Extract the Degradation Information in Squeezed States with Machine Learning

Yi-Ru Chen*, Hsien-Yi Hsieh, Hsun-Chung Wu,*
Hua Li Chen*, Yao-Chin Huang*, Chien-Ming Wu*,
Ray-Kuang Lee 李瑞光*

National Tsing Hua University, Taiwan
*KAGRA collaborator

*http://mx.nthu.edu.tw/~rklee

JGW: G2113077-v1

arXiv: 2106.04058 (2021).

KIW-8, 2021

PHYSICAL REVIEW LETTERS

VOLUME 45 | 14 JULY 1980 | NUMBER 2

Quantum-Mechanical Radiation-Pressure Fluctuations in an Interferometer

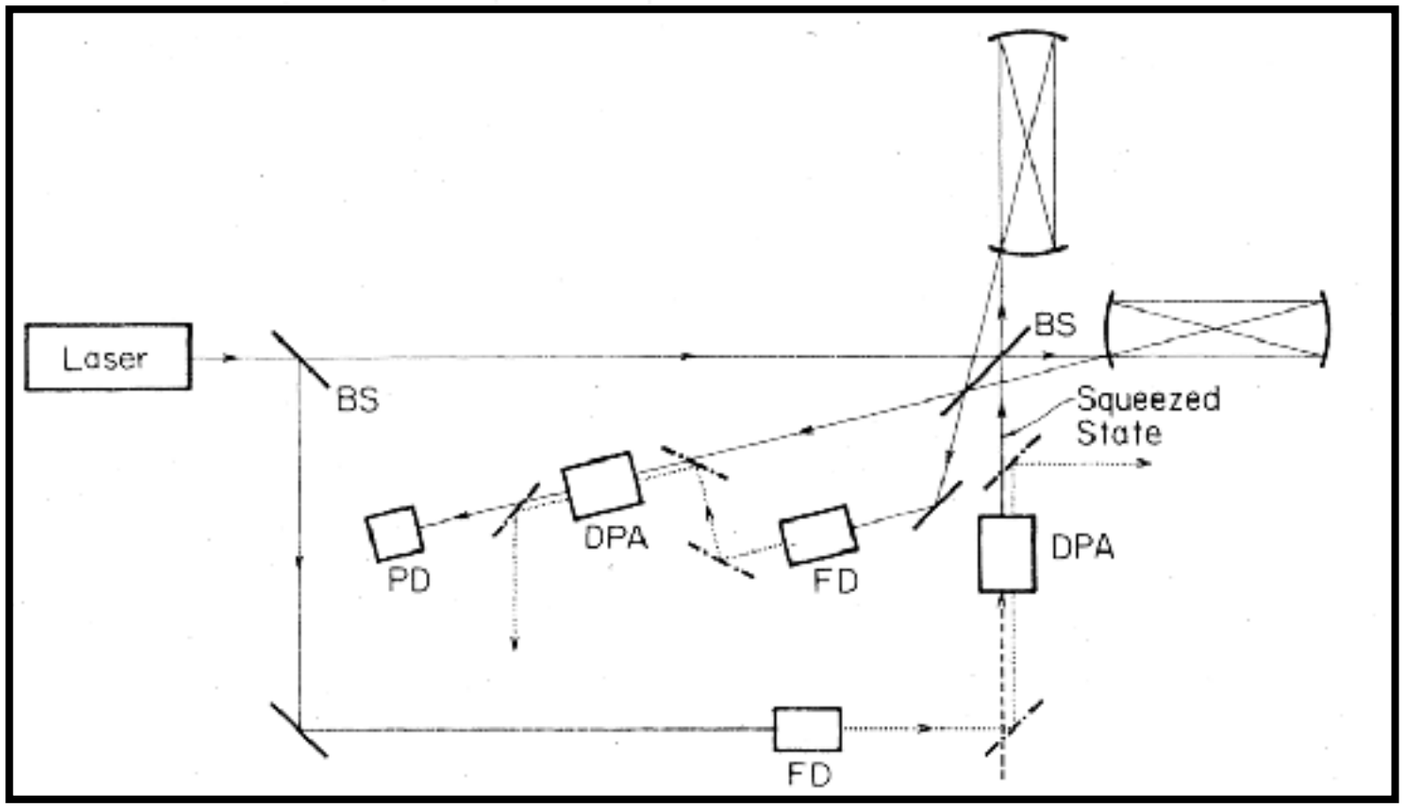
Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 29 January 1980)

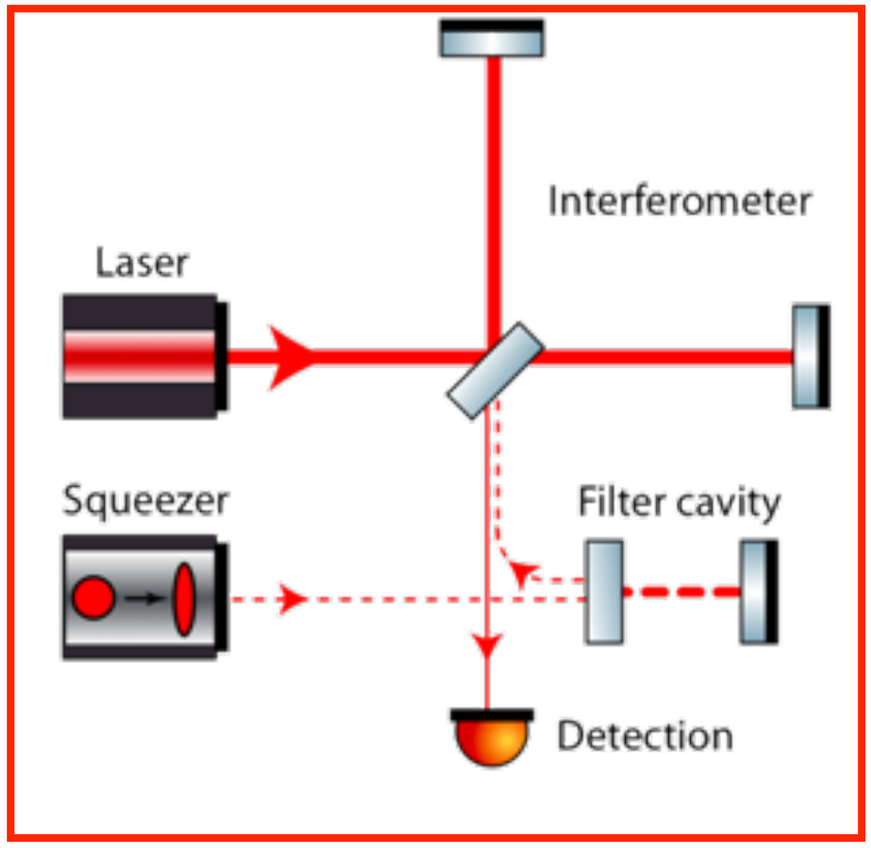
The interferometers now being developed to detect gravitational waves work by measuring small changes in the positions of free masses. There has been a controversy whether quantum-mechanical radiation-pressure fluctuations disturb this measurement. This Letter resolves the controversy: They do.

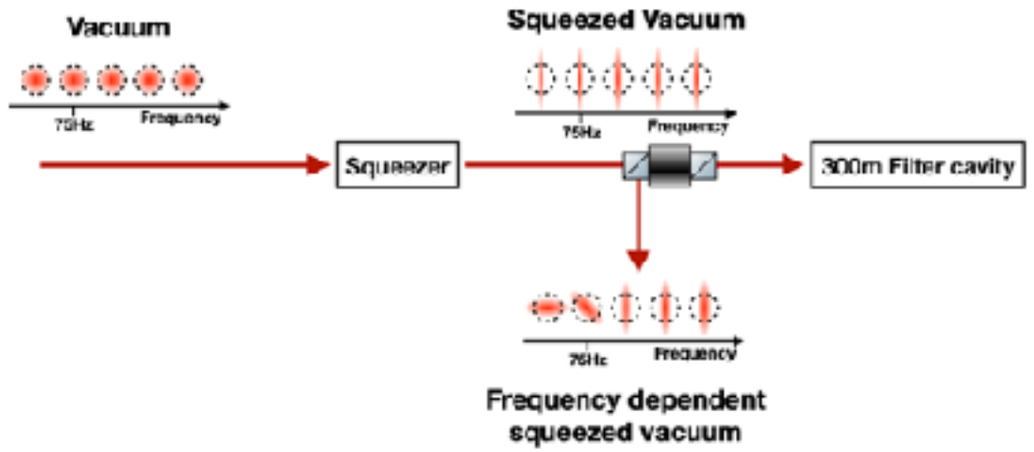
PHYSICAL REVIEW D | VOLUME 23, NUMBER 8 | 15 APRIL 1981

Quantum-mechanical noise in an interferometer

Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 15 August 1980)

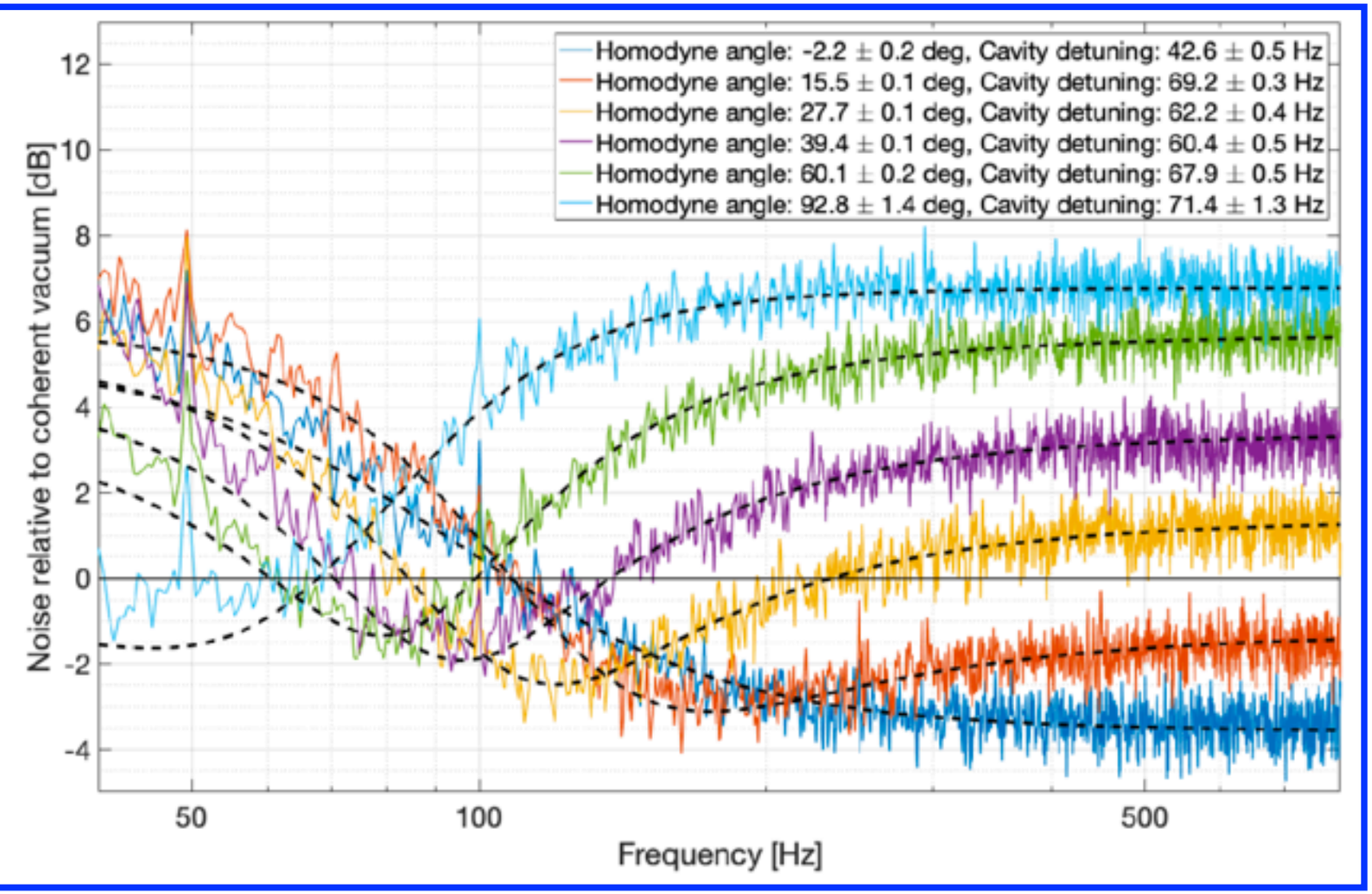






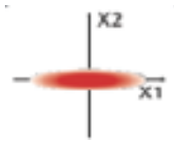
Courtesy: Yuhang Zhao (NAOJ/ICRR)

Frequency Dependent Squeezing Measurement

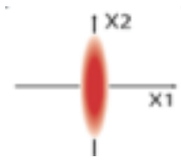


Squeezing degradation parameter	Value
Filter cavity losses	120 ± 30 ppm
Propagation losses	$34\% \pm 1\%$
Mode-mismatch squeezer-filter cavity	$6\% \perp 1\%$
Mode-mismatch squeezer-local oscillator	$2\% \pm 1\%$
Filter cavity length noise (RMS)	6 ± 1 pm
Phase noise	$30 + 5$ mrad
Produced squeezing	$8.3 + 1$ dB

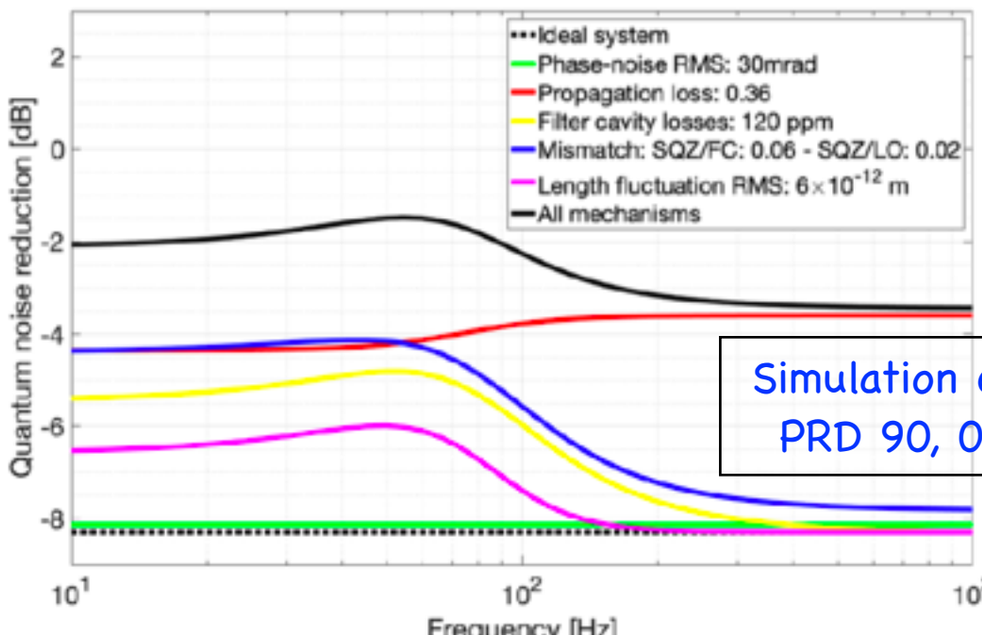
TABLE II. Parameters used in the estimation of squeezing degradation use to fit the frequency dependent noise curves.



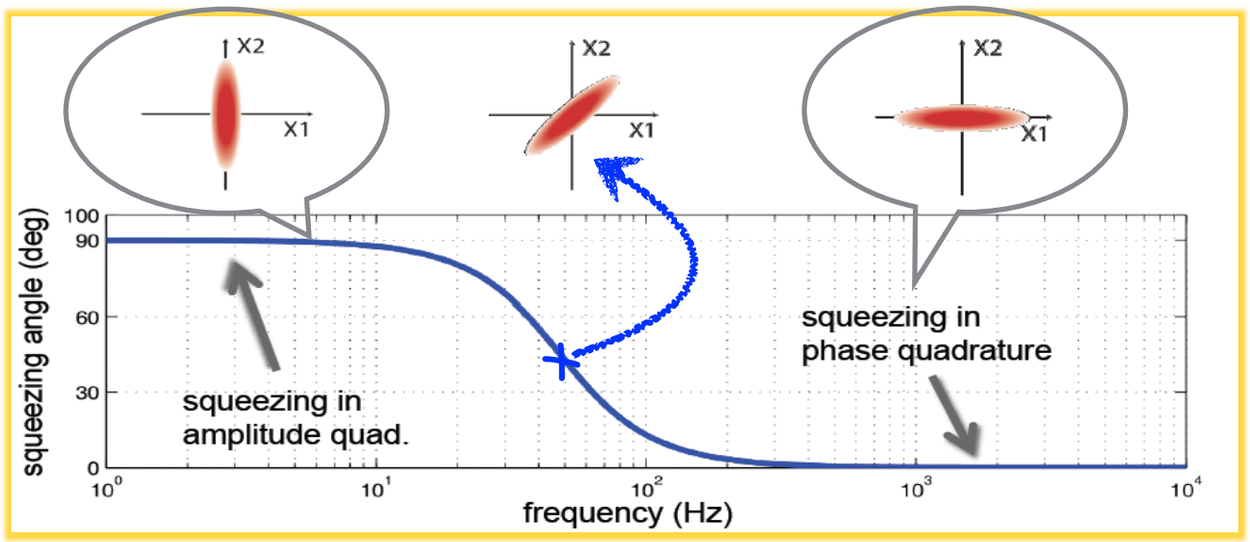
Hi_f: squeezed; 3.4(4)dB
(phase squeezing)
Lo_f: Anti-squeezed
(amplitude squeezing)



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



Simulation code based on
PRD 90, 062006 (2014).



For aLIGO parameters, about 10dB injection is optimal.

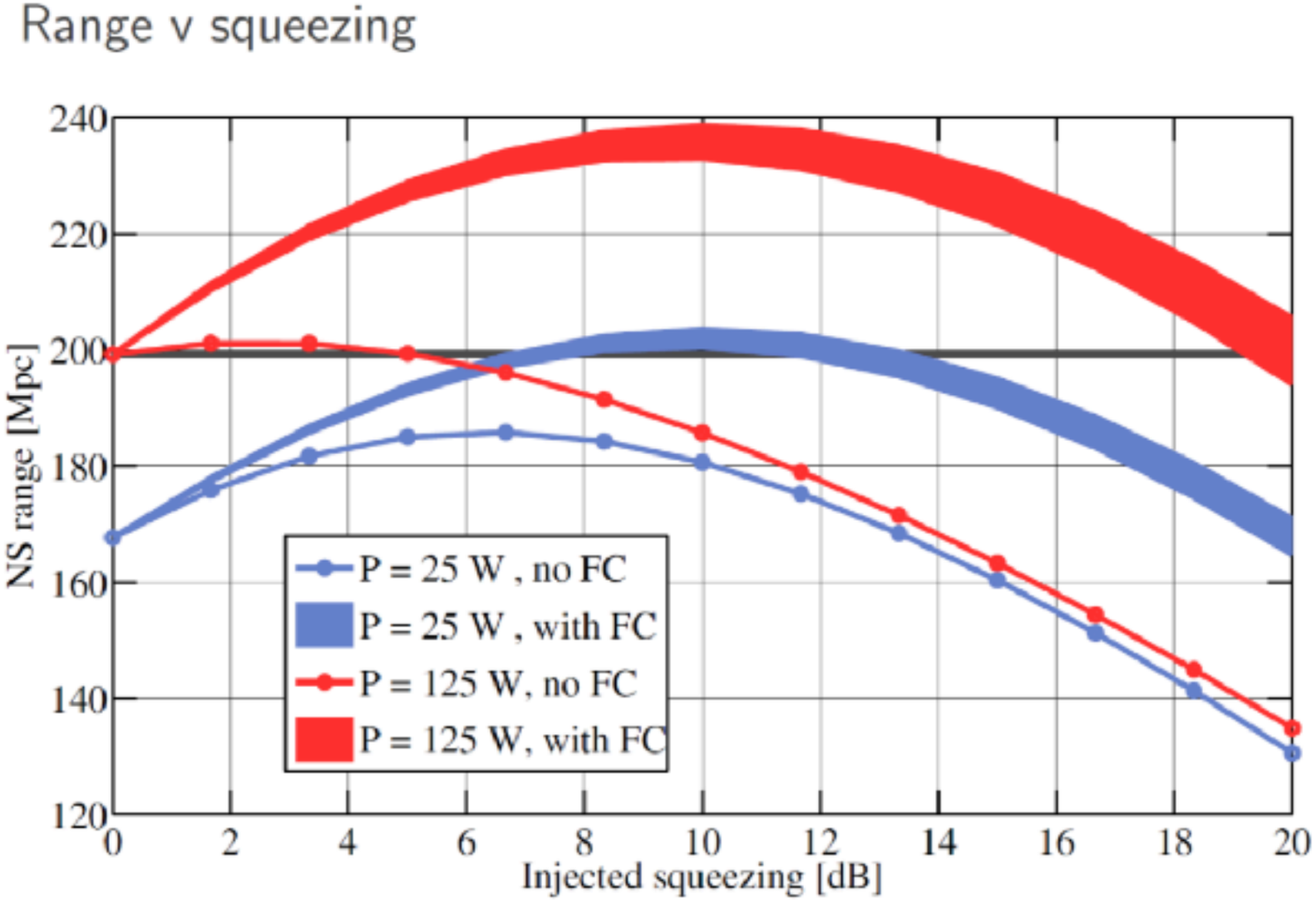
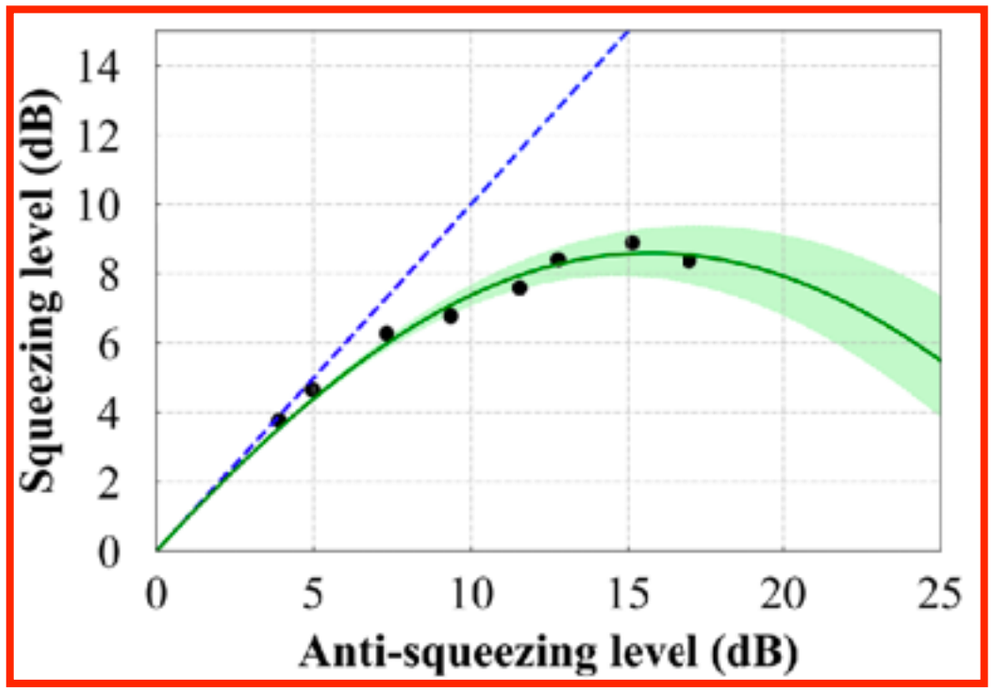


Figure Credit: John Miller

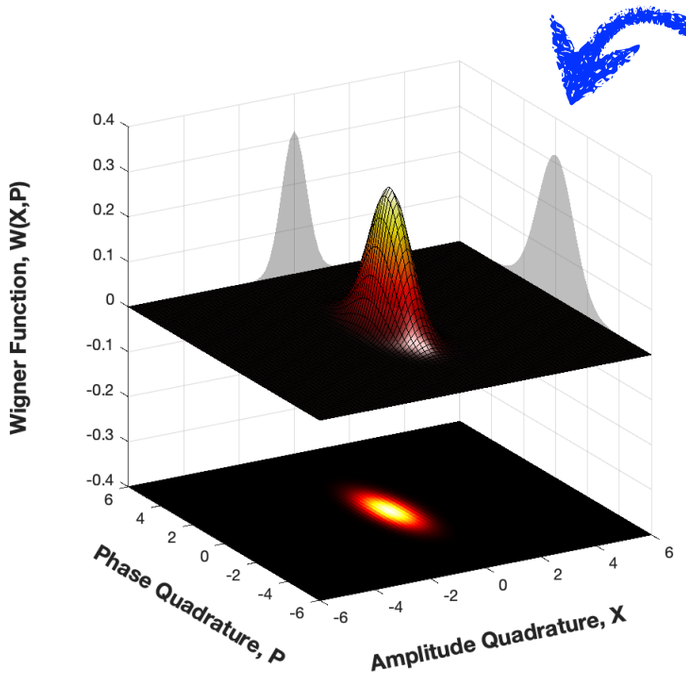
- Injecting more squeezing is not always a good thing
- Coupling from anti-squeezing can increase the noise



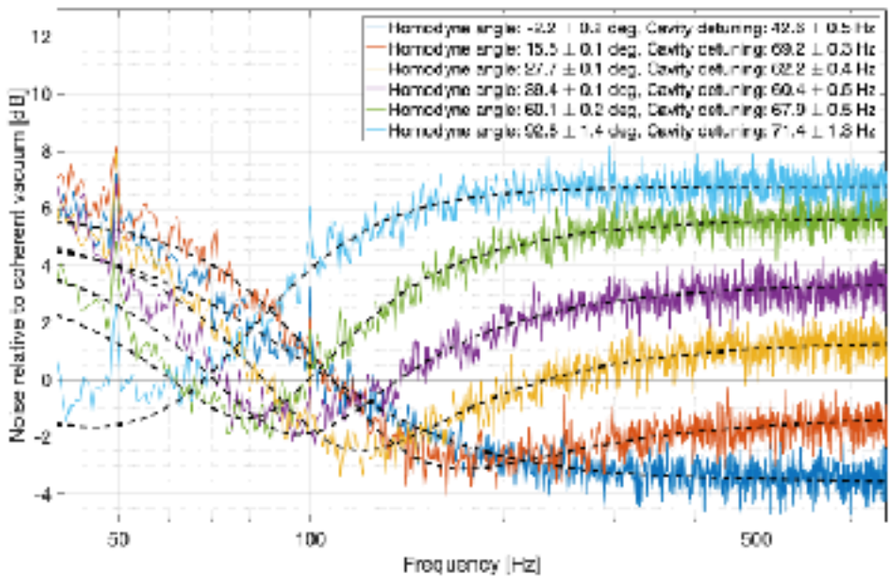
10dB squeezing reduces shot noise, but contributed 20dB to the radiation pressure noise.

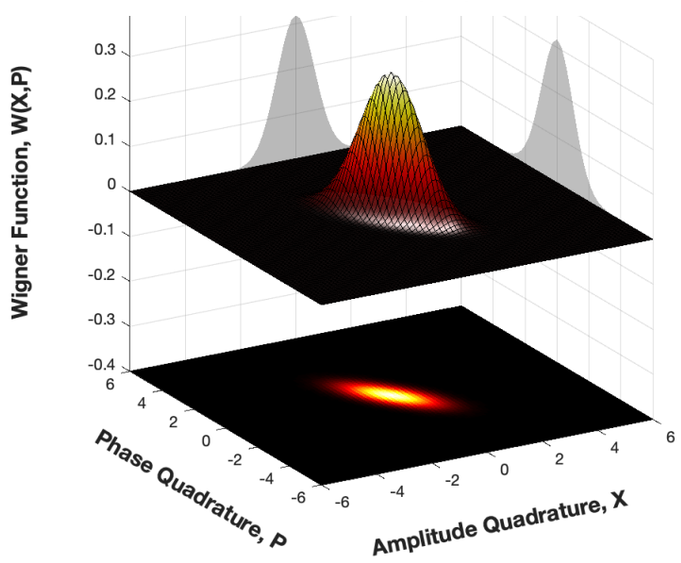
Diagnosis with Quantum State Tomography

Can we Monitor the purity of the quantum state?

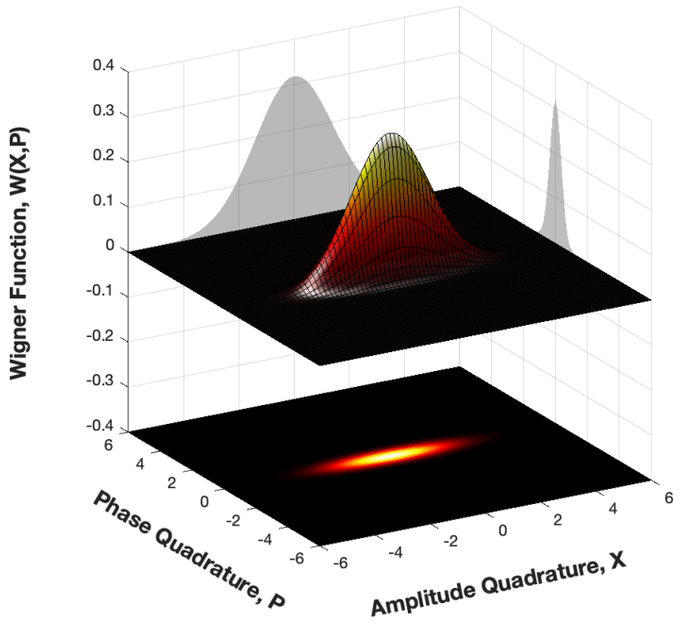


Low frequency region



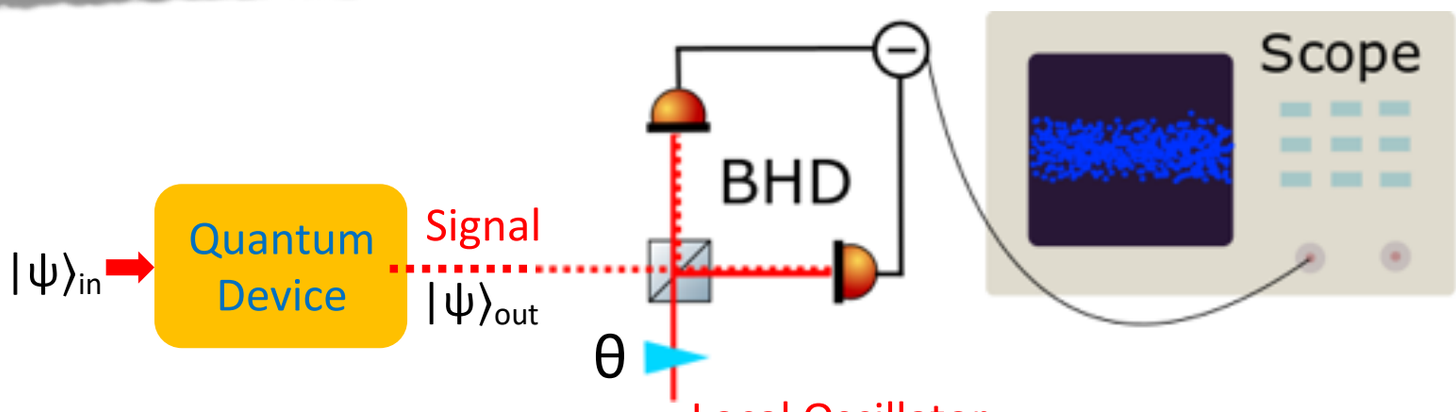


Middle frequency region

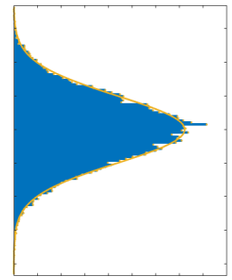


High frequency region

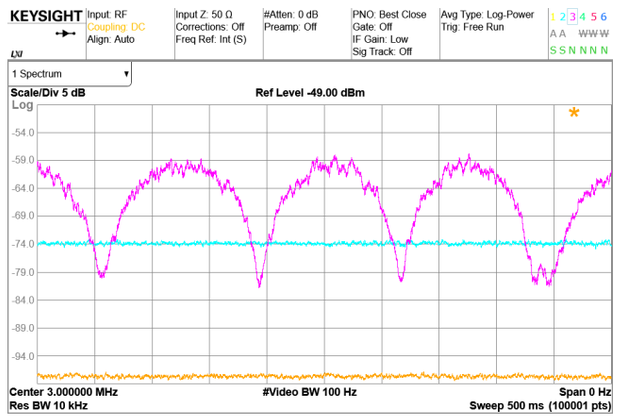
Diagnosis with Quantum State Tomography

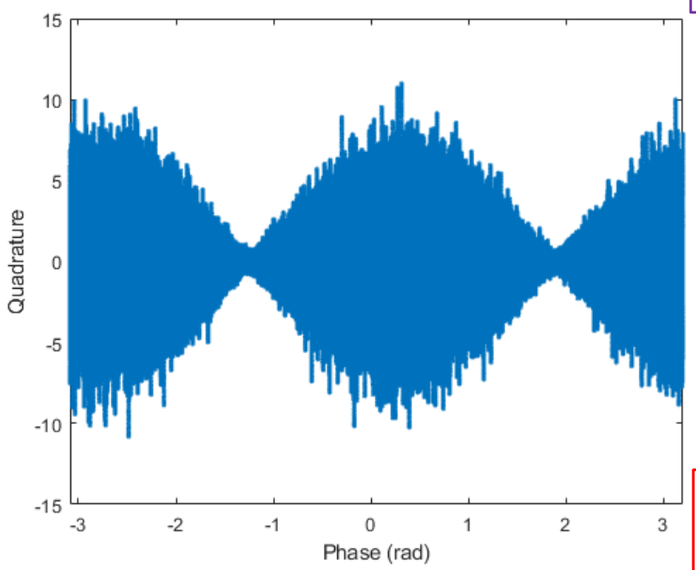


Probability distribution
Pr(q, θ)



Reconstruction Algorithms

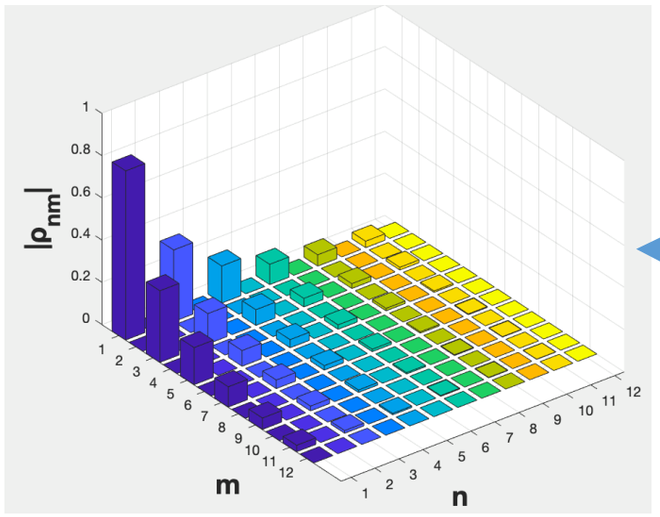


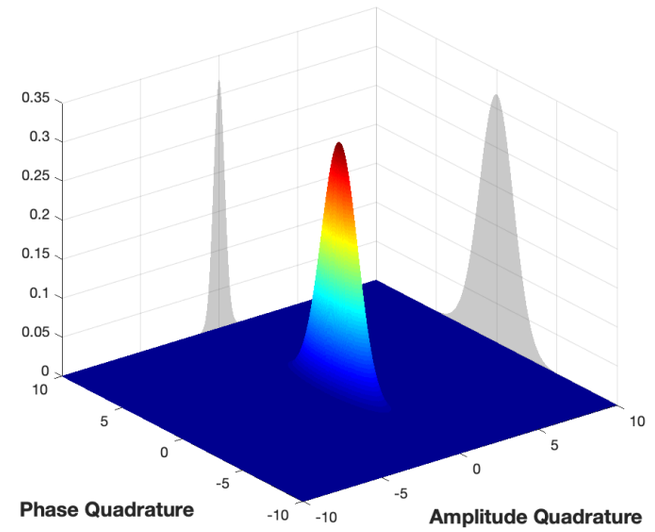


few minutes to reconstruct

< 1s to reconstruct

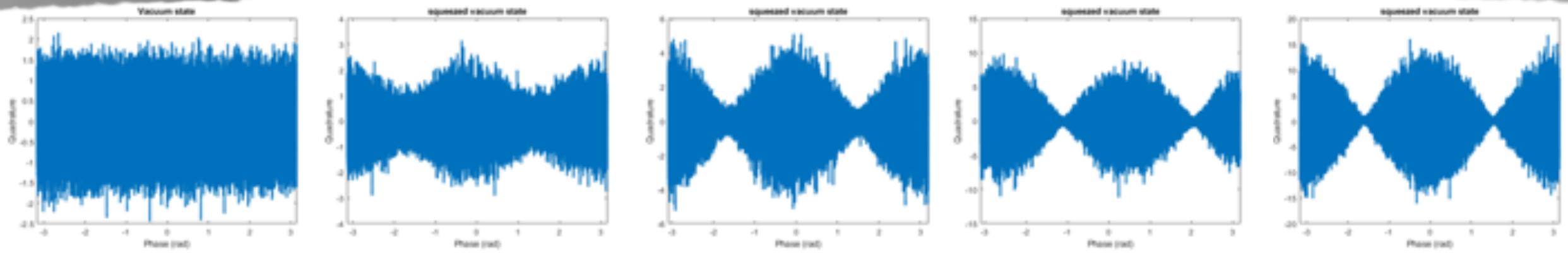
Max. Likelihood Estimation, MLE

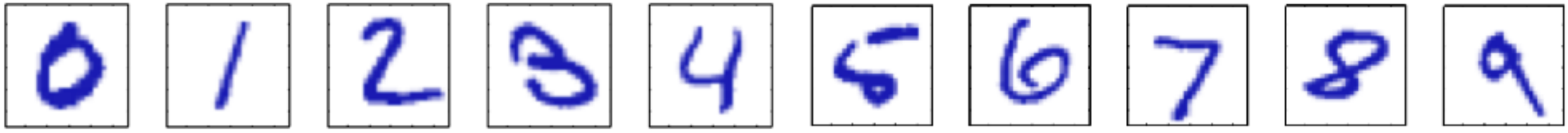




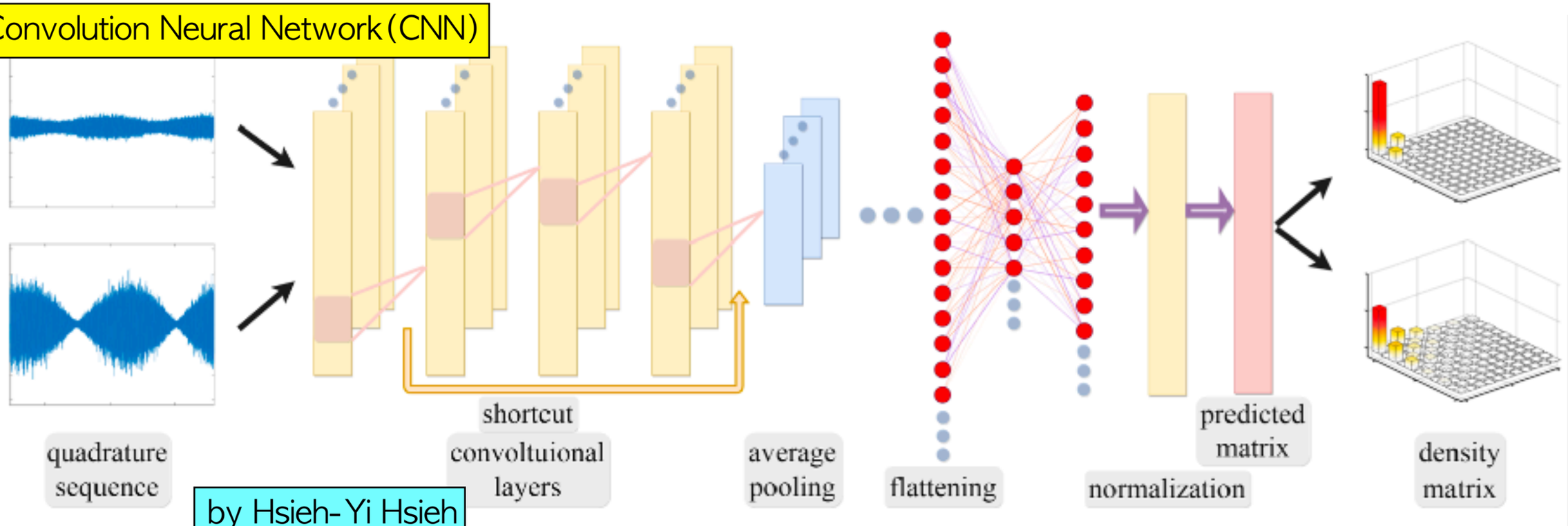
Machine Learning (SQ Learner), CNN

Pattern Recognition & Machine Learning



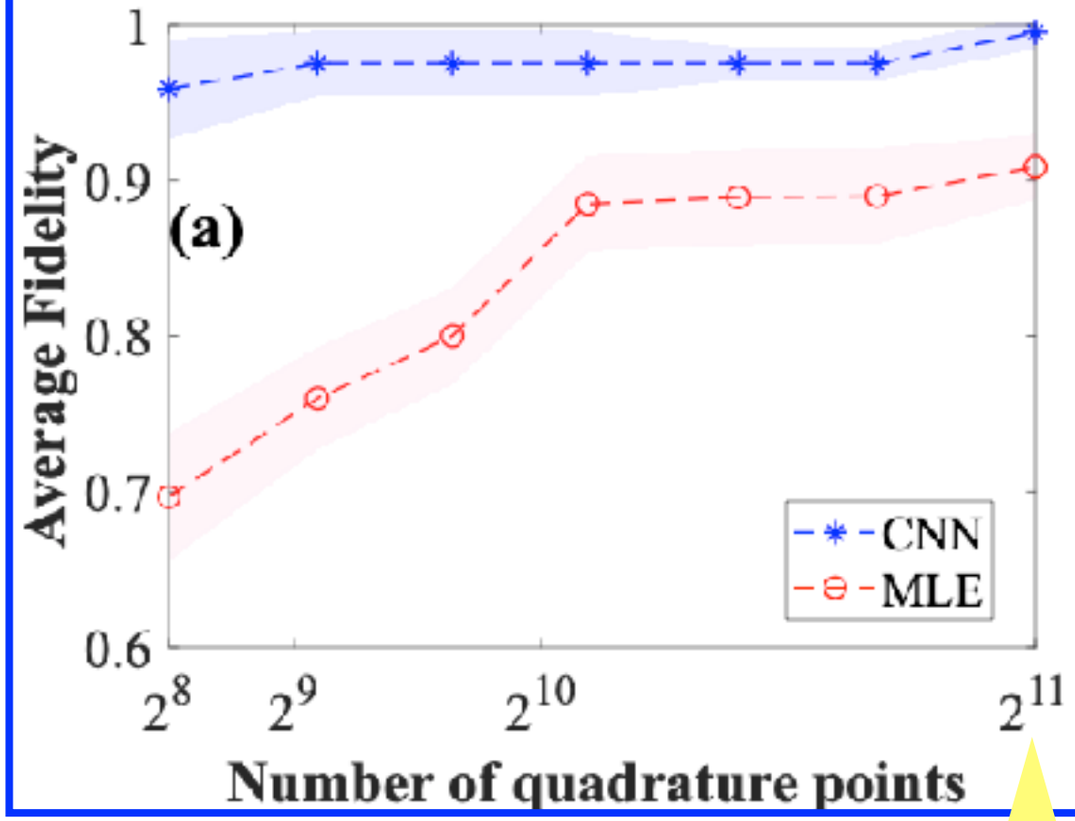


Convolution Neural Network (CNN)



by Hsieh-Yi Hsieh

Machine Learning (SQ Learner) vs MLE



8 - 14 dB Squeezing

in less than one Second

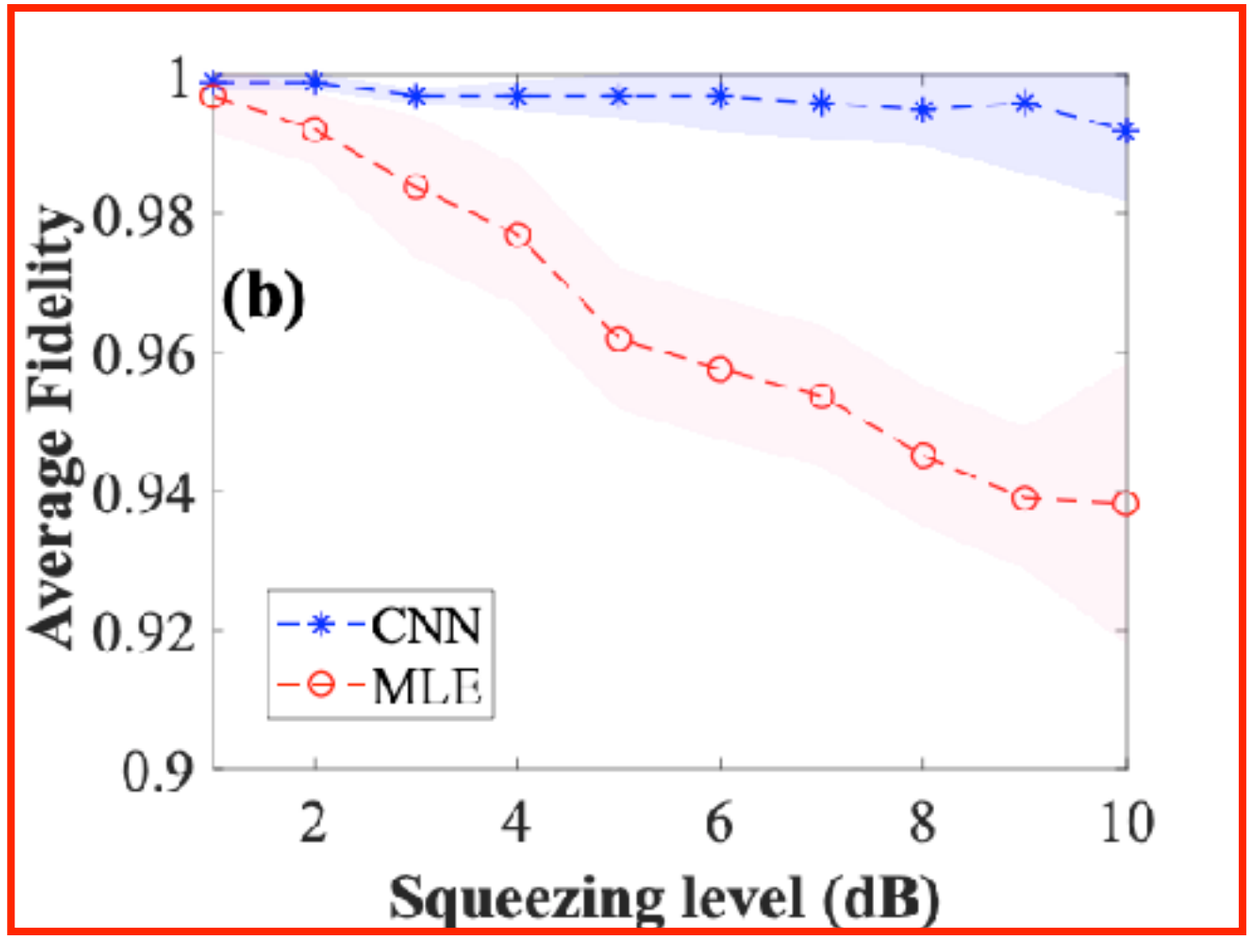
Real-Time Reconstruction

Fidelity:

$$F(\rho,\sigma) \equiv [\mathrm{Tr}\{\sqrt{\sqrt{\rho},\sigma\sqrt{\rho}}\}]^2$$

at Least several Hours to reconstruct wavefunction

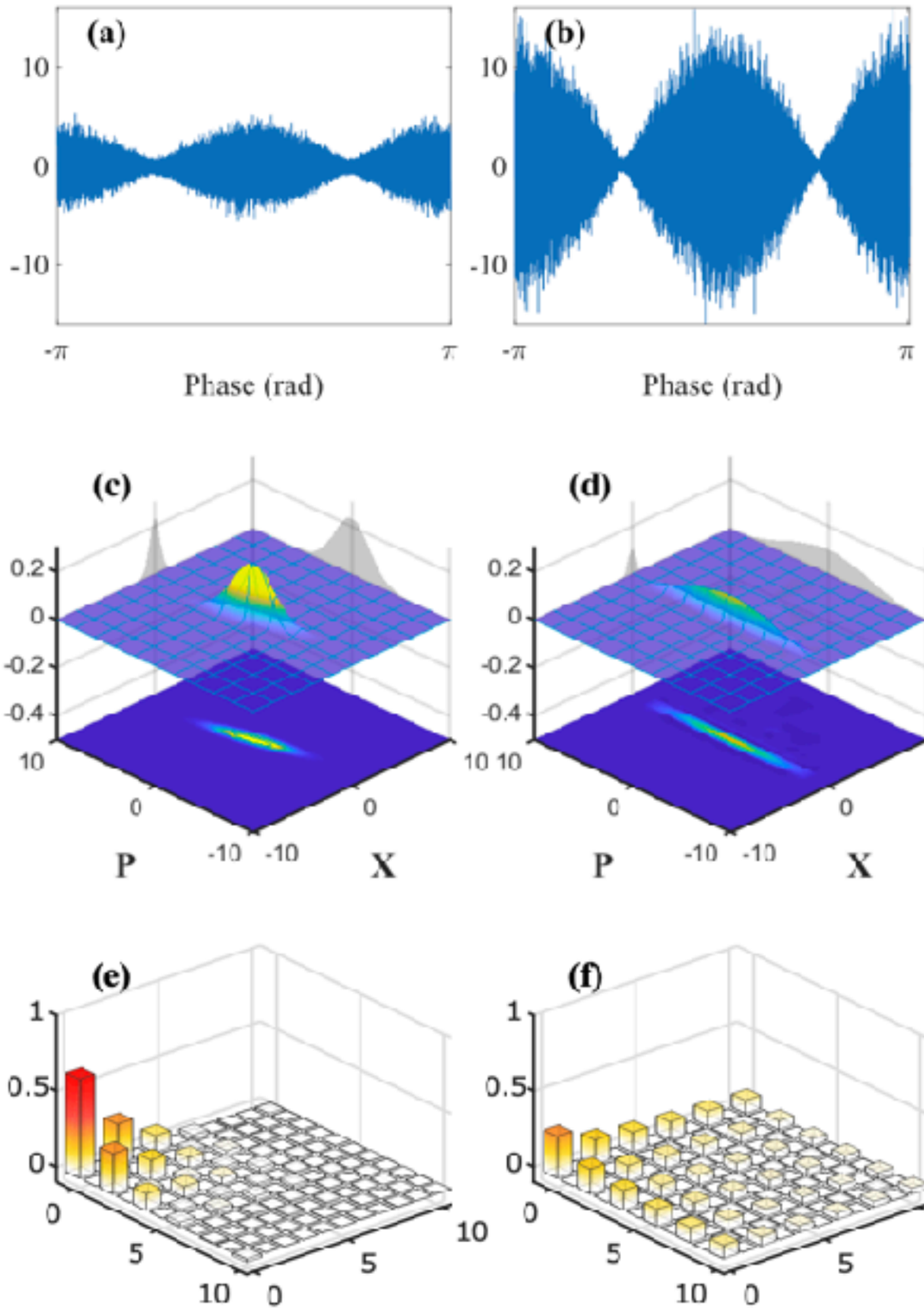
2K Data Points

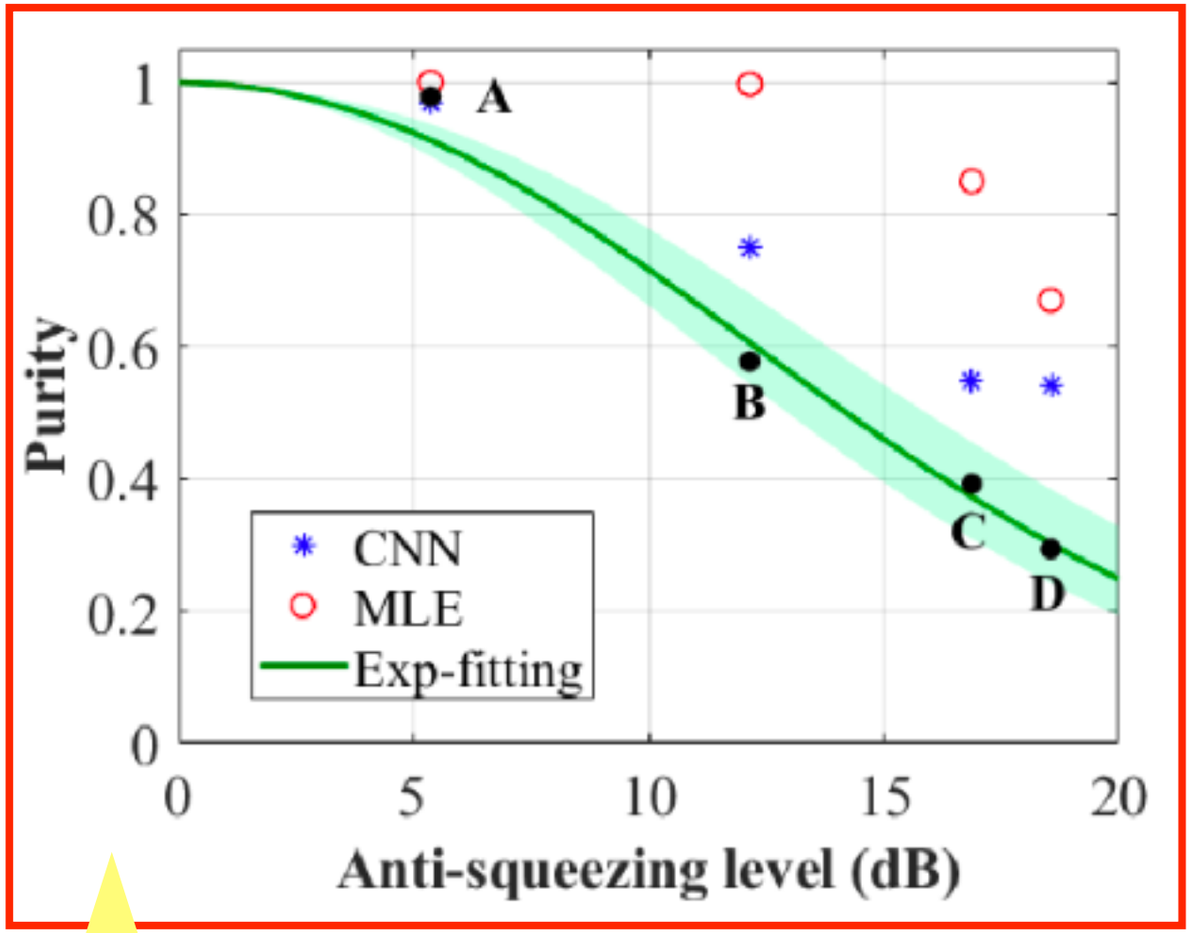


arXiv: 2106.04058 (2021).

sq: 7.39dB
anti: 12.16 dB

sq: 7.91dB
anti: 18.56 dB

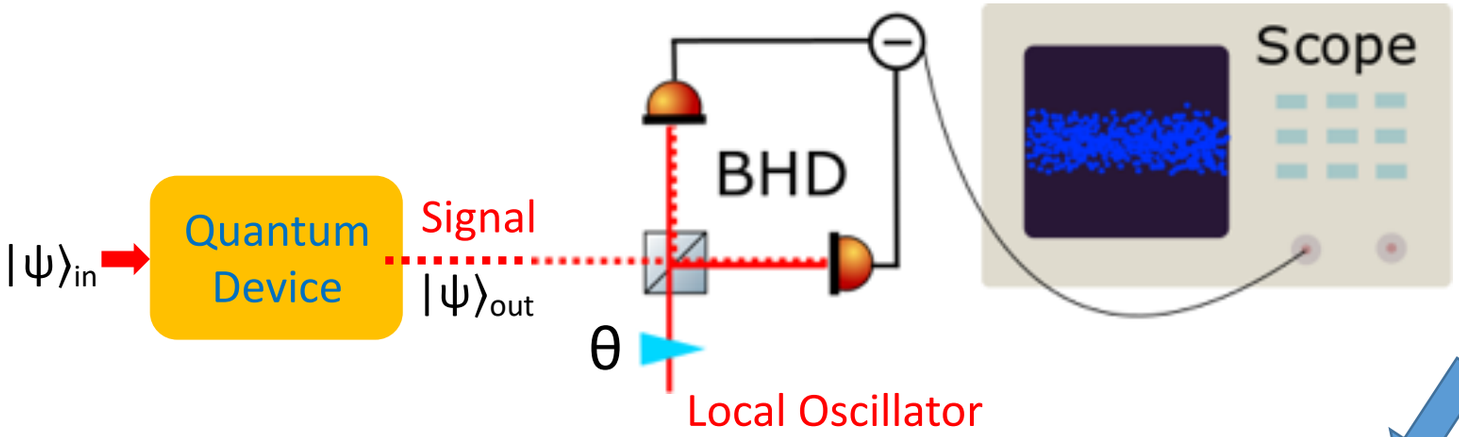




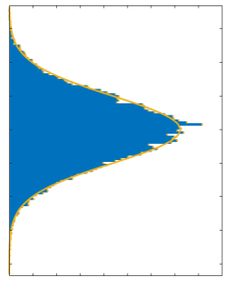
- **MLE: over-estimate (over-fitting problem)**
- **Exp-fitting: under-estimate (lack of thermal reservoir information)**

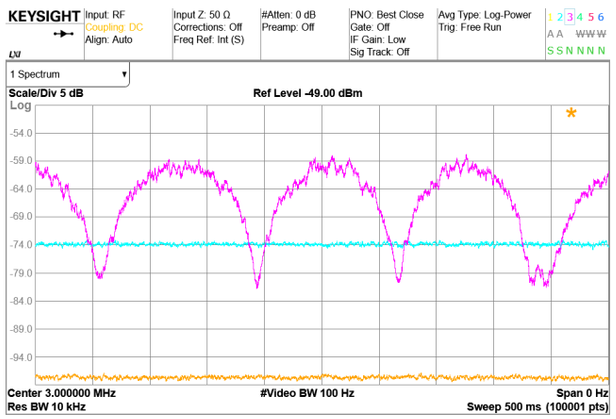
arXiv: 2106.04058 (2021).

Quantum State Tomography with ML



Probability distribution
Pr(q, θ)

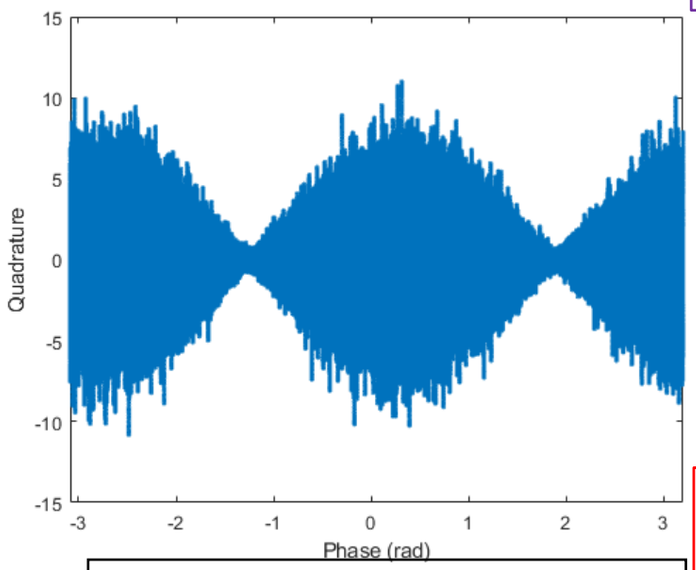




Reconstruction Algorithms

Max. Likelihood Estimation, MLE

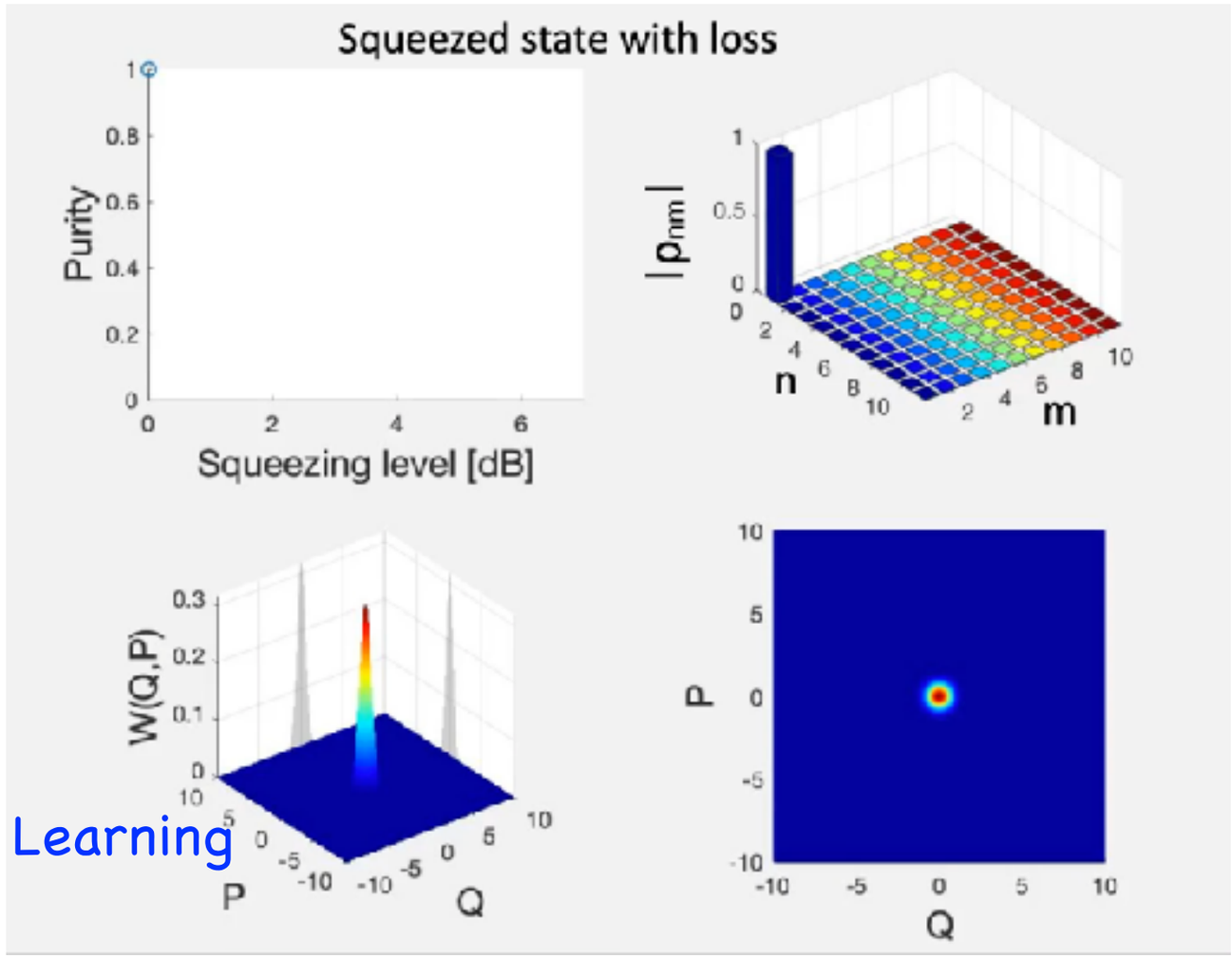
few minutes to reconstruct



arXiv: 2106.04058 (2021).

< 1s to reconstruct

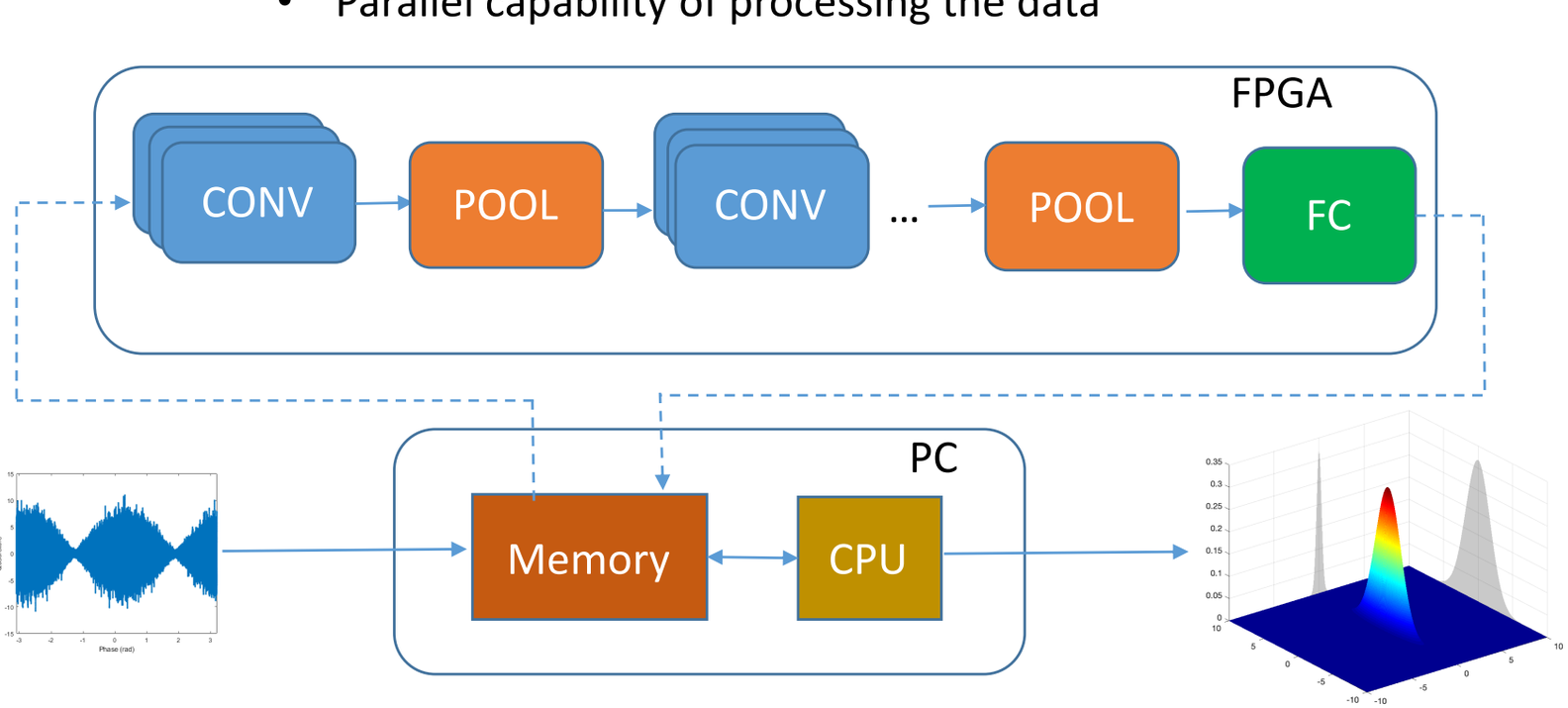
CNN, Machine Learning

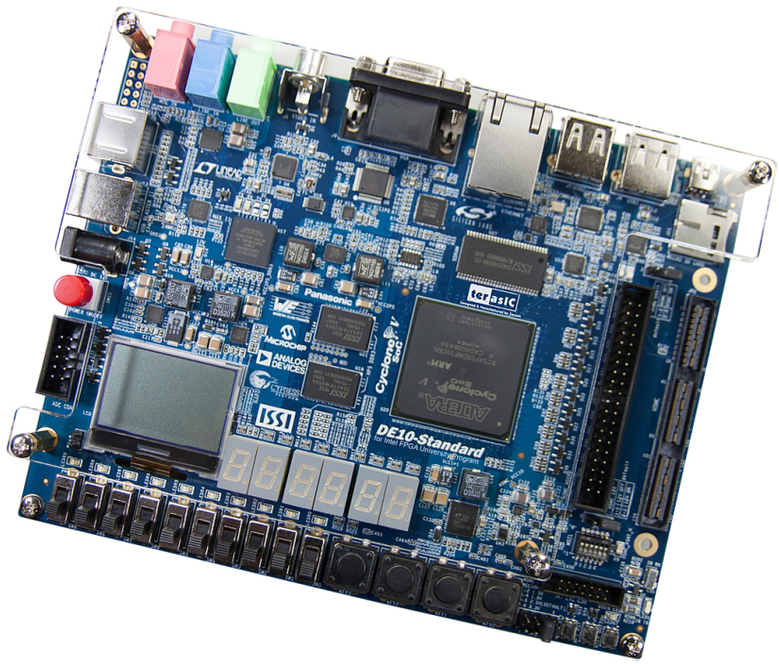


Real-time Q-State Tomography: with FPGA Accelation

Next: FPGA Acceleration of Convolutional Neural Networks

- Parallel capability of processing the data





DE10-Standard

- Reducing the loading of CPU

Summary

- **Our well-trained machine not only completes the task of the reconstruction of Wigner function in less than one second, but also keeps the high fidelity in the predict density matrix.**

- **Compared to the over-estimation by MLE and under-estimation by empirically fitting at high squeezing levels, the purity of squeezed states at squeezing level close to 10 dB is demonstrated experimentally.**

- **Such a fast, robust, and precise quantum state tomography enables us to extract the degradation information in squeezing, which should be a useful diagnosis tool for the GW detectors.**

.

Thanks for your attentions ^.^