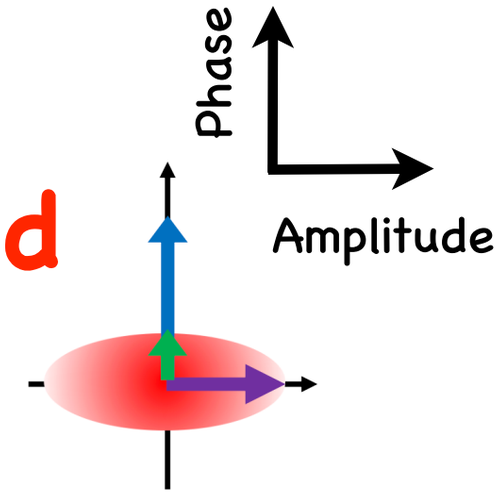


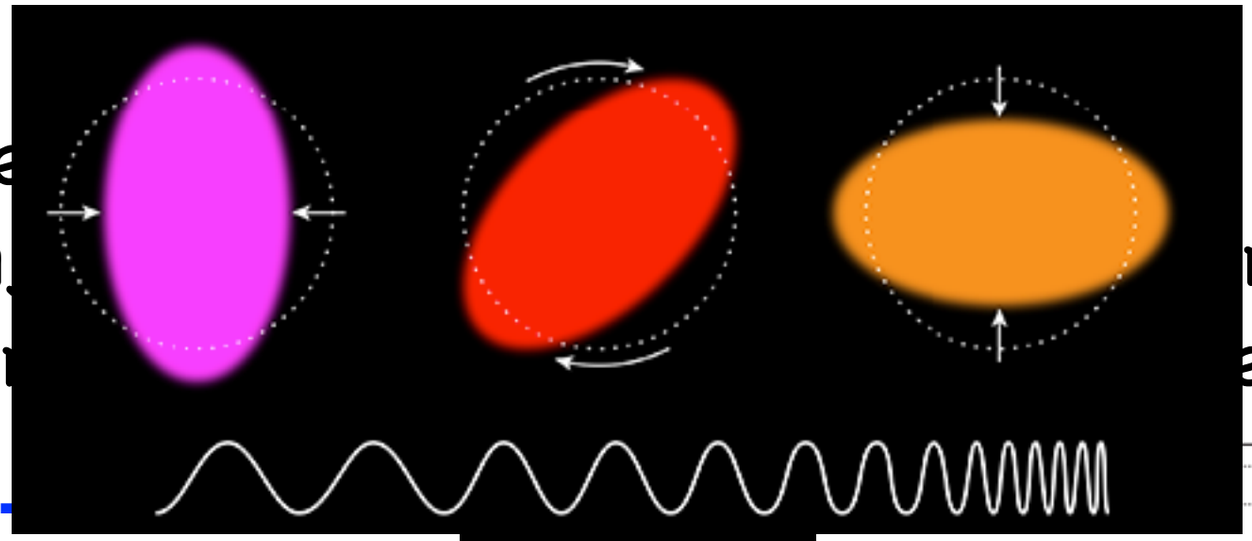
Black trace: Reference without squeezing
Blue trace: Amplitude Squeezed State (increase 8.5dB @2.8kHz)
Red trace: Phase Squeezed State (reduce 3.2dB @2.8kHz)

Phys. Rev. Lett. 123, 231108 (2019)

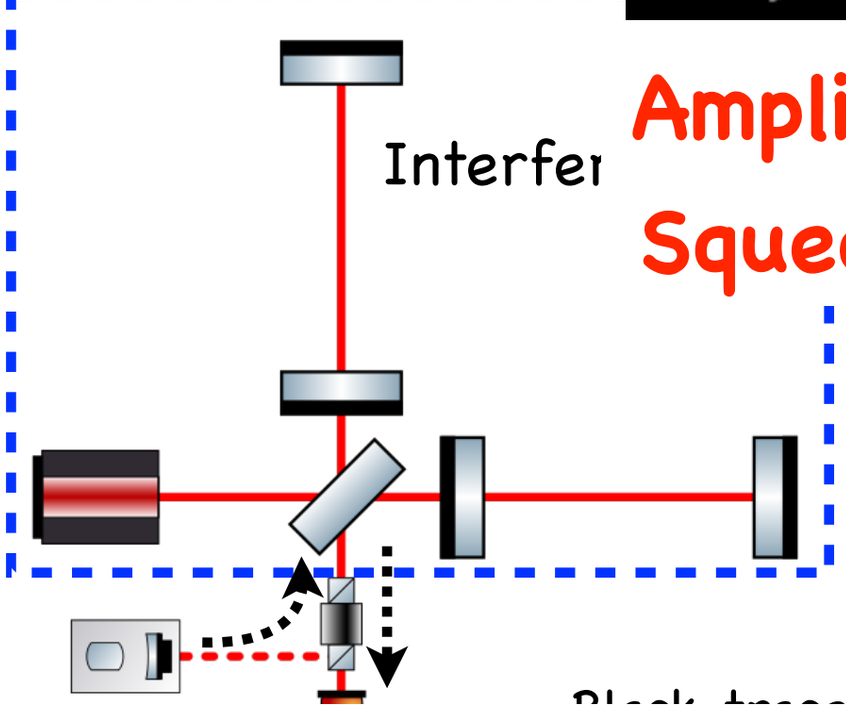
Squeezed Vacuum State

- Squeezed vacuum state used to reduce shot noise in **Frequency Dependent Squeezed**



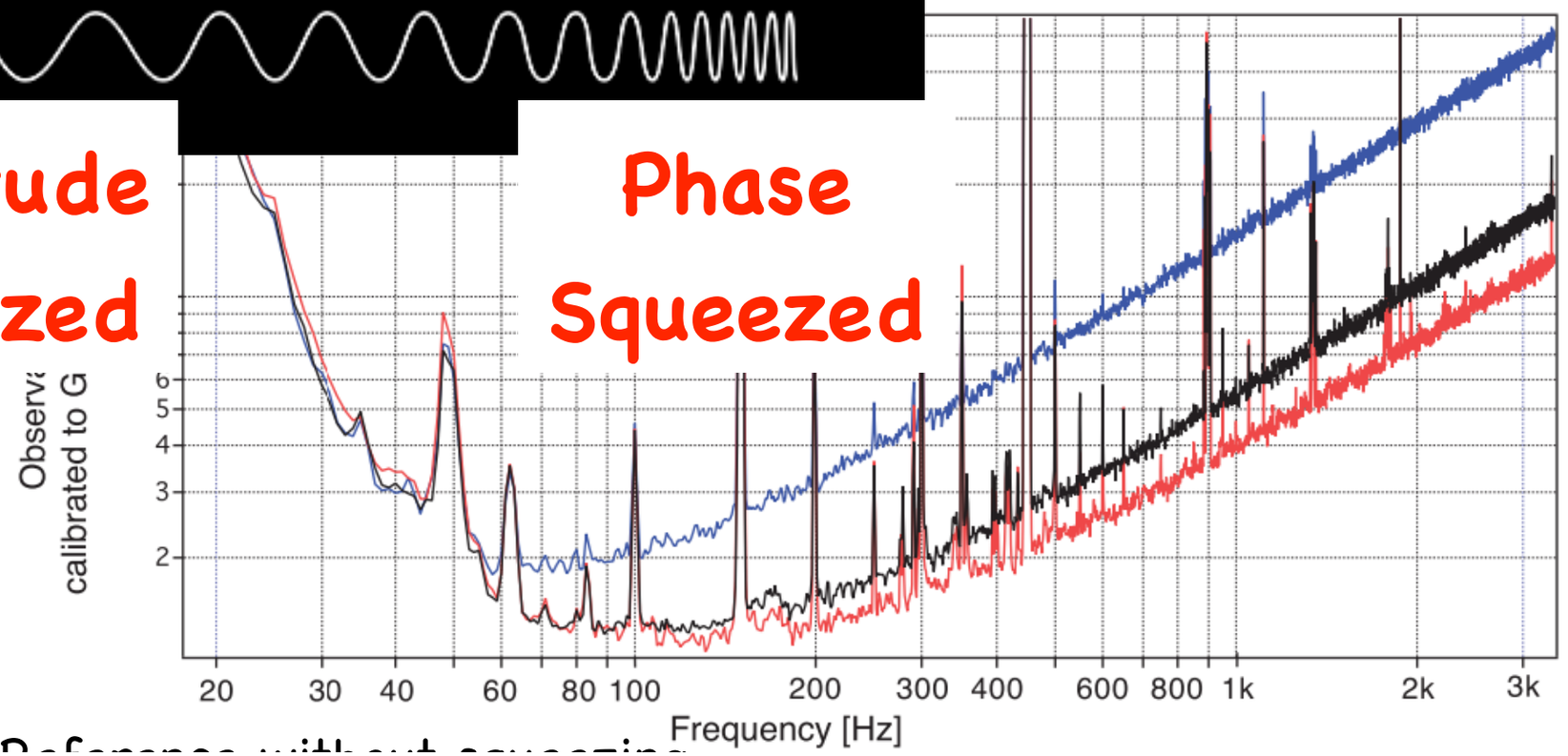


- Shot noise re
  squeezing in rgo in 2019.
- Increase of ed with Phase SQZ.



Amplitude Squeezed

Phase Squeezed



Black trace: Reference without squeezing

Red trace: Phase Squeezed State (reduce 5.2dB @2.8kHz)

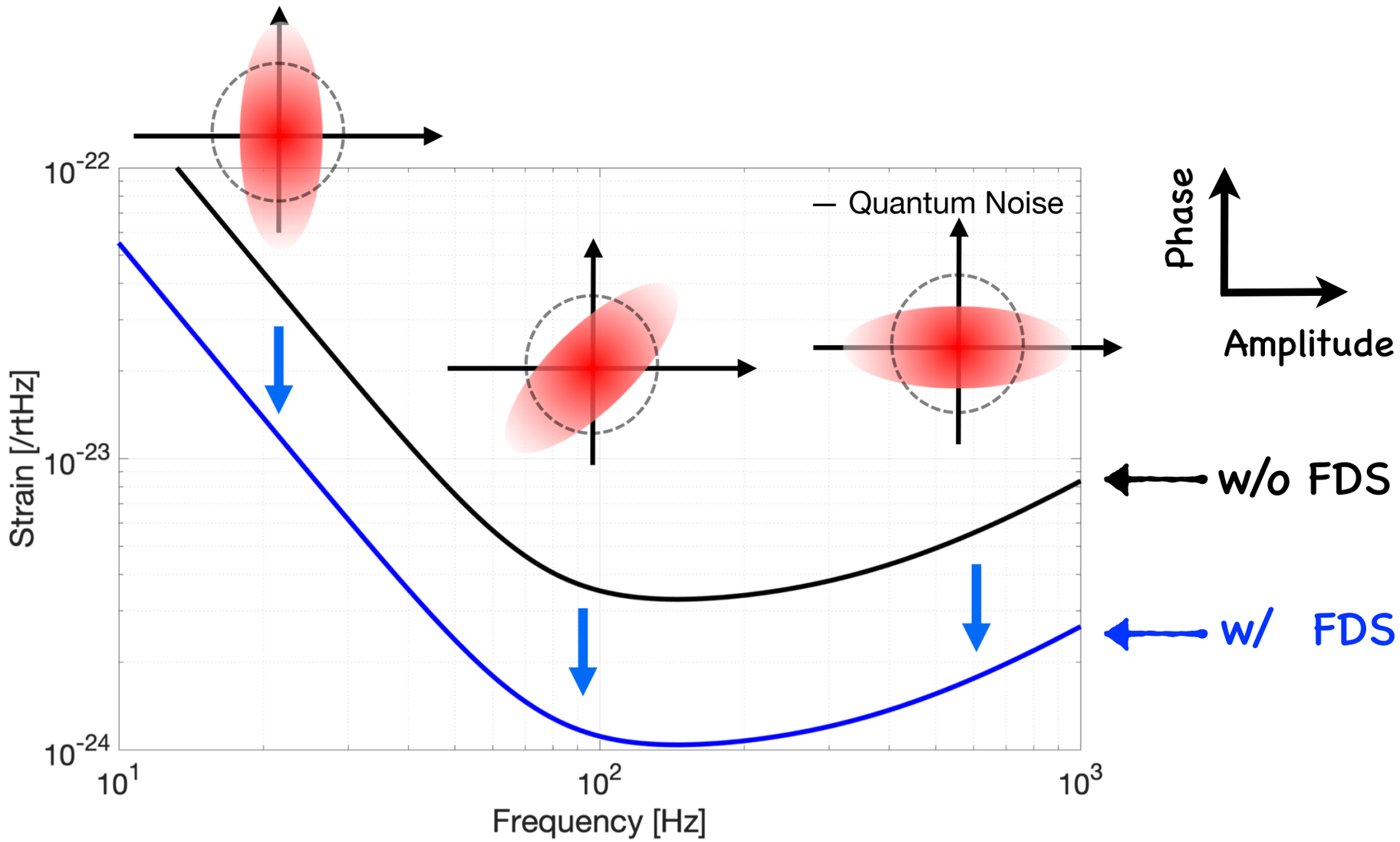
Frequency [Hz]

Broadband suppression of the quantum noise

Phys. Rev. Lett. 123, 231108 (2019)

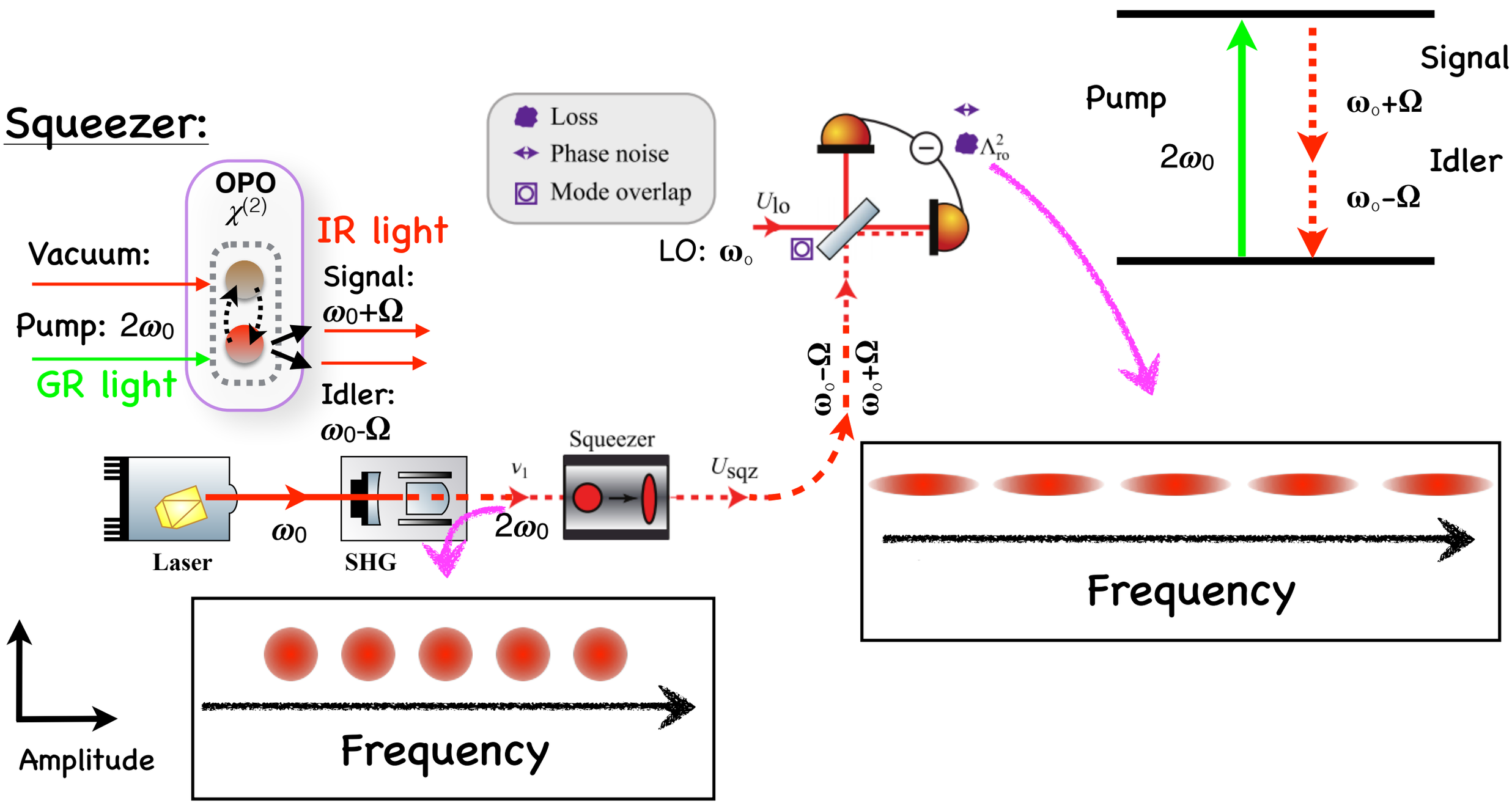
Reduce Quantum Noise with Squeezed light

- To reduce shot-noise and radiation pressure noise at the same time, frequency dependent squeezed vacuum states are necessary. The squeezing angle rotates by 90 deg below 100Hz.



Squeezed Light Source @ 1064 nm

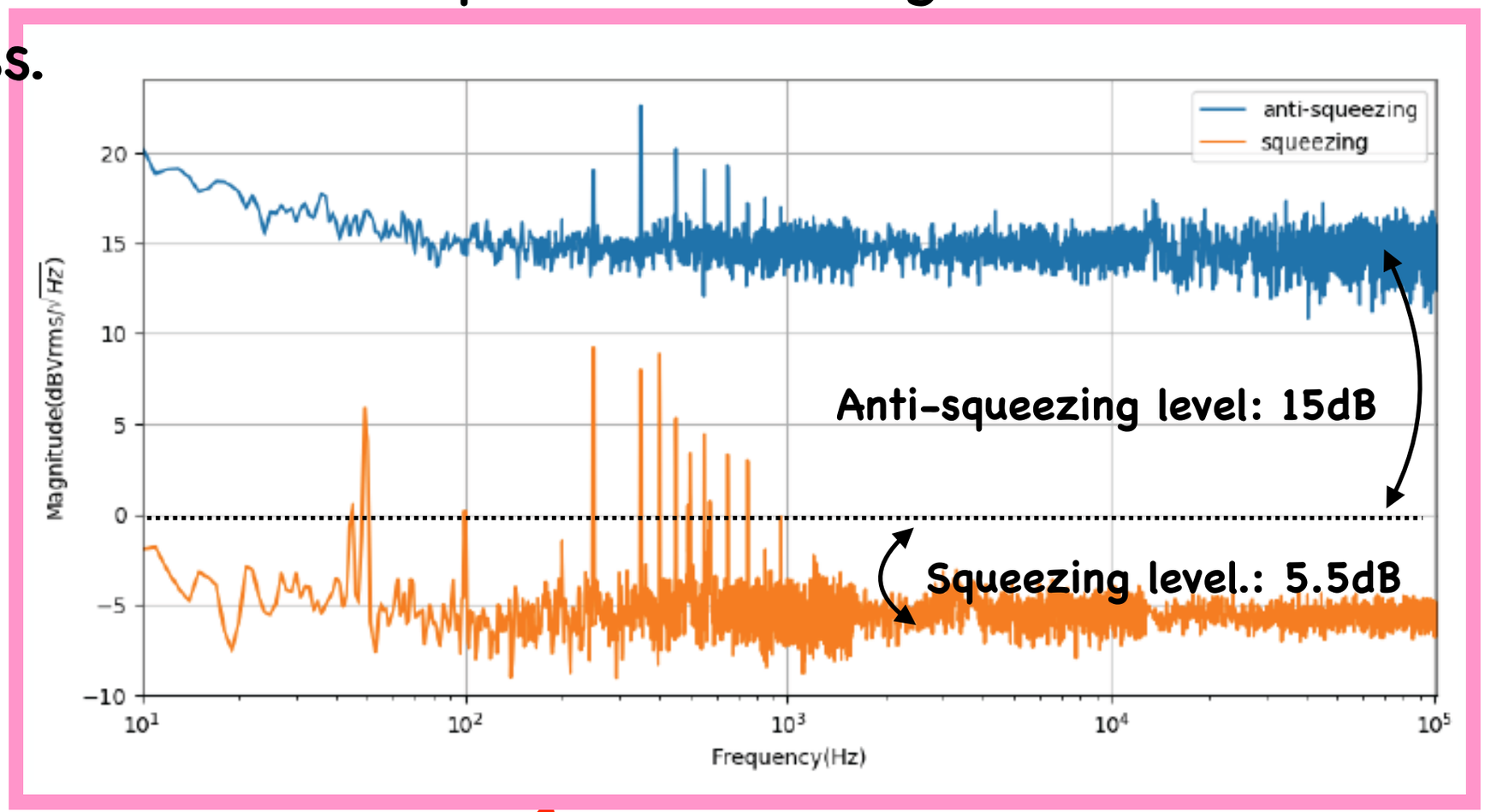
- Squeezed vacuum state could be produced through nonlinear interaction process.
- Signal and idler light are correlated photon-pair.



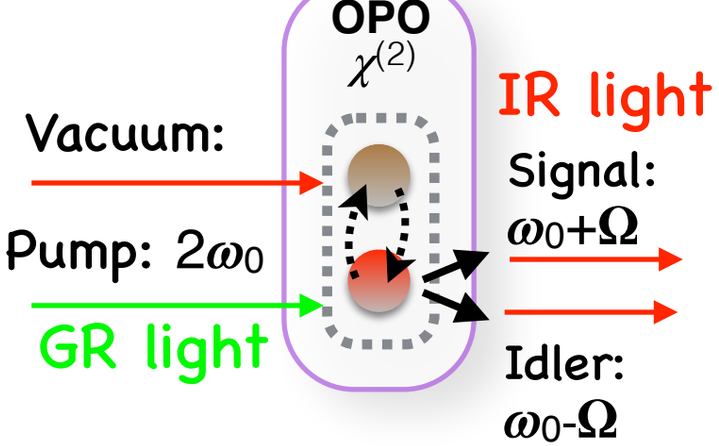
Squeezed Light Source @ 1064 nm

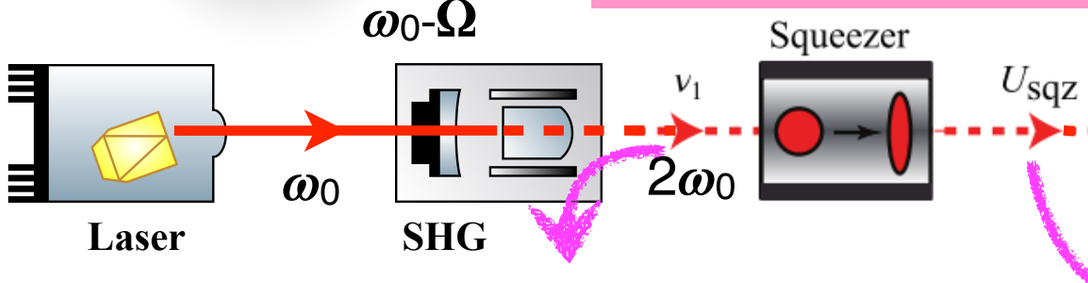
- Squeezed vacuum state could be produced through nonlinear interaction process.
- Above 20Hz

  Squeezed level: -5.5dB



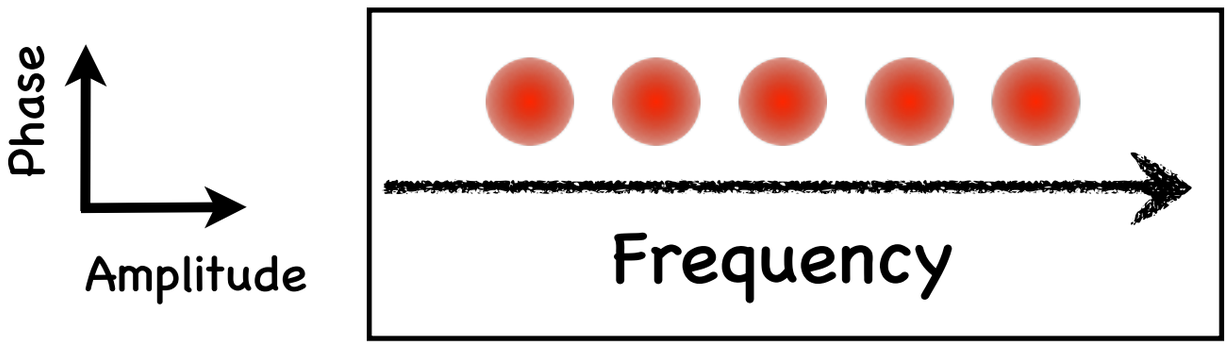
Squeezer:

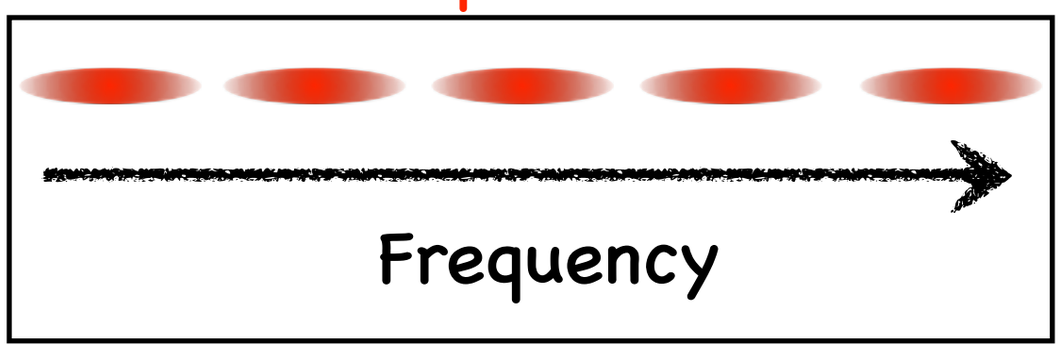




Frequency independent Squeezing

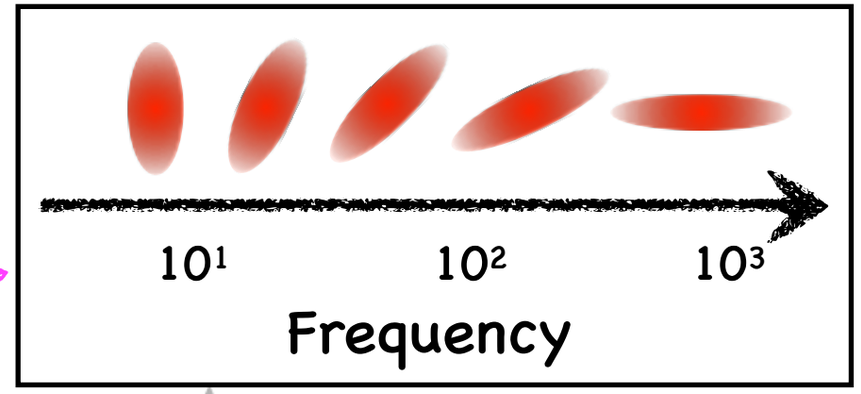
"Phase Squeezed State"



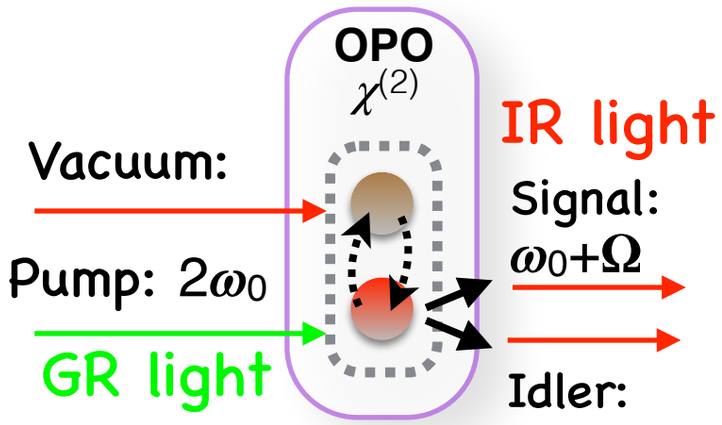


Frequency Dependent Squeezing (FDS)

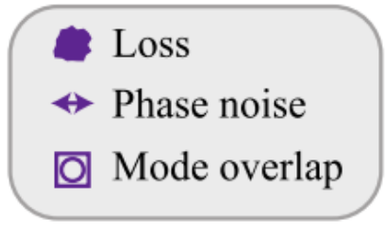
- Rotation angle is defined that average of filter cavity reflection phase between signal and idler.
- Rotate the squeezing ellipse below 100Hz.

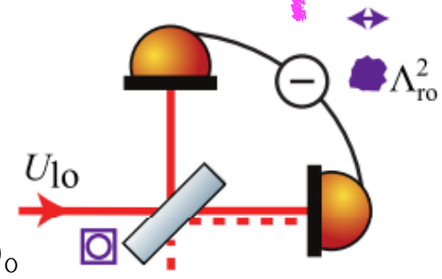


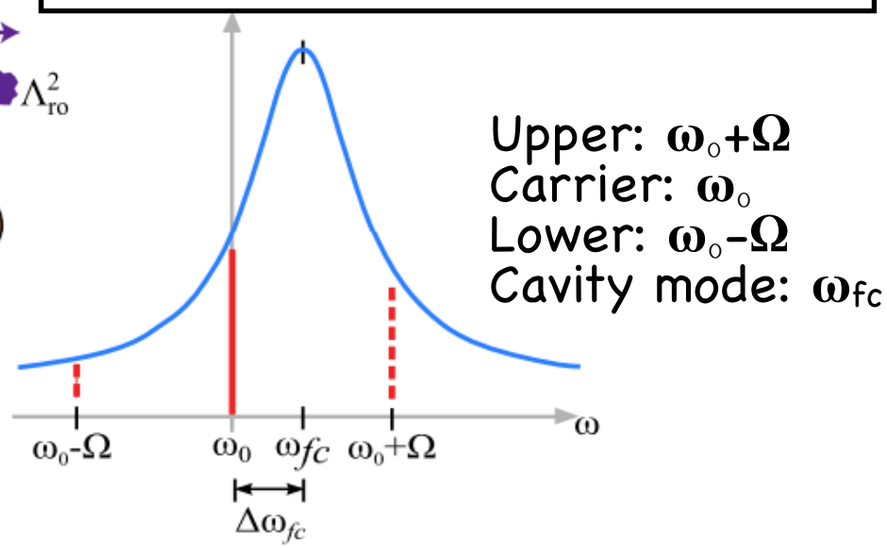
Squeezer:

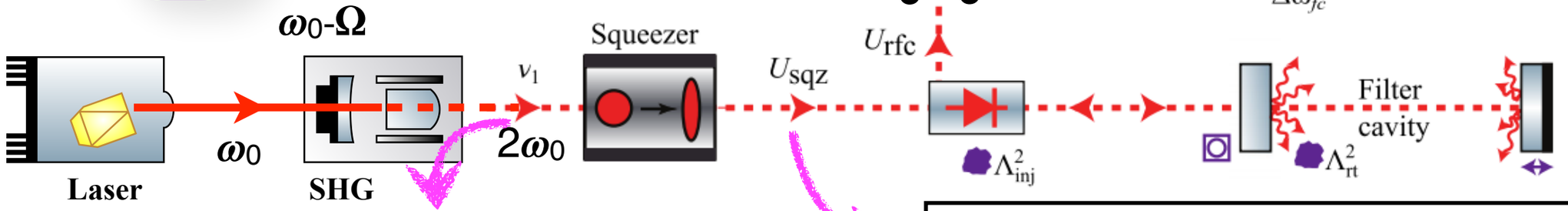


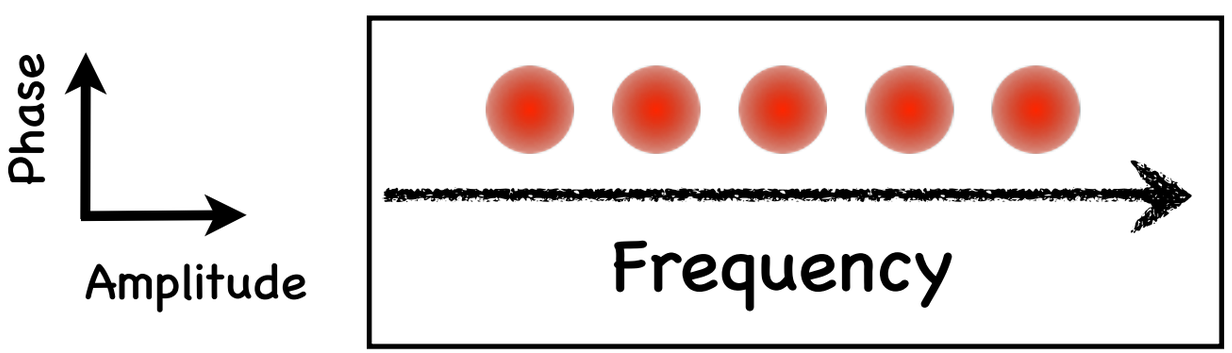
Photon Pairs

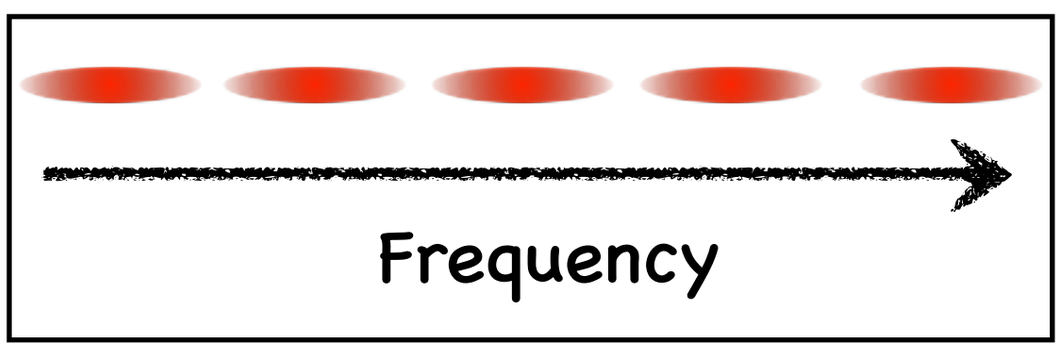






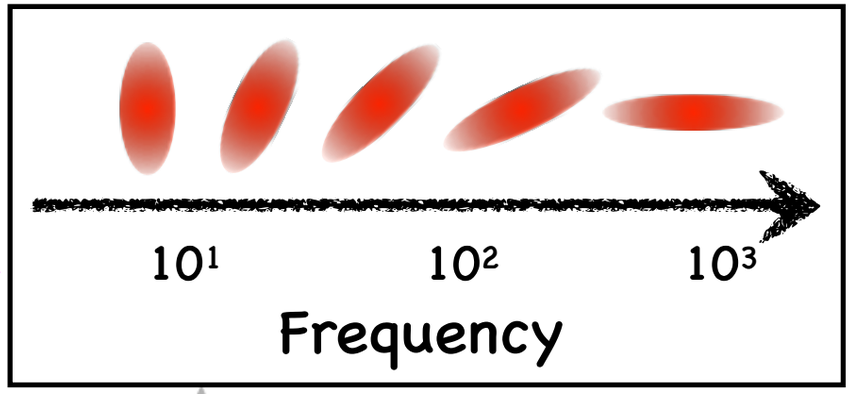




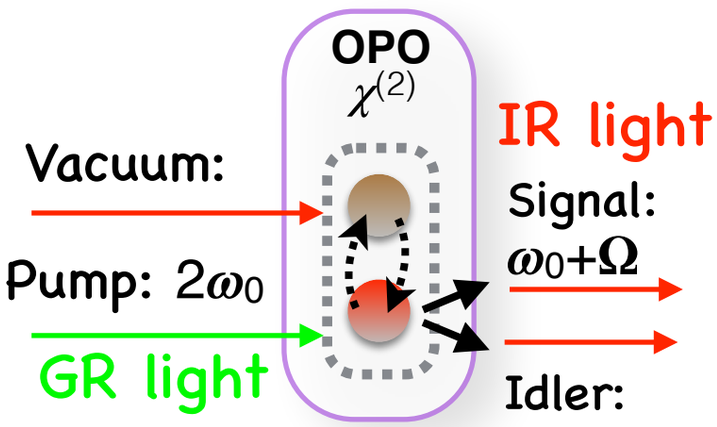


Frequency Dependent Squeezing (FDS)

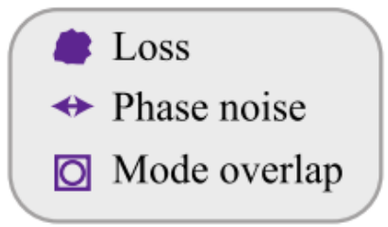
- Rotation angle is defined that average of filter cavity reflection phase between signal and idler.
- Rotate the squeezing ellipse below 100Hz.

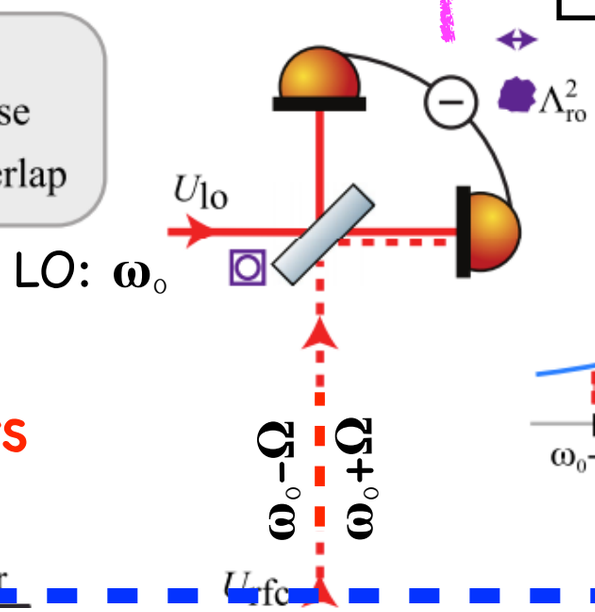


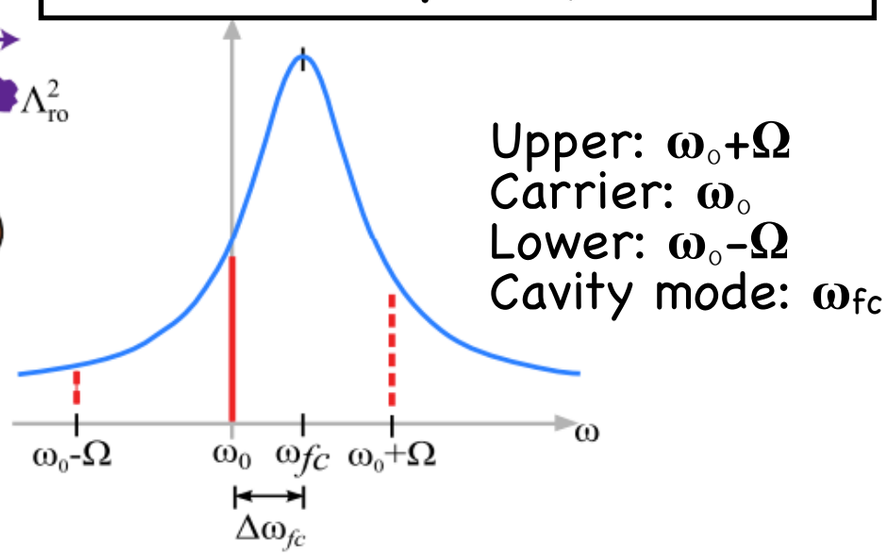
Squeezer:



Photon Pairs

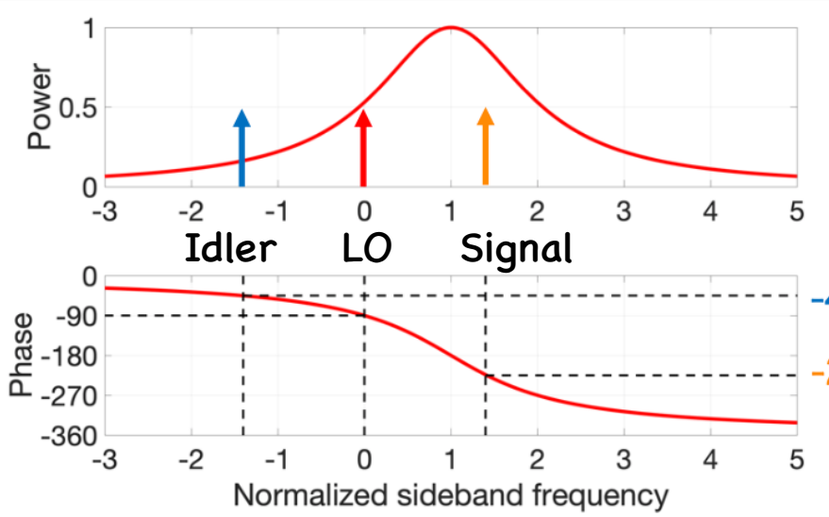


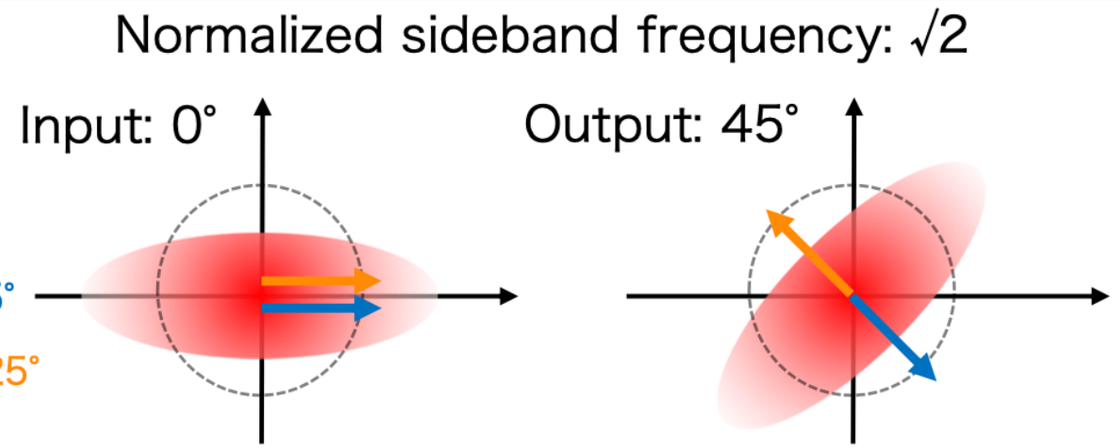




FC Intra-cavity Power

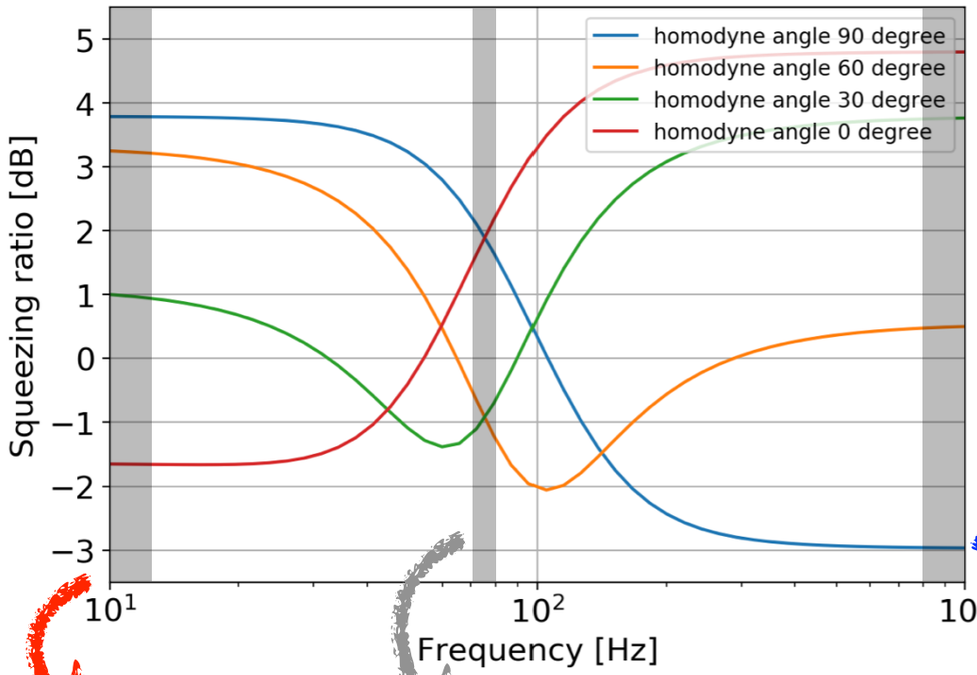
FC Reflectivity Phase

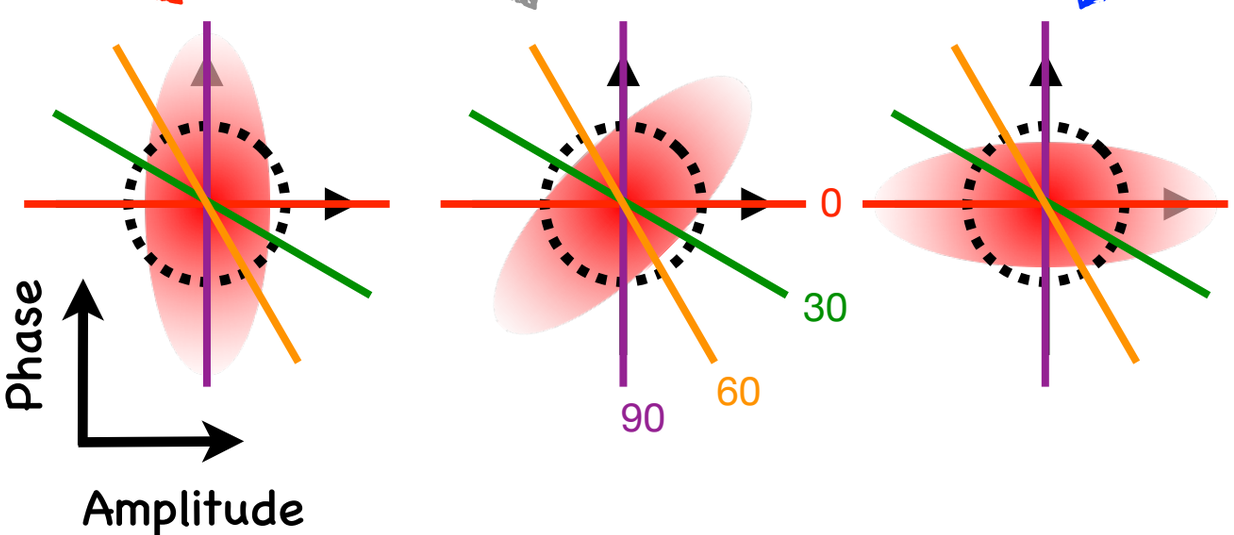




Noise Fluctuation Distribution

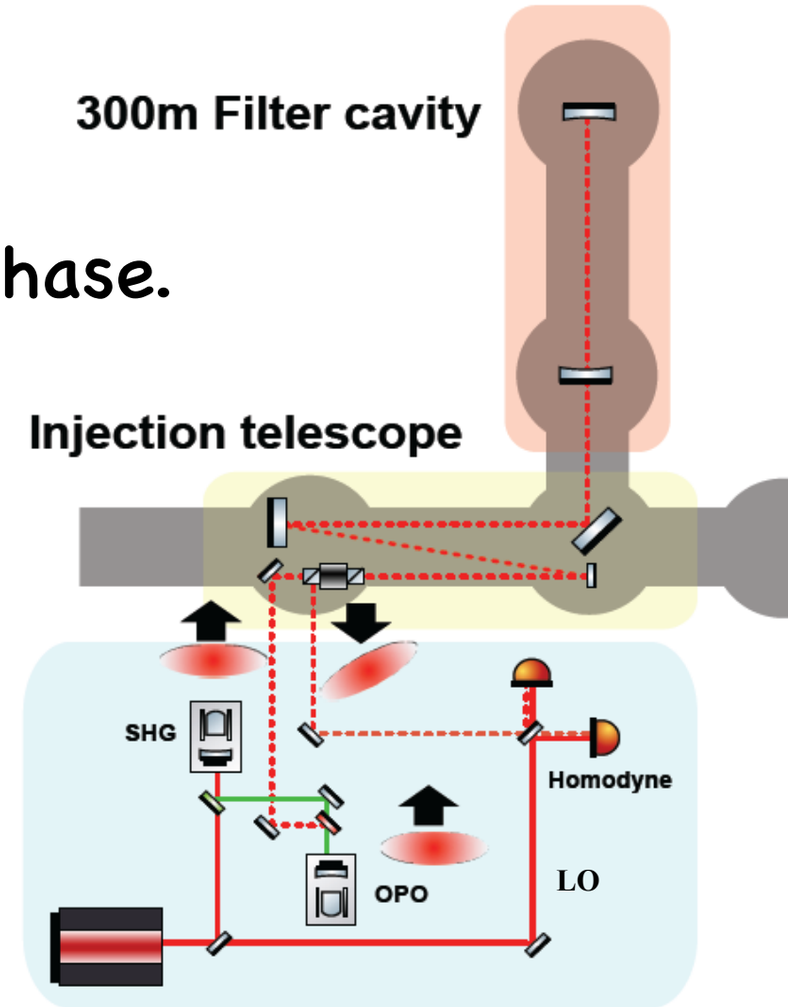
- Noise distribution measured by changing LO phase.
- Noise distribution after Filter Cavity:
  - ☑ 3.4 dB at high frequency in phase direction
  - ☑ 2 dB at low frequency in amplitude direction

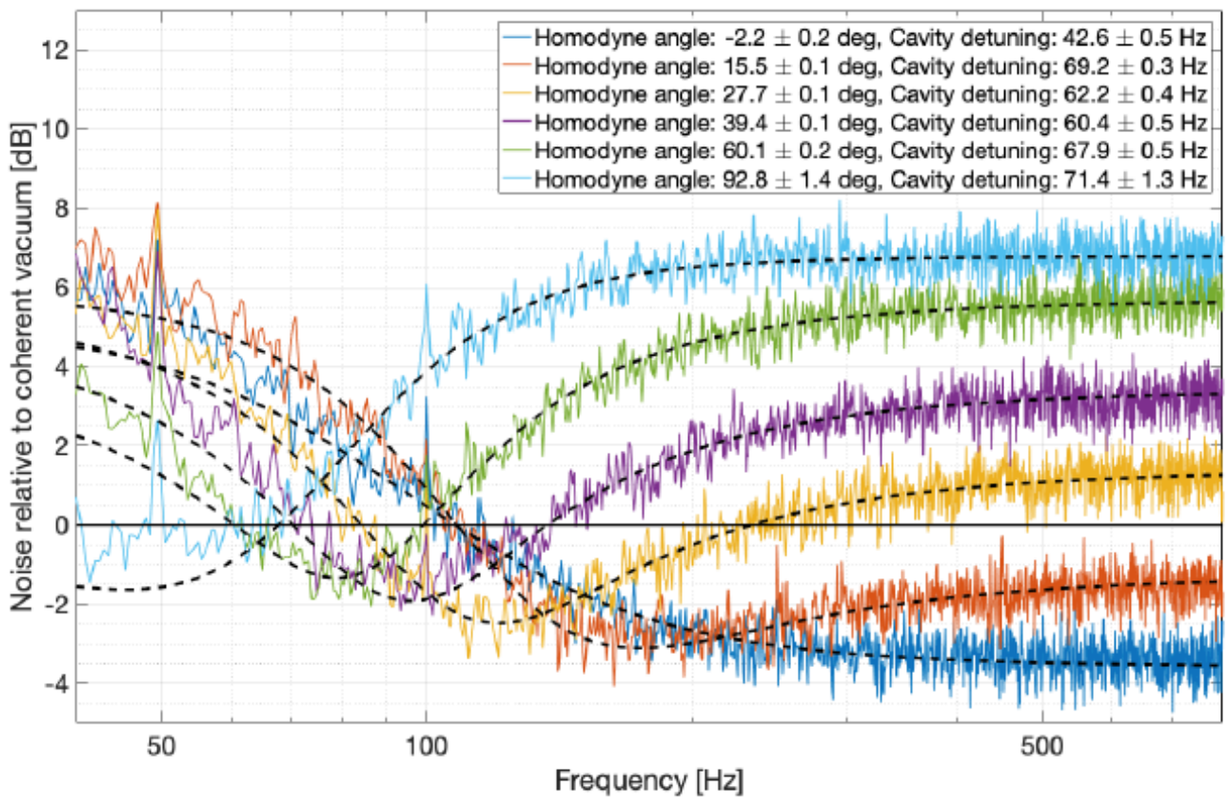




(Note: Degradation)

- Filter cavity loss
- Injection/Readout loss
- Mode mismatch
- Phase noise



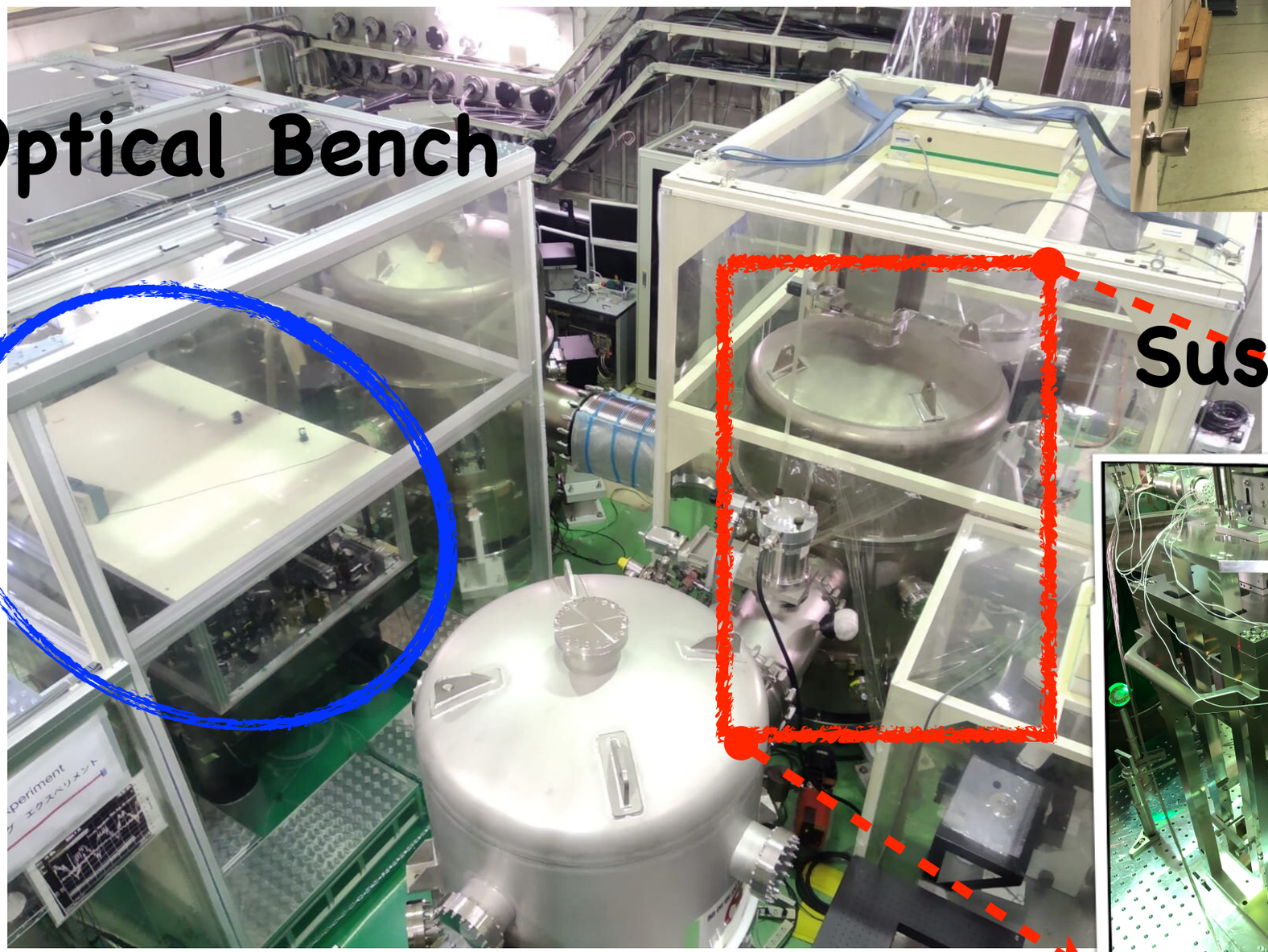


NAOJ – TAMA300

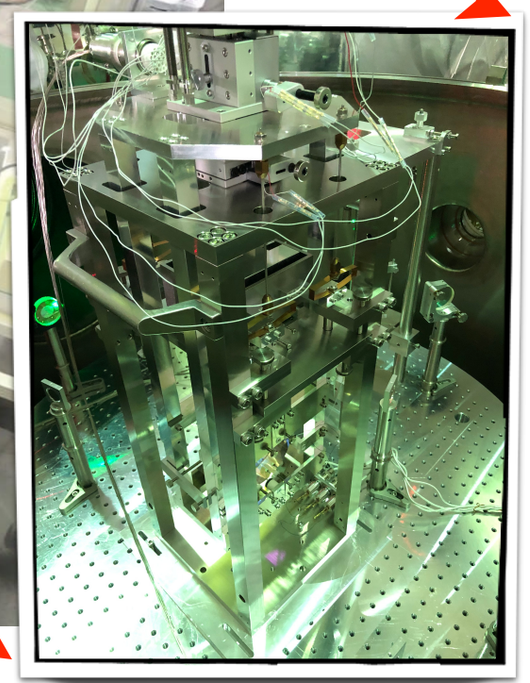
- NAOJ located in Mitaka, Tokyo
- The length of filter cavity is 300m.

Filter Cavity

Optical Bench

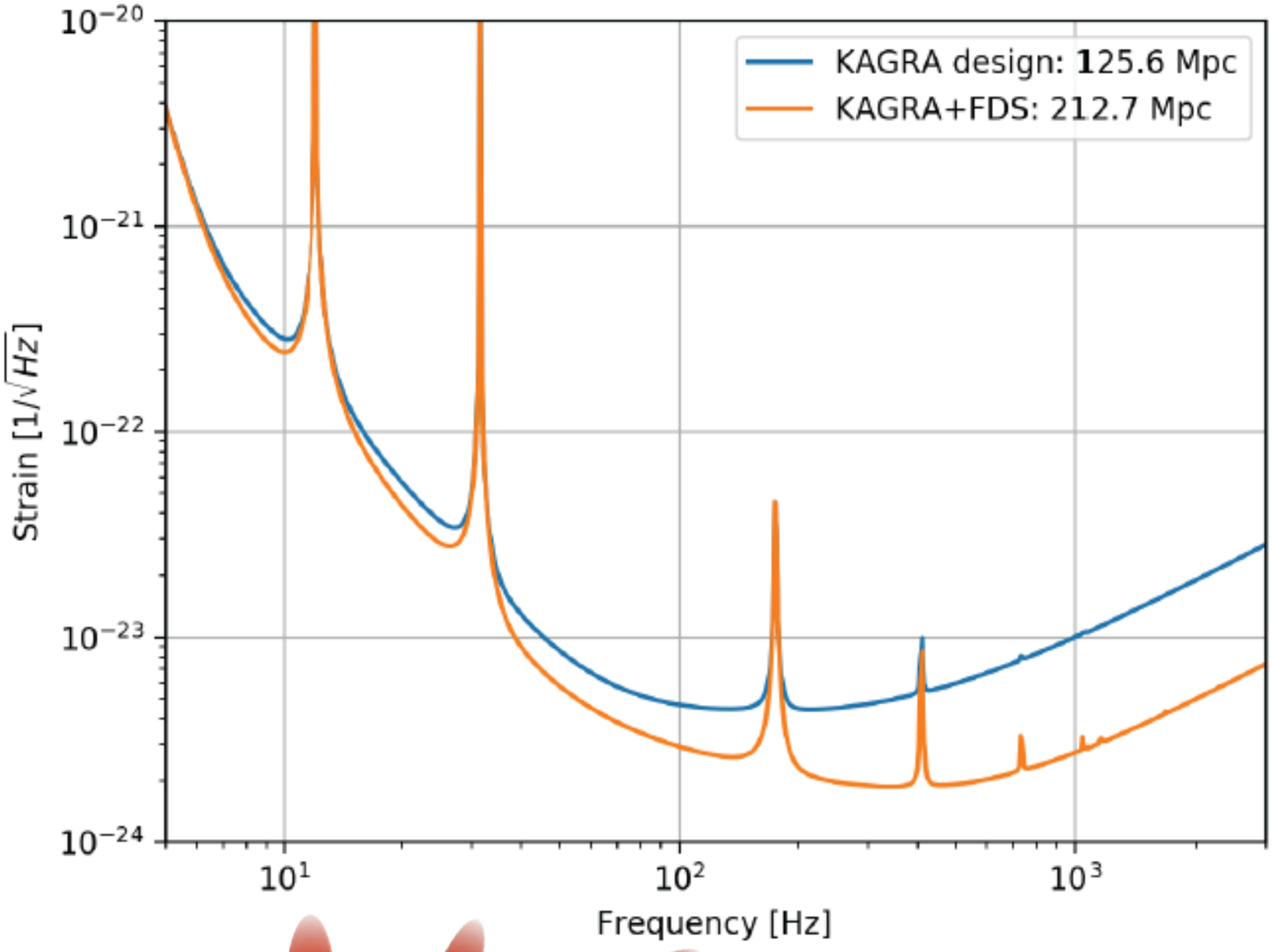


Suspension System

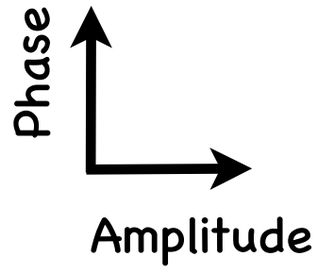


KAGRA Sensitivity Budget with FDS

- FDS will enable "broadband quantum noise reduction" in advanced gravitational wave detectors.
- Installing the FDS squeezer in KAGRA, detection range will increase more 70%.

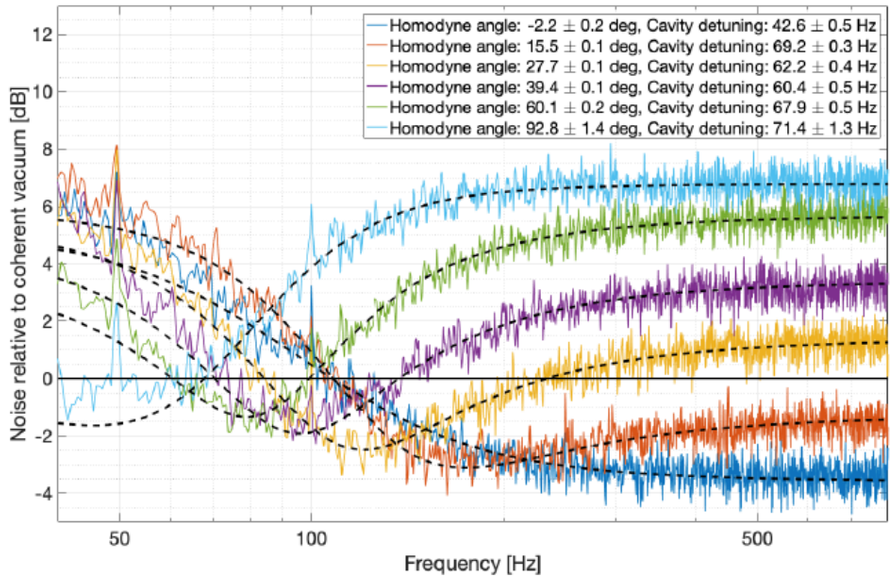


Squeezed light type:

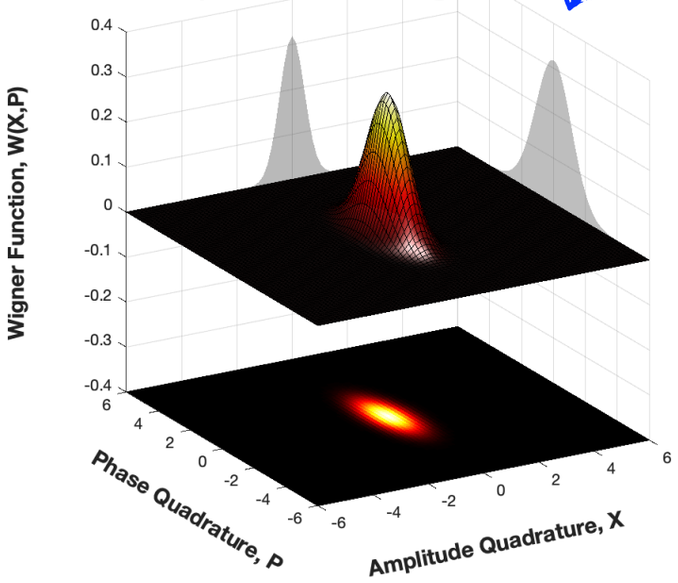


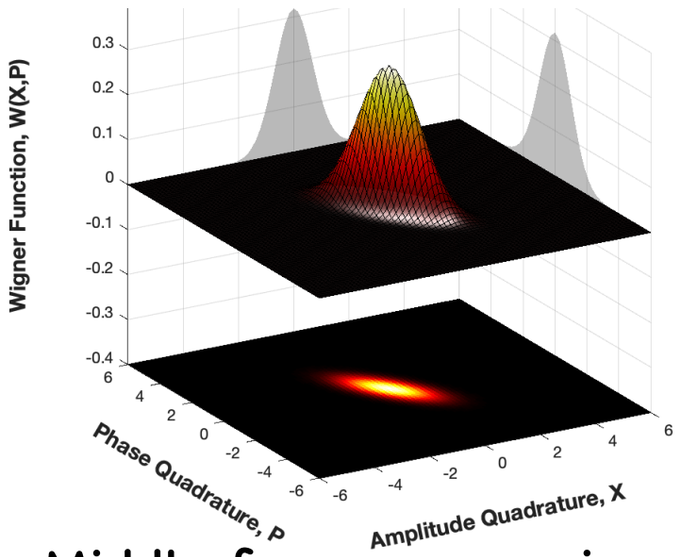
Part II : Quantum State Tomography

It is the process by which a quantum state is reconstructed using measurements on an ensemble of identical quantum state.



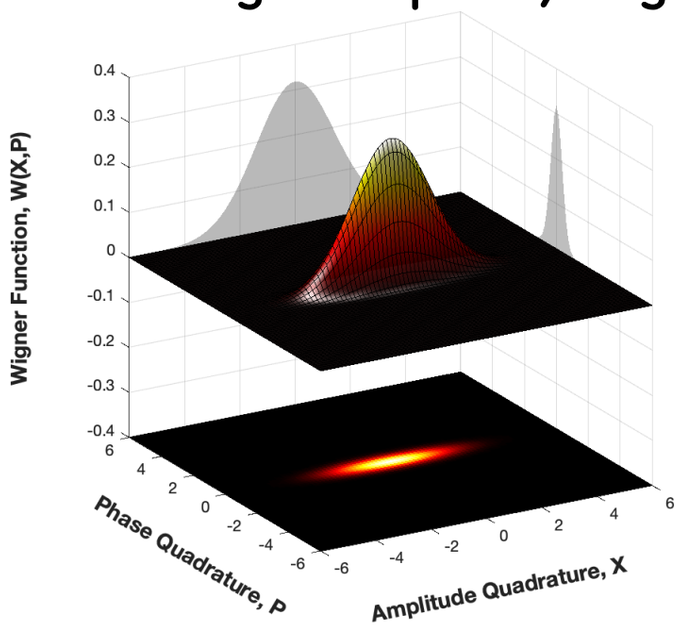
Low frequency region





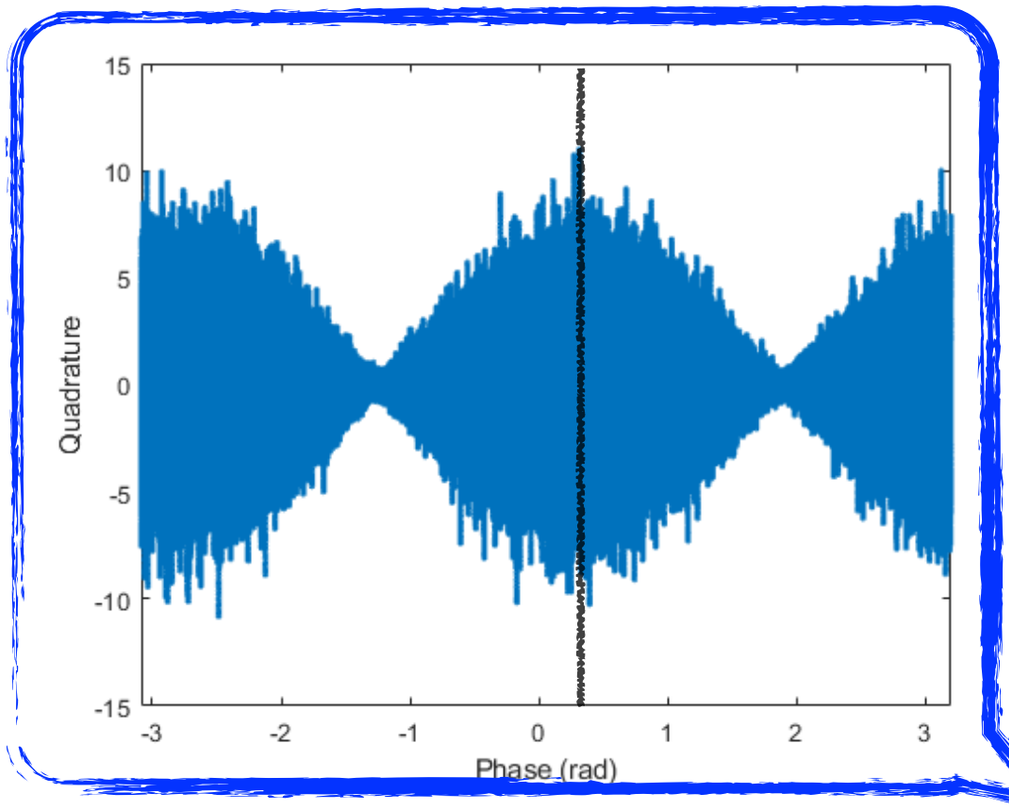
Middle frequency region

High frequency region



Optical Homodyne Tomography

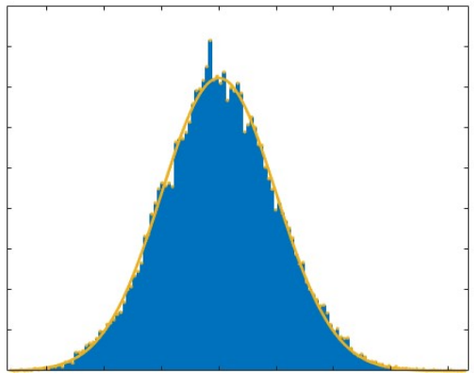
- Collect all probability distribution $\Pr(Q_\theta,\theta)$ over the 2π interval.
- Use reconstruction algorithm (ex: Max. Likelihood method) to convert experimental data into Wigner function or density matrix.

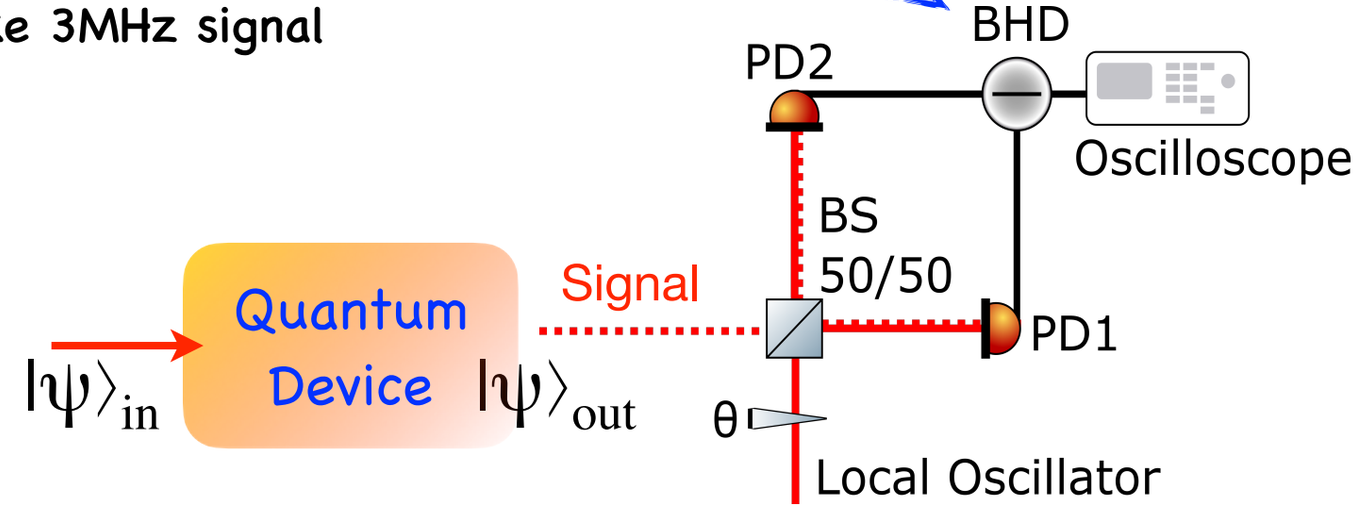


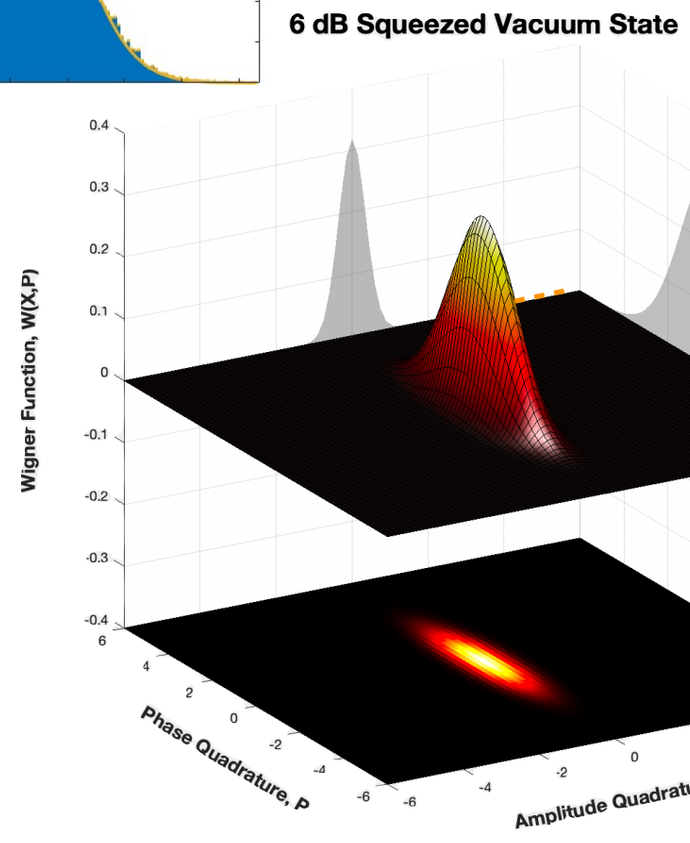
Take 3MHz signal

Reconstruct

Probability distribution
$\Pr(Q_\theta,\theta)$



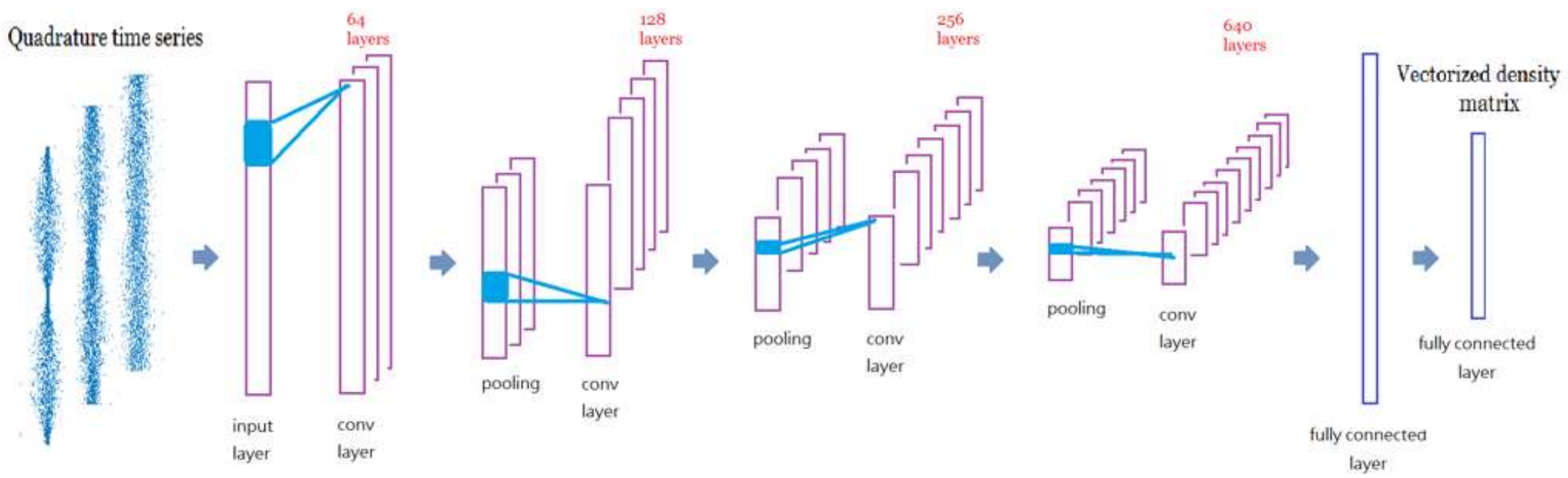




DOI: 10.1103/RevModPhys.81.299

Convolutional Neural Network (CNN): SQ-learner

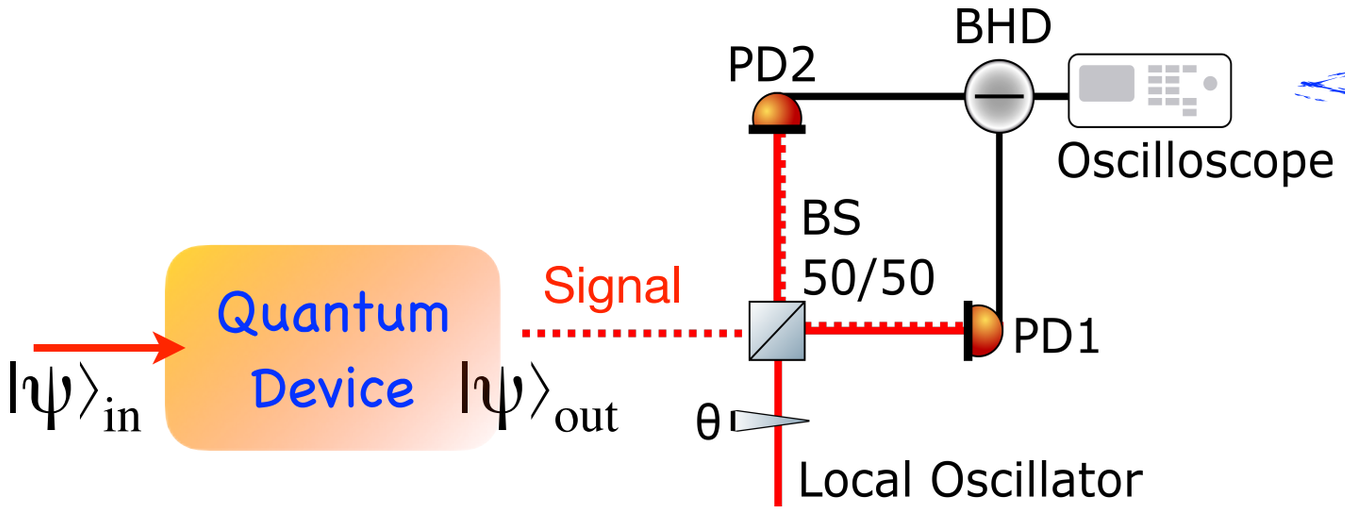
- To reduce the dimensionality of the input and send the meaningful feature to the neuron network.
- Many data series train this "SQ-learner" model with machine learning to optimize parameters.
- SQ-leaner(<1sec) is faster than Max. Likelihood method(few mins.) during reconstruction process.

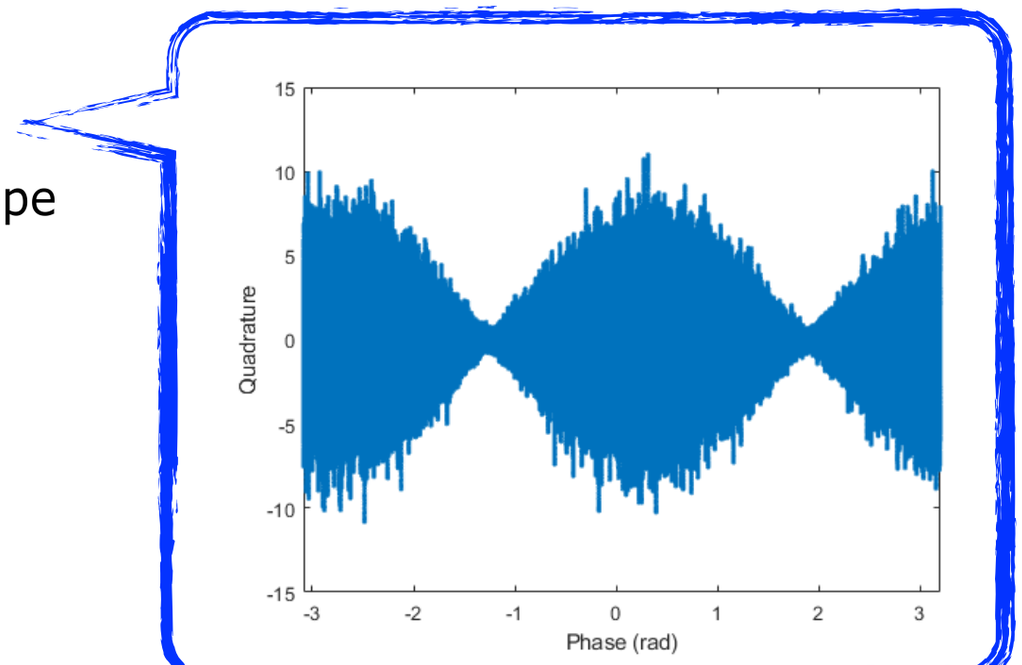


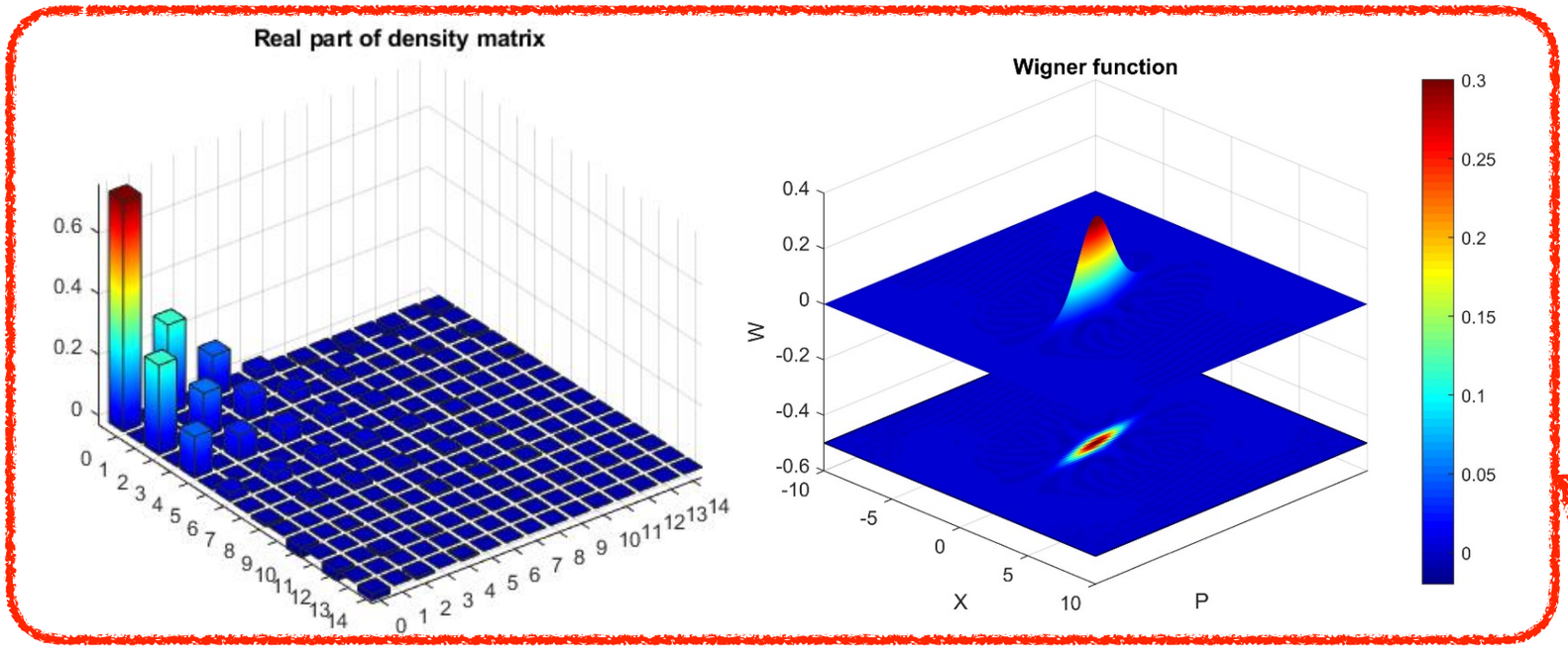
1D CNN model built by Hsien-Yi Hsieh

Toward Real-time Quantum Tomography

- Monitor the purity of the quantum state.
- Using SQ-learner to convert the data of optical homodyne detector into Wigner function or density matrix.





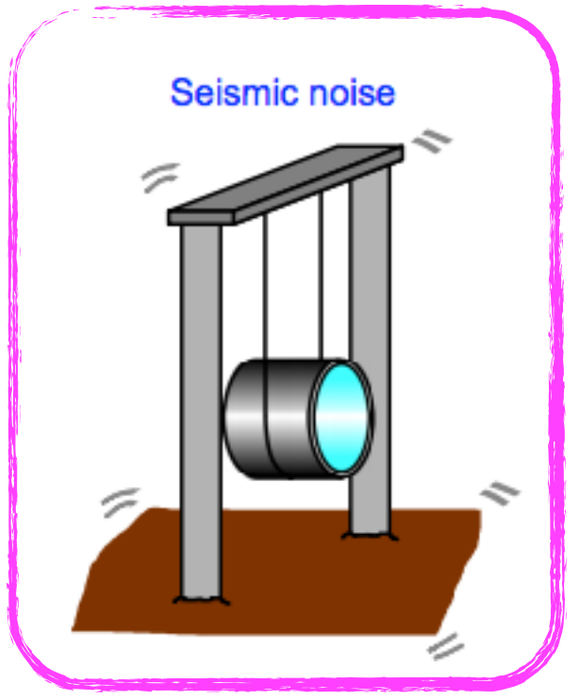


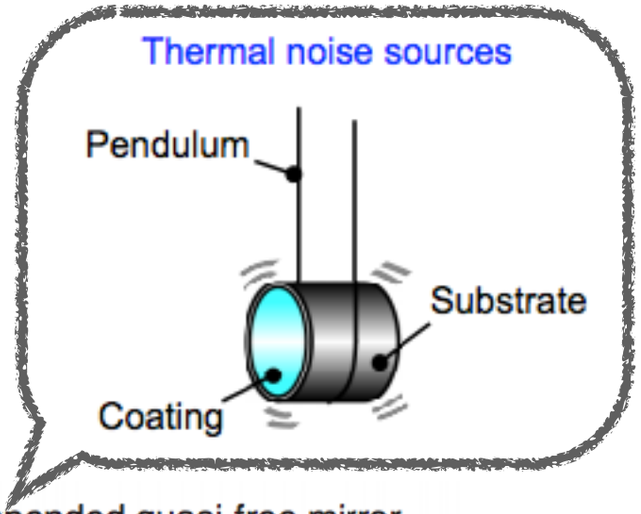
Thanks for yours attention

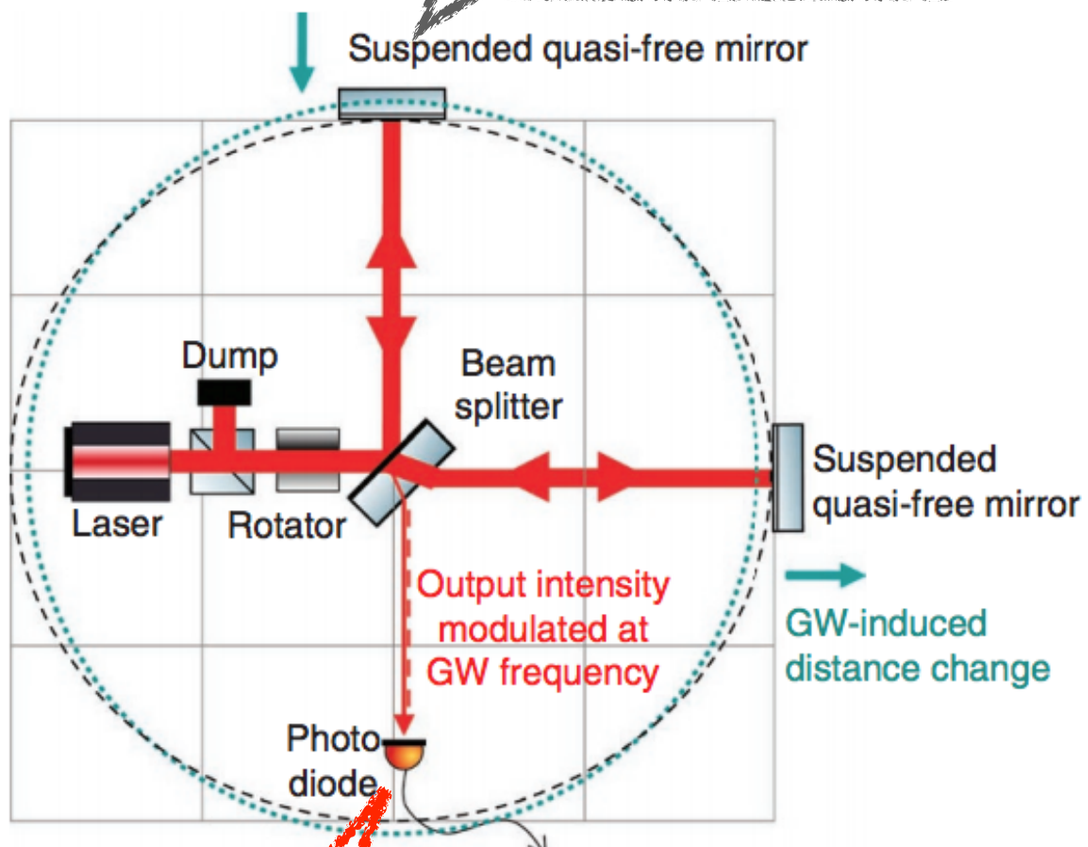
Extra Slides

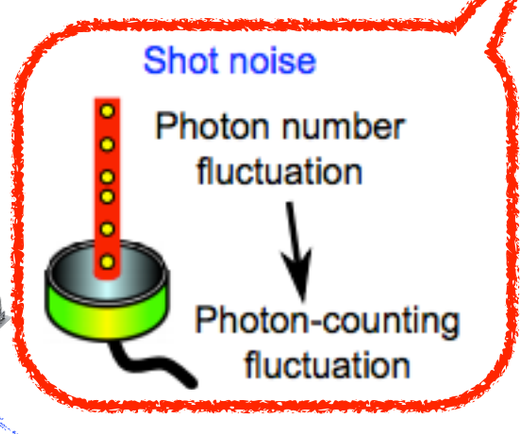
Noise Source of GW Detector:

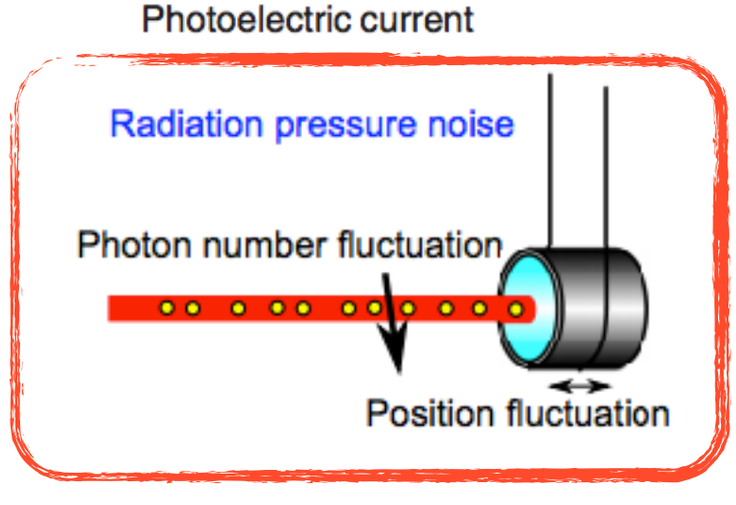
- Laser Noise (Nd:YAG_1064 nm)
  - ☑ Intensity δI
  - ☑ Frequency δf
- Seismic Noise
- Residual Gas
- Thermal Noise
- Quantum Noise
  - ☑ Shot noise
  - ☑ Radiation pressure noise



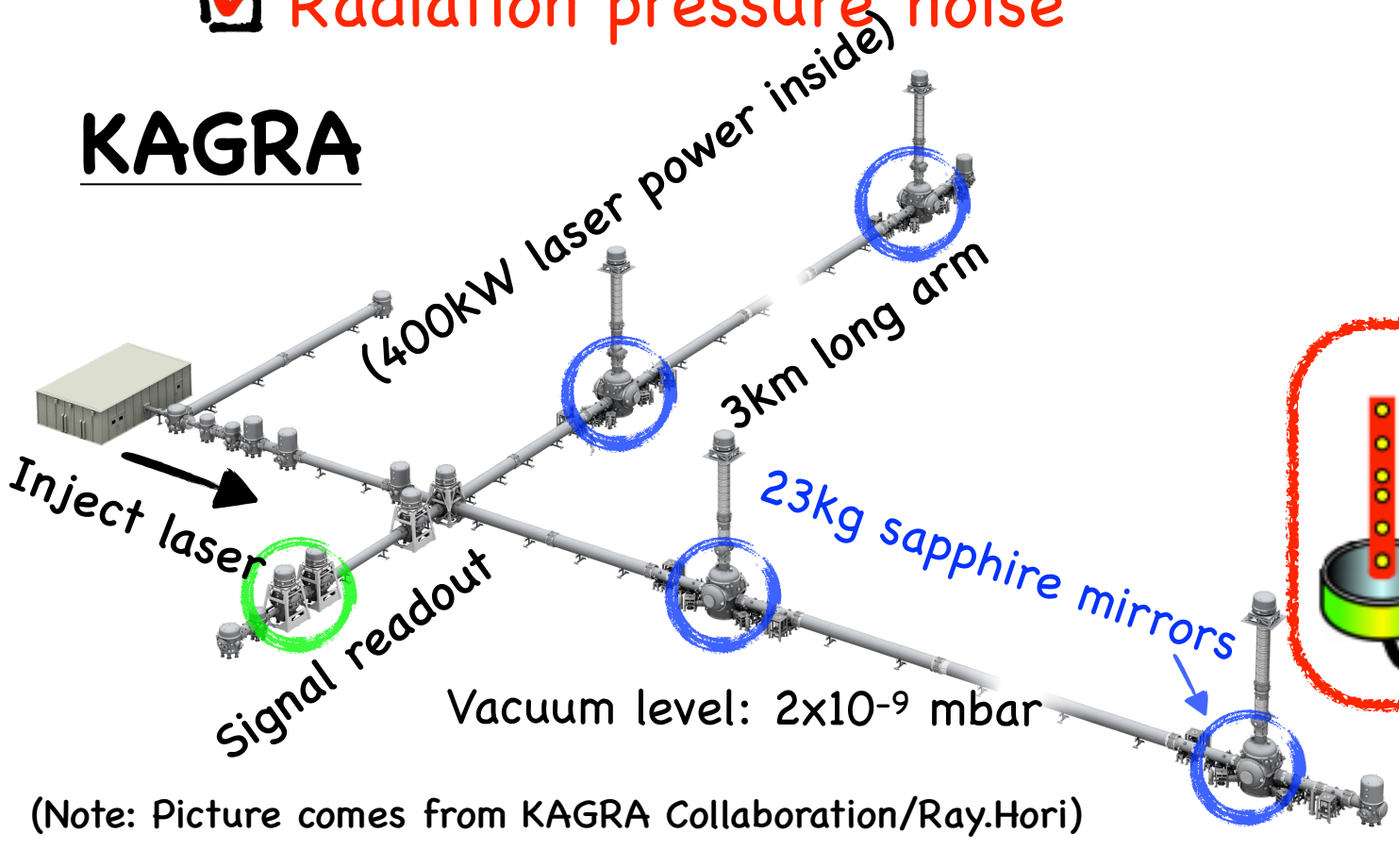




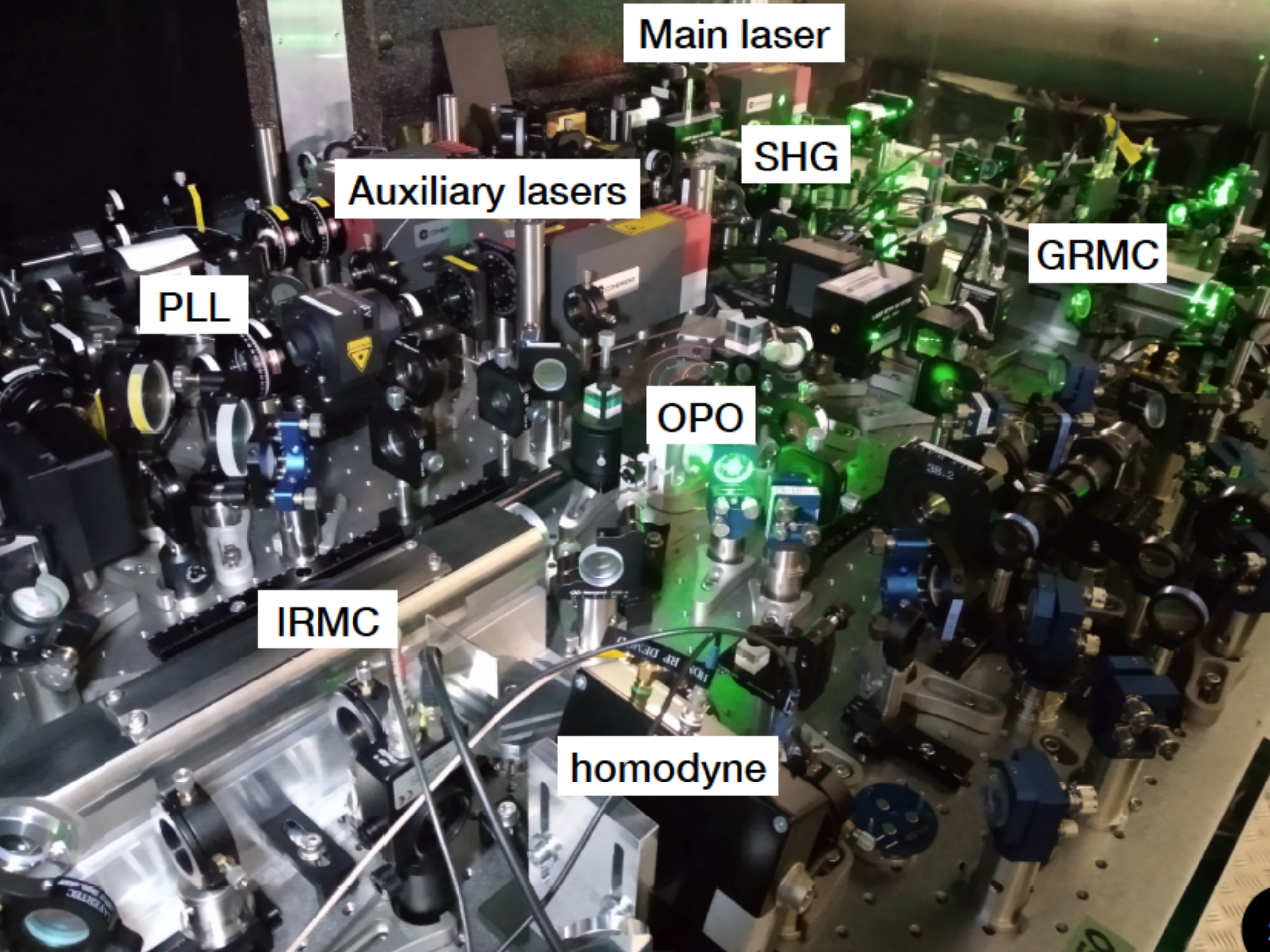




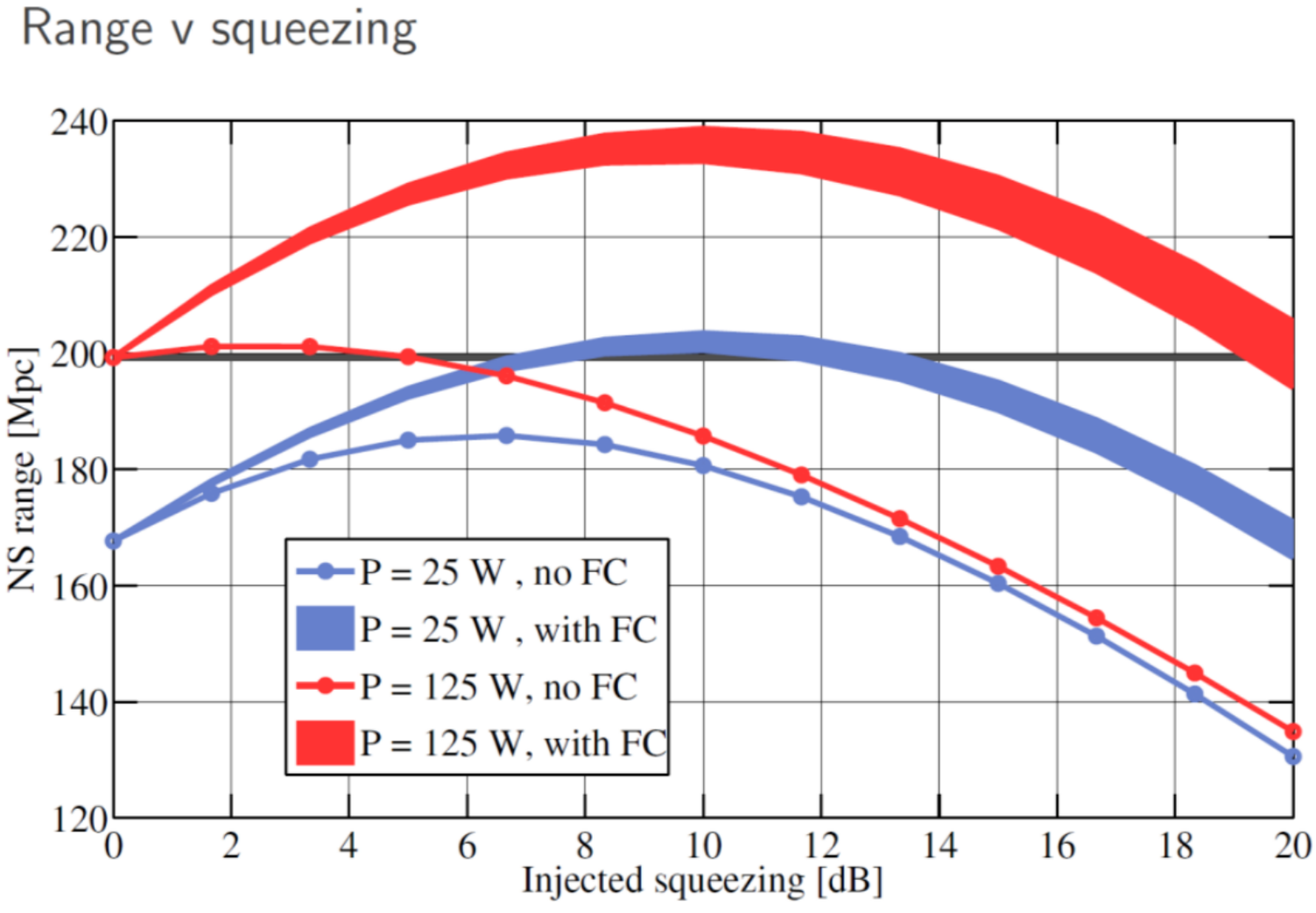
KAGRA



(Note: Picture comes from KAGRA Collaboration/Ray.Hori)


Main laser
SHG
Auxiliary lasers
GRMC
PLL
OPO
IRMC
homodyne

For aLIGO parameters, about 10dB injection is optimal.

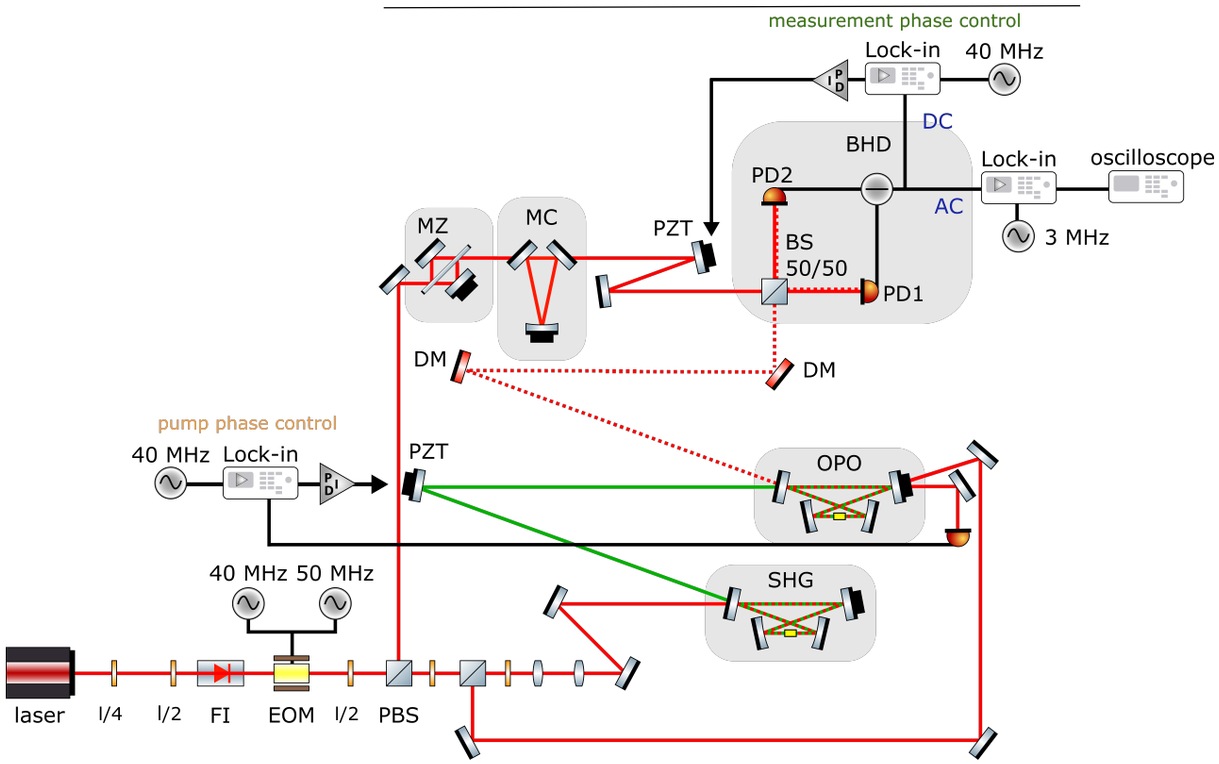


- Injecting more squeezing is not always a good thing
- Coupling from anti-squeezing can increase the noise

Figure Credit: John Miller

Squeezed Vacuum States of 10dB In NTHU

96 mW incident power of OPO
14.5 mW output power of LO
Zero span at 3 MHz



Shot noise:-72.931 dB

Clearance: 20.856 dB

Dark noise:-92.856 dB