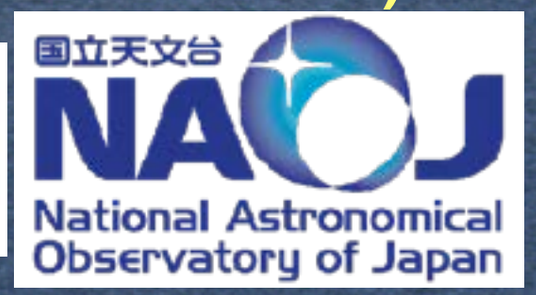
令和五年度東京大学宇宙線研究所共同利用研究成果発表会
Research Result Presentation meeting of
the ICRR Inter-University Research Program

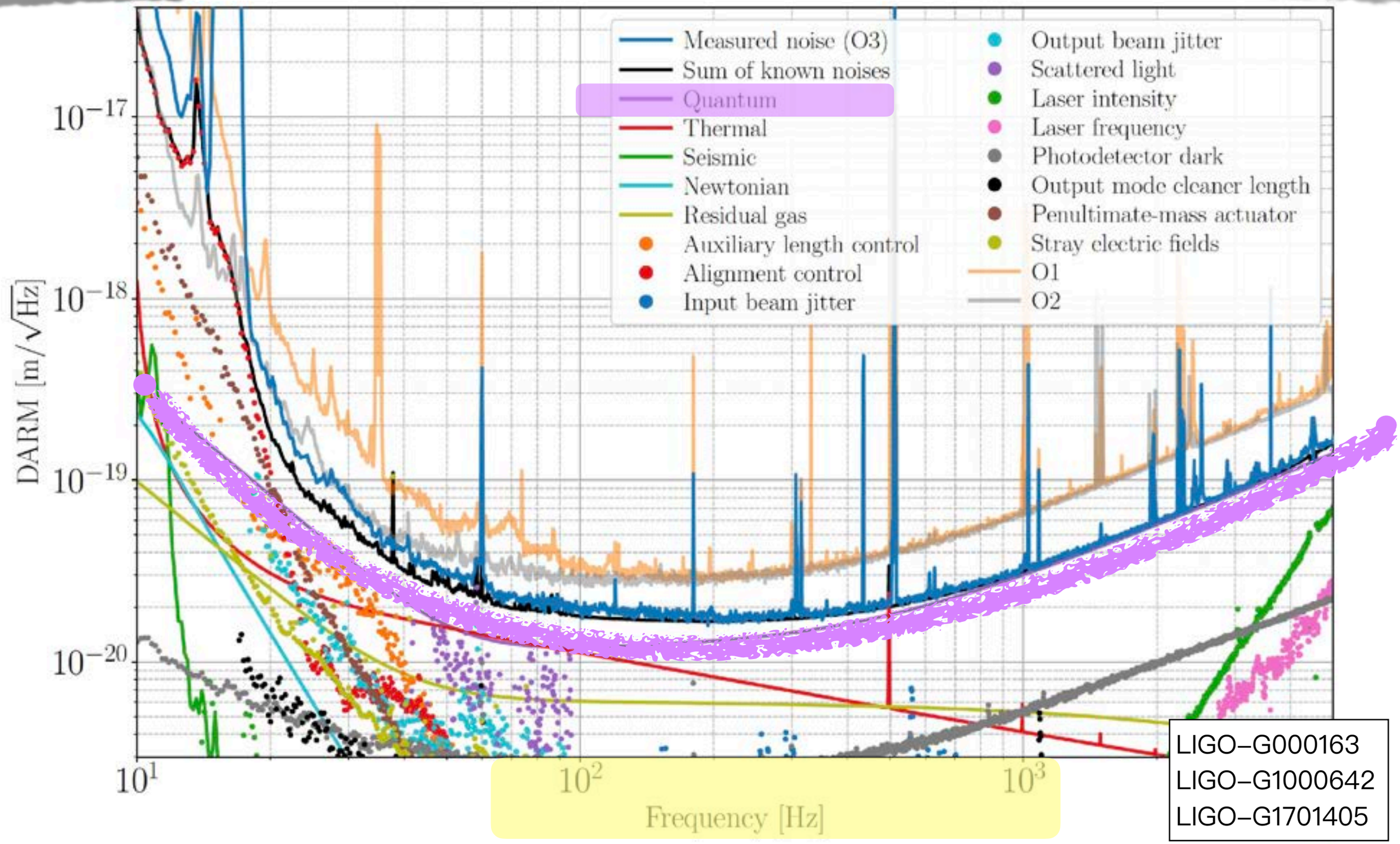
Filter cavity experiments for Frequency Dependent Squeezed light source (with Machine Learning Quantum State Tomography) for KAGRA

PhD students: Yi-Ru Chen, Hsun-Chun Wu, Hua Li Chen, Jingyu Ning,
Dr. Hsien-Yi Hsieh, Dr. Chien-Ming Wu, Ray-Kuang Lee 李瑞光*
National Tsing Hua University (NTHU), Taiwan
Shinji Miyoki
(+Marc Eisenmann, Michael Page, Yoichi Aso, Takayuki Tomaru)
(+Yu-hang Zhao, Matteo Leonardi)

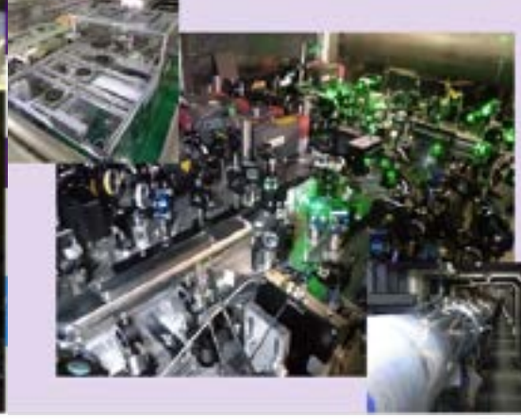


Feb. 21st, 2024

Noise Budget:



LIGO–G000163
LIGO–G1000642
LIGO–G1701405



Synopsis: Feeling the Squeeze at All Frequencies

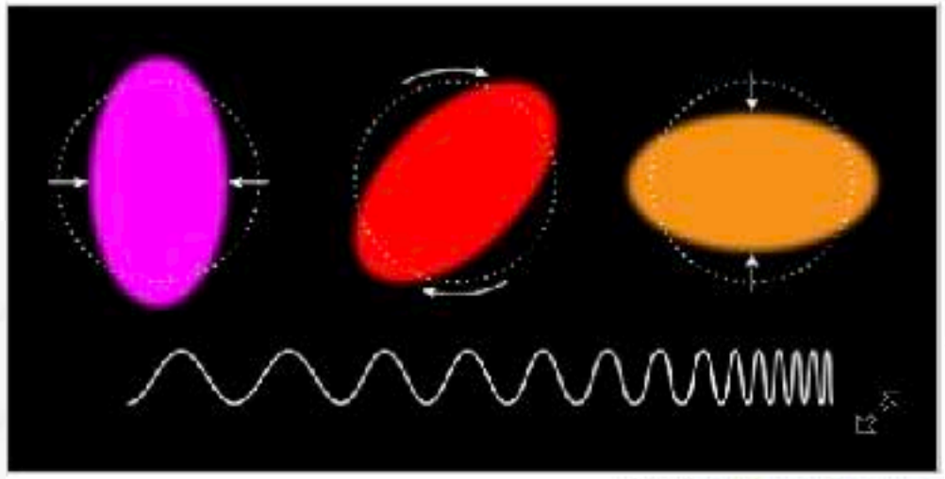
April 28, 2020 • *Physics* 13, s55

Two teams demonstrate frequency-dependent quantum squeezing, which could double the sensitivity of gravitational-wave detectors.

The First Experimental Realization of FDS at 70 Hz.

KAGRA Filter Cavity (KFC) Team

KFC sogood



APS/Alan Stonebraker

Frequency-Dependent Squeezed Vacuum Source for Broadband Quantum Noise Reduction in Advanced Gravitational-Wave Detectors

Yuhang Zhao, Naoki Aritomi, Eleonora Capocasa, Matteo Leonardi, Marc Eisenmann, Yuefan Guo, Eleonora Polini, Akihiro Tomura, Koji Arai, Yoichi Aso, Yao-Chin Huang, Ray-Kuang Lee, Harald Lück, Osamu Miyakawa, Pierre Prat, Ayaka Shoda, Matteo Tacca, Ryutaro Takahashi, Henning Vahlbruch, Marco Vardaro, Chien-Ming Wu, Matteo Barsuglia, and Raffaele Flaminio

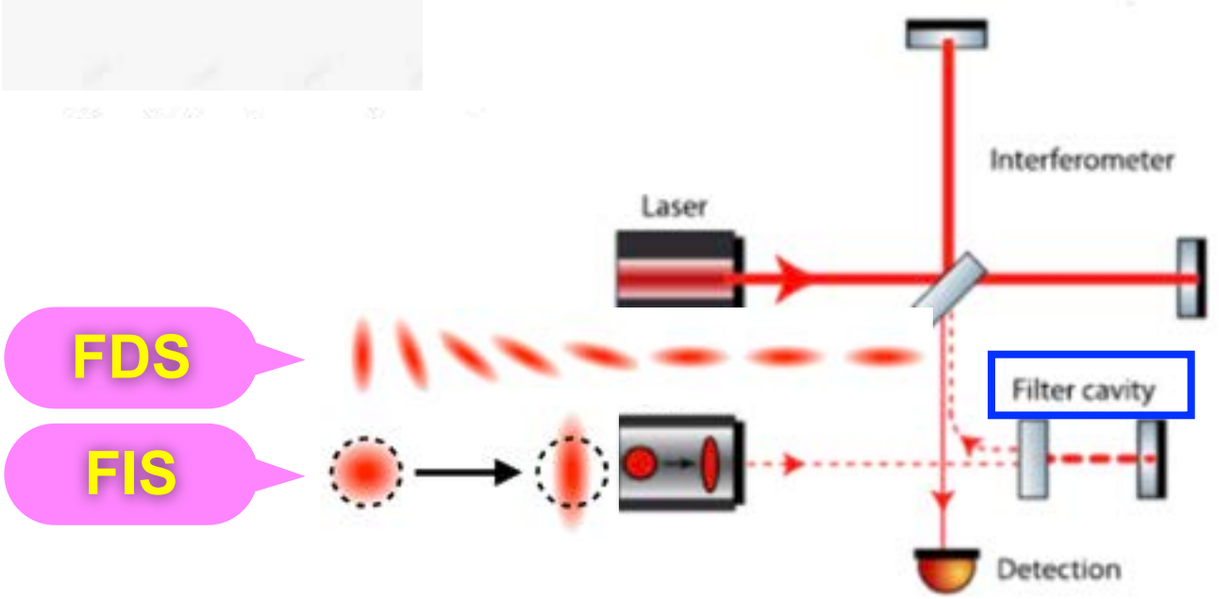
Phys. Rev. Lett. 124, 171101 (2020)

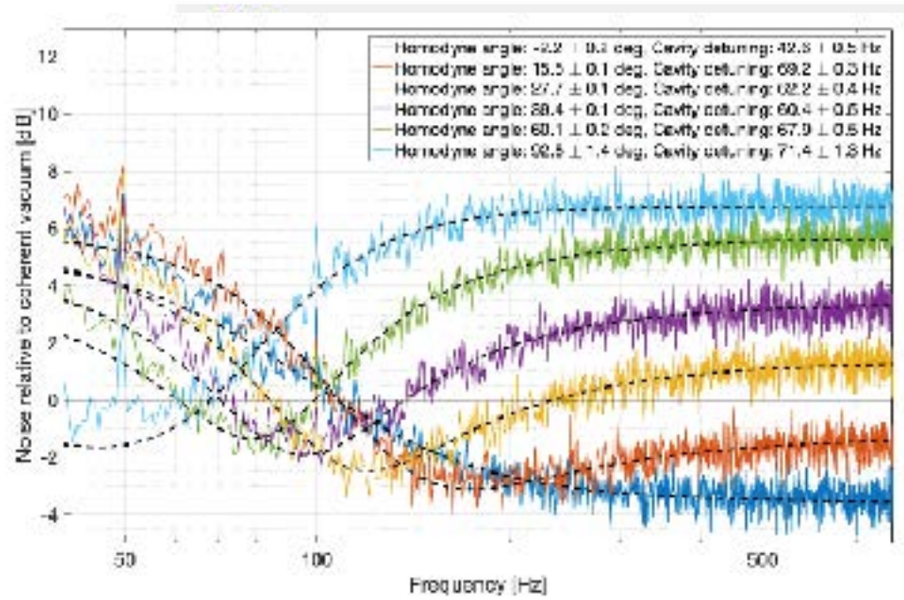
Published April 28, 2020

Frequency dependent squeezed vacuum state

FDS

FIS





Degradation in Squeezers

- ✓ **Frequency-Dep. Squeezing (FDS) for GW detectors** **w/ NAOJ** PRL 124, 171101 (2020).

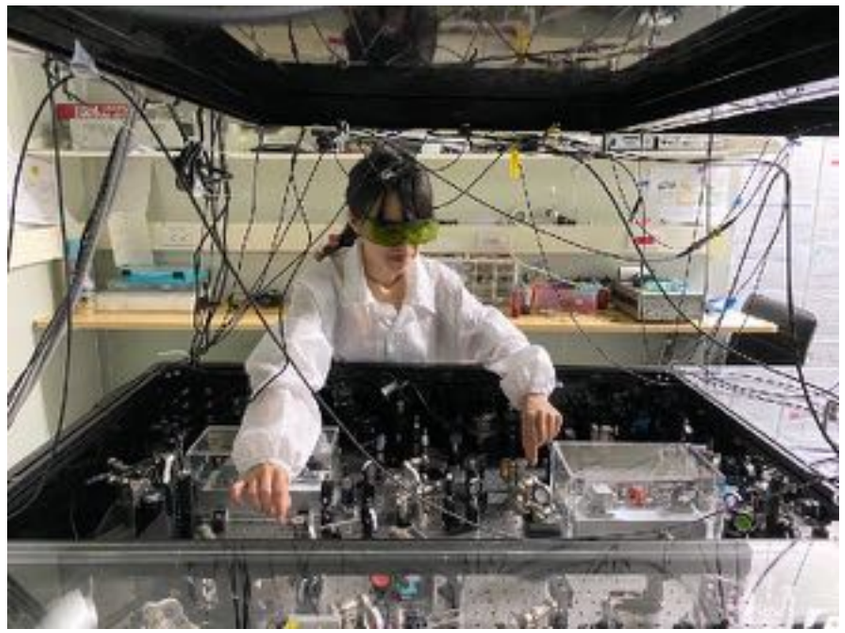
Unavoidable coupling from the noisy environment makes the quantum light in a mixed state with **Degradation** embedded.

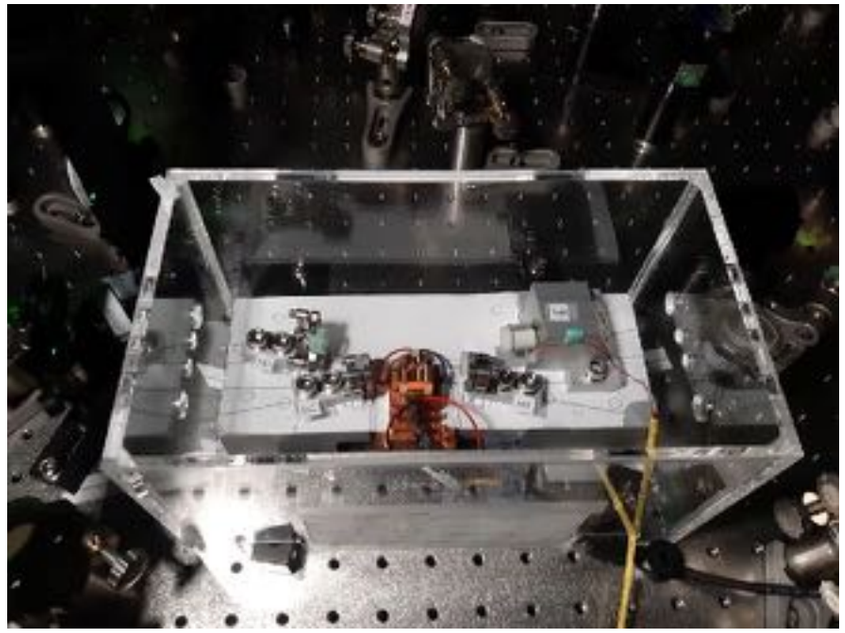
- ✓ **Extract the Degradation Information** in Squeezed States with **Machine Learning**, Phys. Rev. Lett. 128, 073604 (2022); Fiscal Year 2021
- ✓ Direct parameter estimations from Machine Learning-enhanced Quantum State Tomography, Symmetry, 14, 874, (2022); Fiscal Year 2022
- ✓ Neural network enhanced single-photon Fock state tomography, Adv. Quant. Tech. (Invited Paper, 2024); Fiscal Year 2023

- ✓ **Reconstruct** Wigner current in Decoherence, Phys. Rev. A 108, 023729 (2023); Fiscal Year 2023

- ➡ **Utilize: Generation of heralded optical `Schrodinger cat' states by photon-addition,** arXiv: 2306.13011 (2023); Fiscal Year 2023

Cavity Parameter	Value	Units
Fundamental field Wavelength	1064	nm



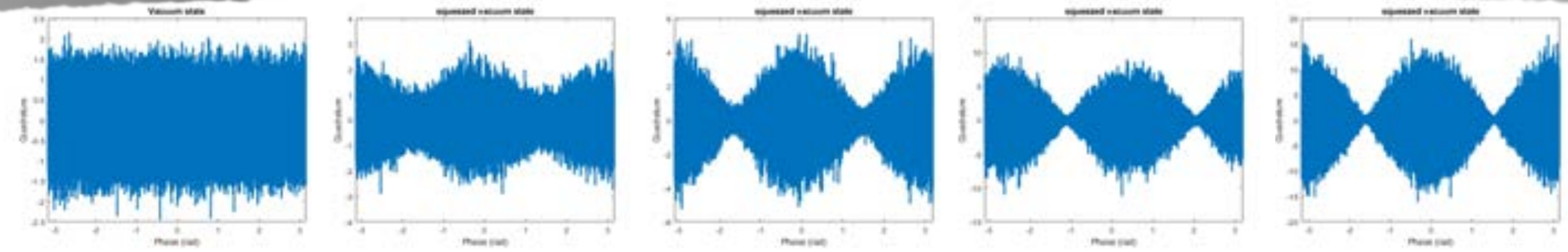


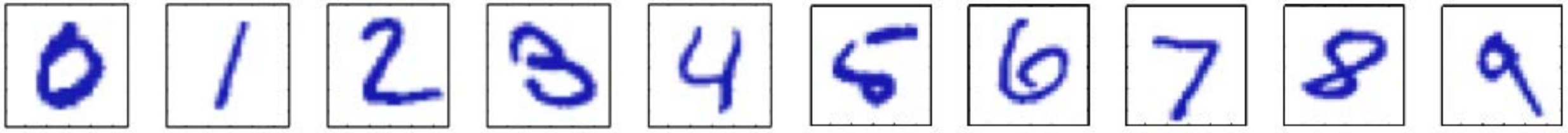
Estimation:

16.2 dB Squeezing

by
Yi-Ru Chen
Chien-Ming Wu

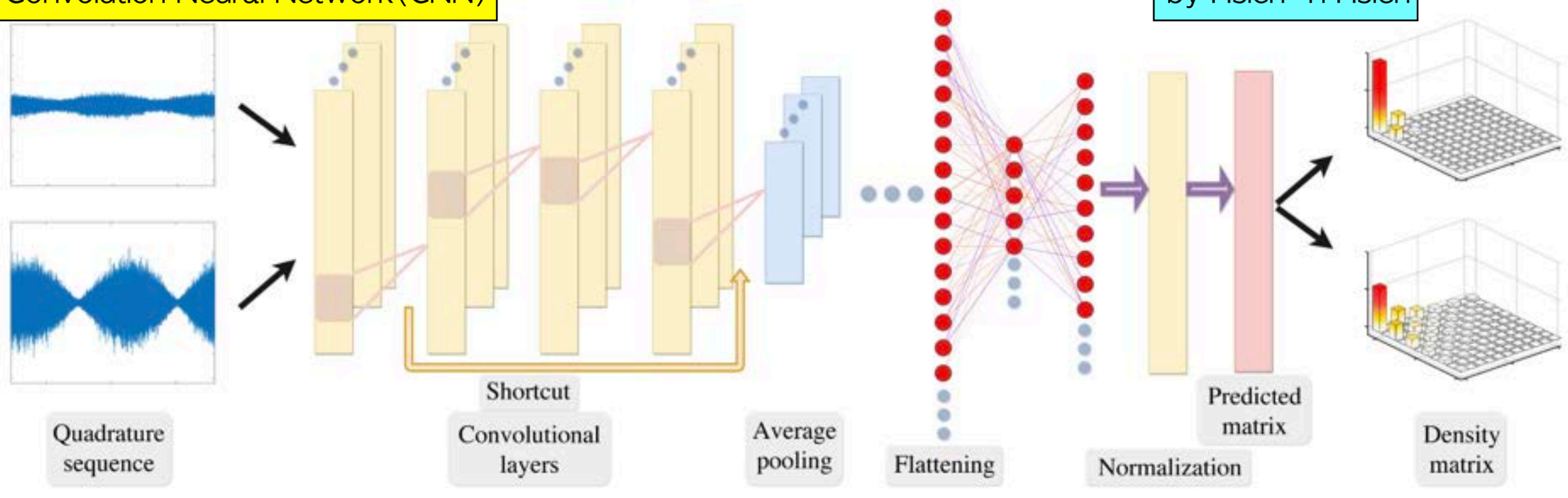
Pattern Recognition & Machine Learning





Convolution Neural Network (CNN)

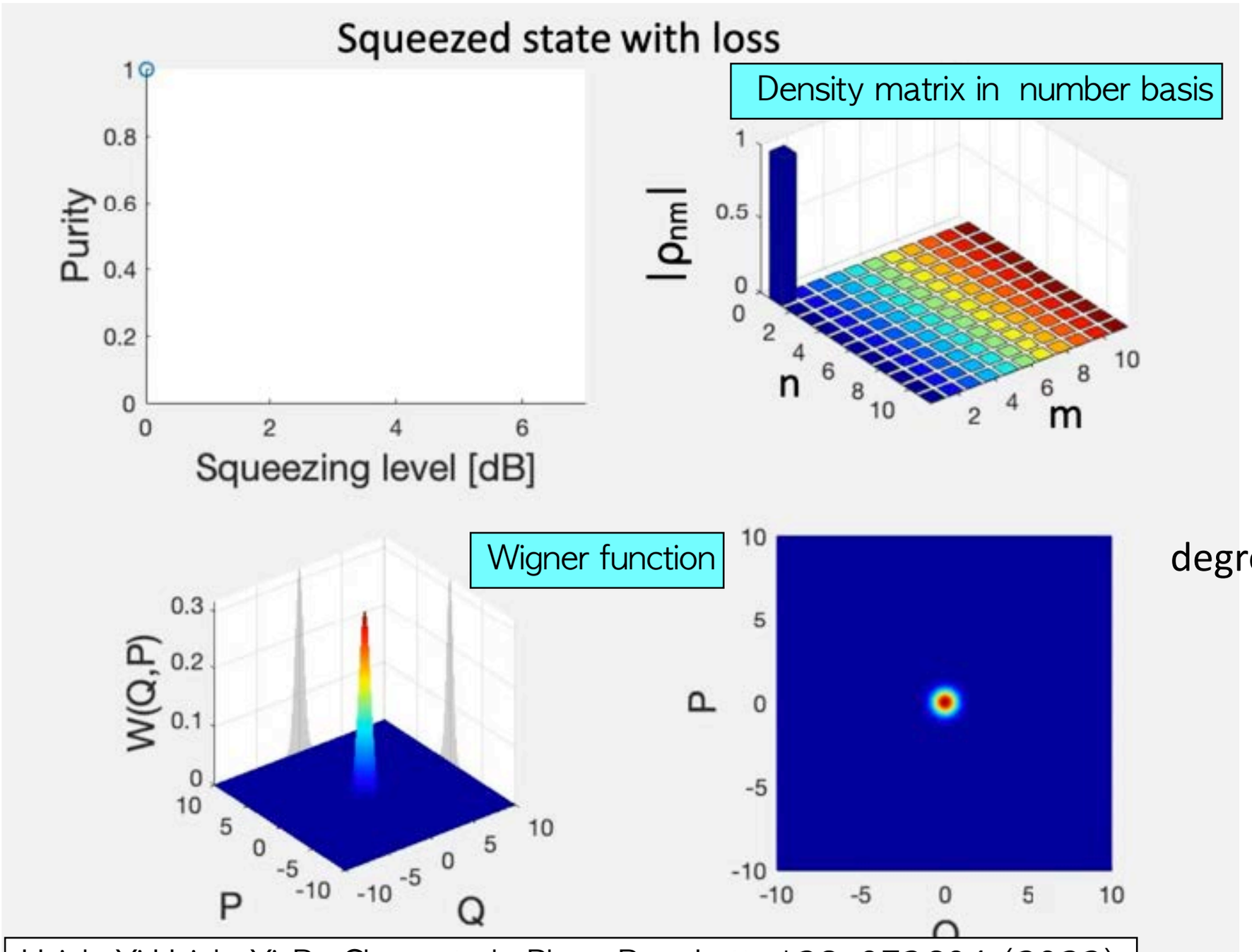
by Hsieh-Yi Hsieh



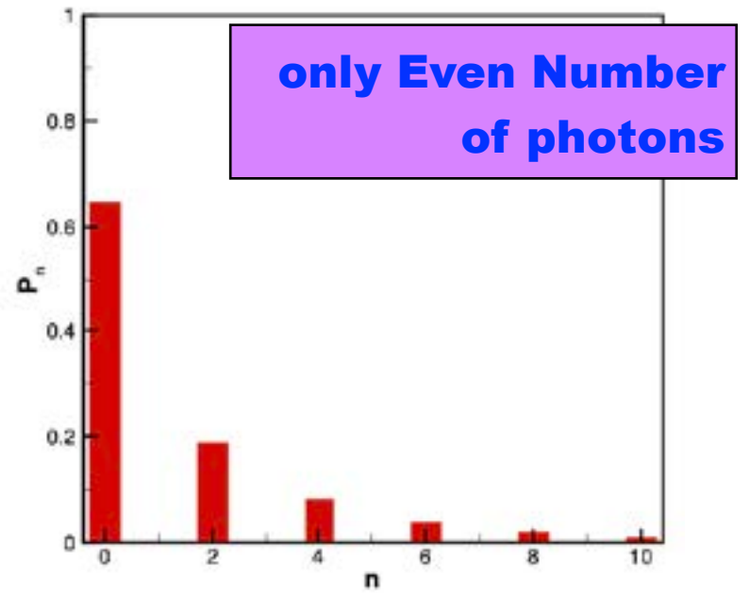
Applications of real-time tomography in squeezed state:

- Monitor the purity of a quantum state in real-time, and reveal the dynamics.
- The purity of a normalized quantum state is a scalar defined as:

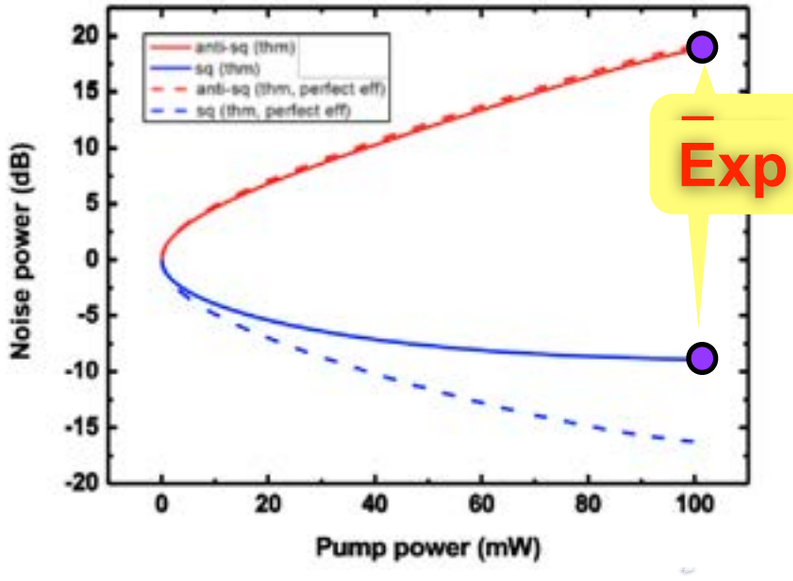
$$\gamma \equiv \mathrm{tr}(\rho^2) \quad , \quad 0 < \gamma \leq 1$$



γ =1 for pure squeezed state

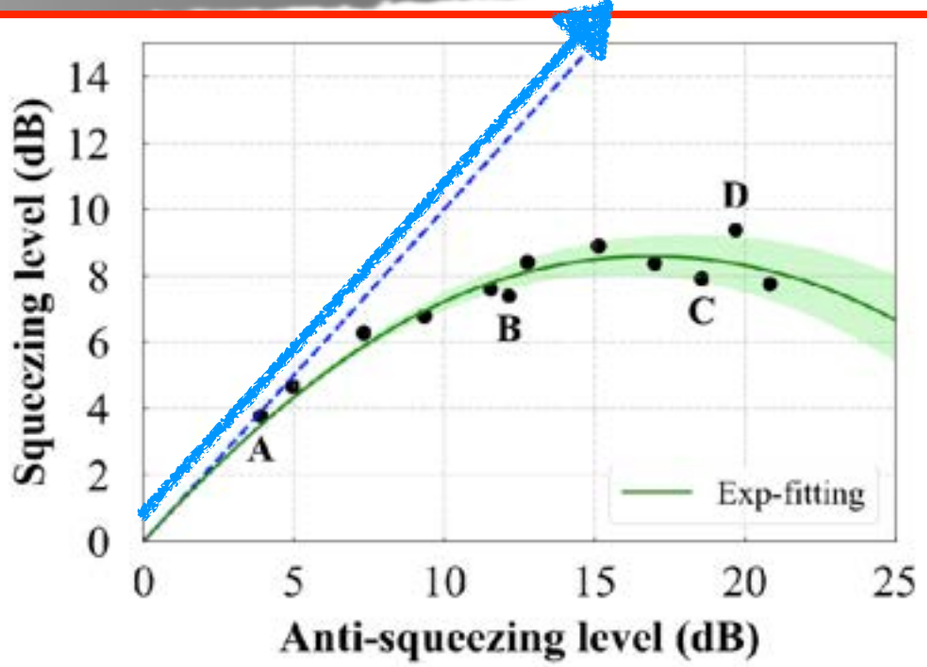


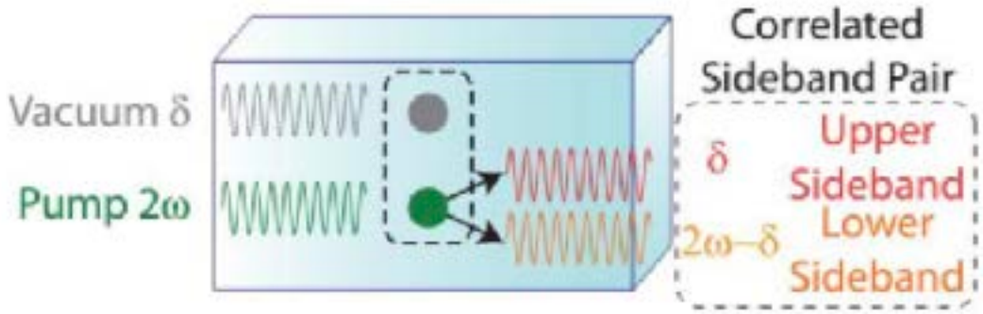
degrees of squeezing/anti-squeezing



Hsieh-Yi Hsieh, Yi-Ru Chen, et al., Phys. Rev. Lett. 128, 073604 (2022).

Degradation: Loss and Phase noise

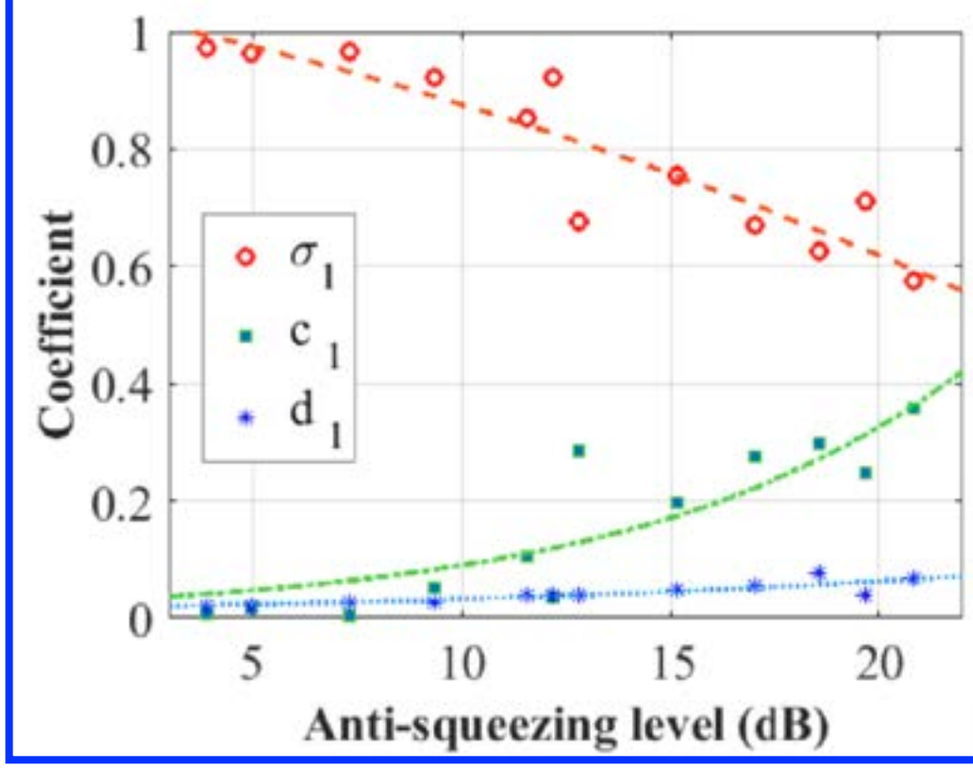




Loss: L
Phase noise: θ

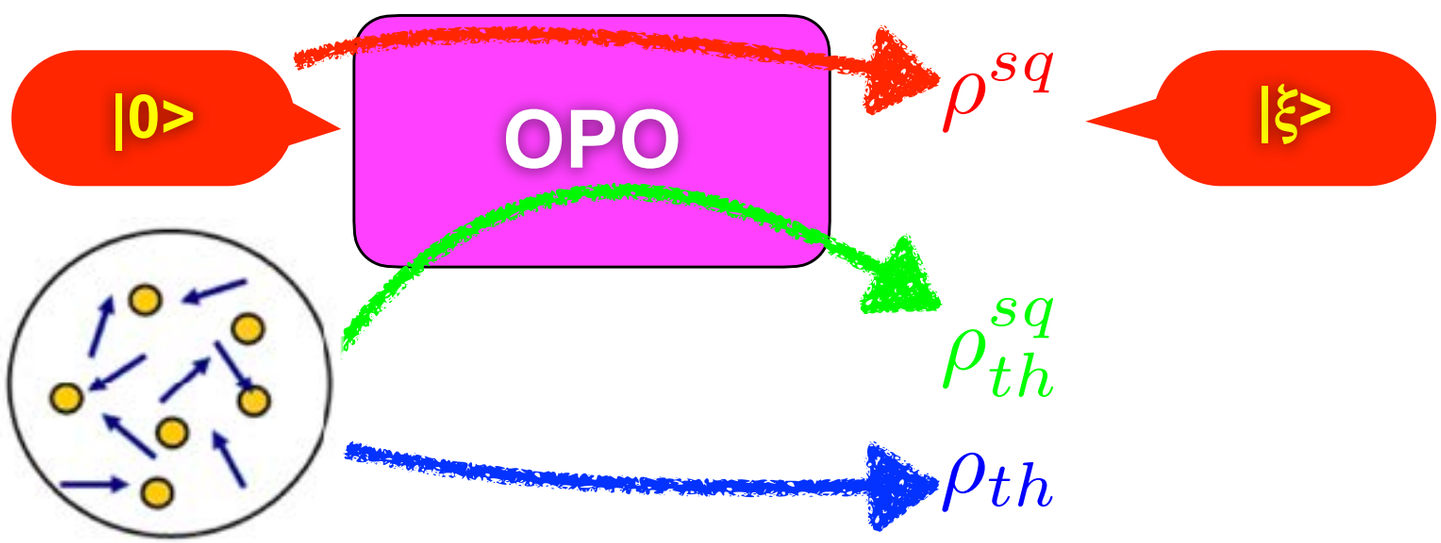
$$V^{\mathrm{sq}} = (1-L)[V^{\mathrm{sq}}_{\mathrm{id}} \times \cos^2\theta + V^{\mathrm{as}}_{\mathrm{id}} \times \sin^2\theta] + L,$$

$$V^{\mathrm{as}} = (1-L)[V^{\mathrm{as}}_{\mathrm{id}} \times \cos^2\theta + V^{\mathrm{sq}}_{\mathrm{id}} \times \sin^2\theta] + L,$$



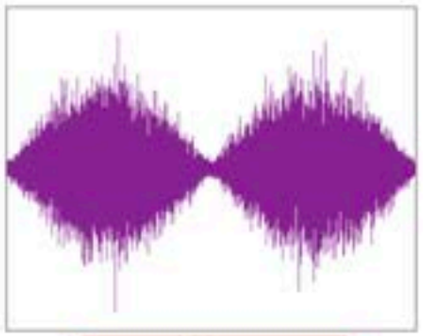
$$\rho = \sigma_1 \rho^{sq} + c_1 \rho^{sq}_{th} + d_1 \rho_{th}$$

SVD



H.-Y. Hsieh, et al., Phys. Rev. Lett. 128, 073604 (2022).

ML: Direct Parameter Estimations



quadrature sequence

1D-CNN kernel

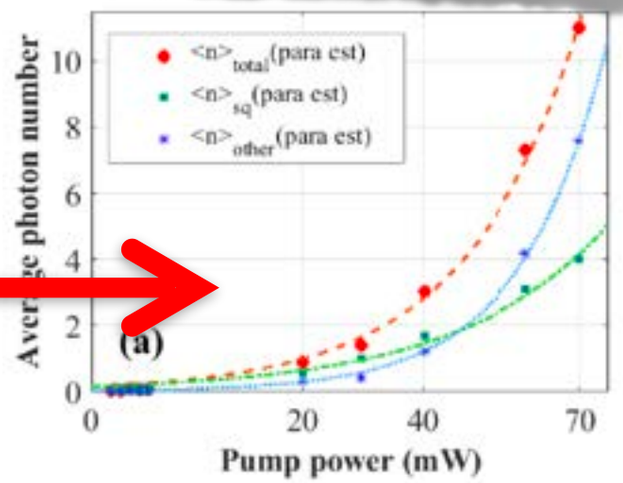
flattening

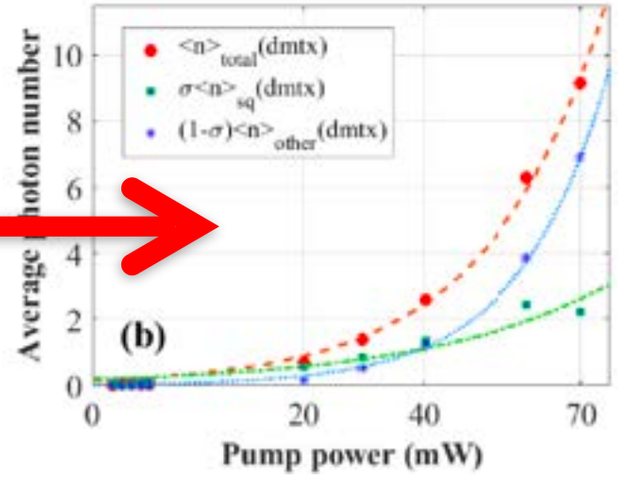
extra fully connected layers

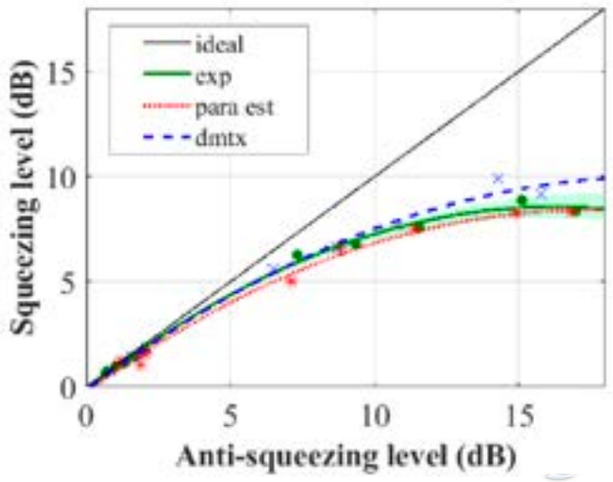
1
2
3

physical parameters

density matrix



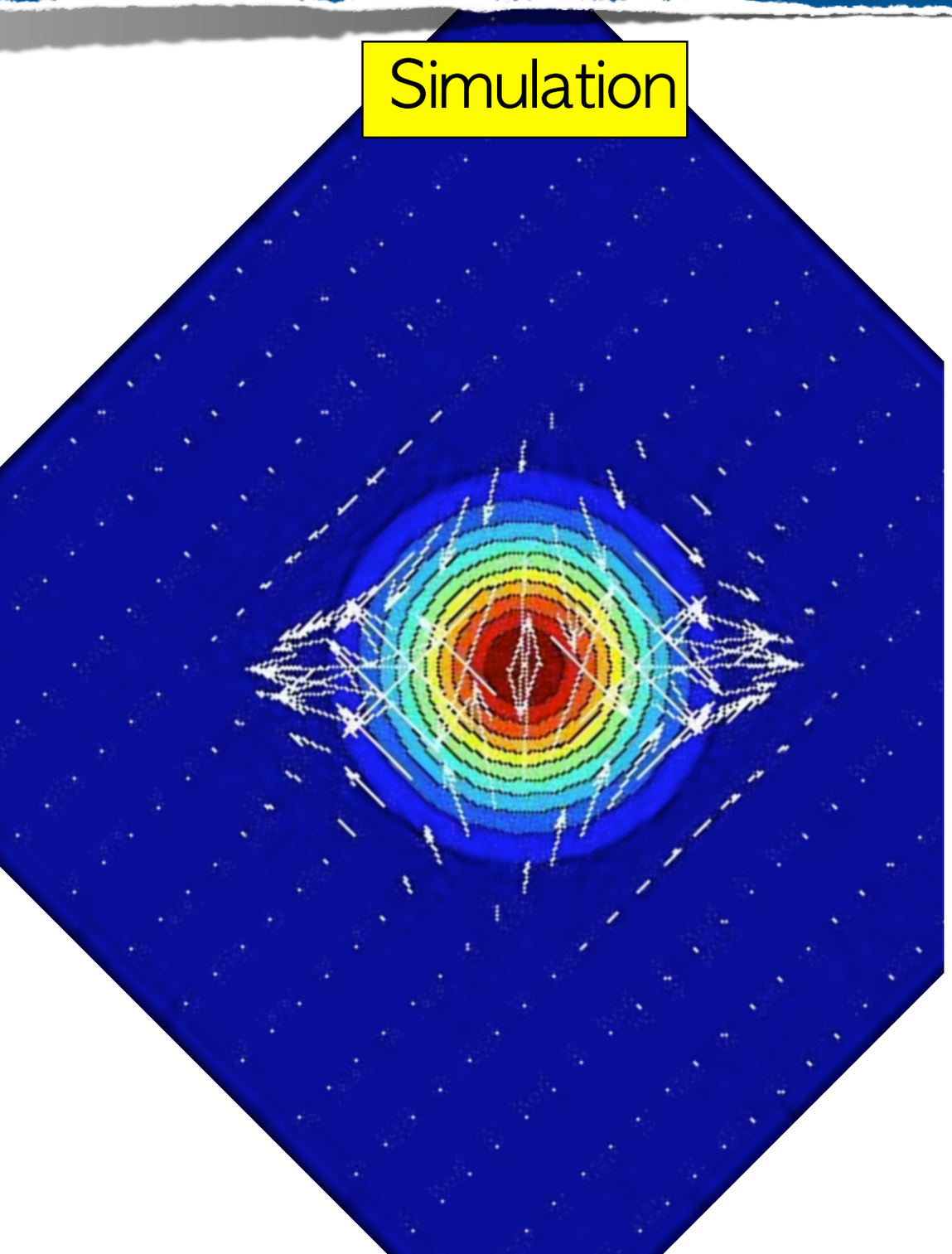




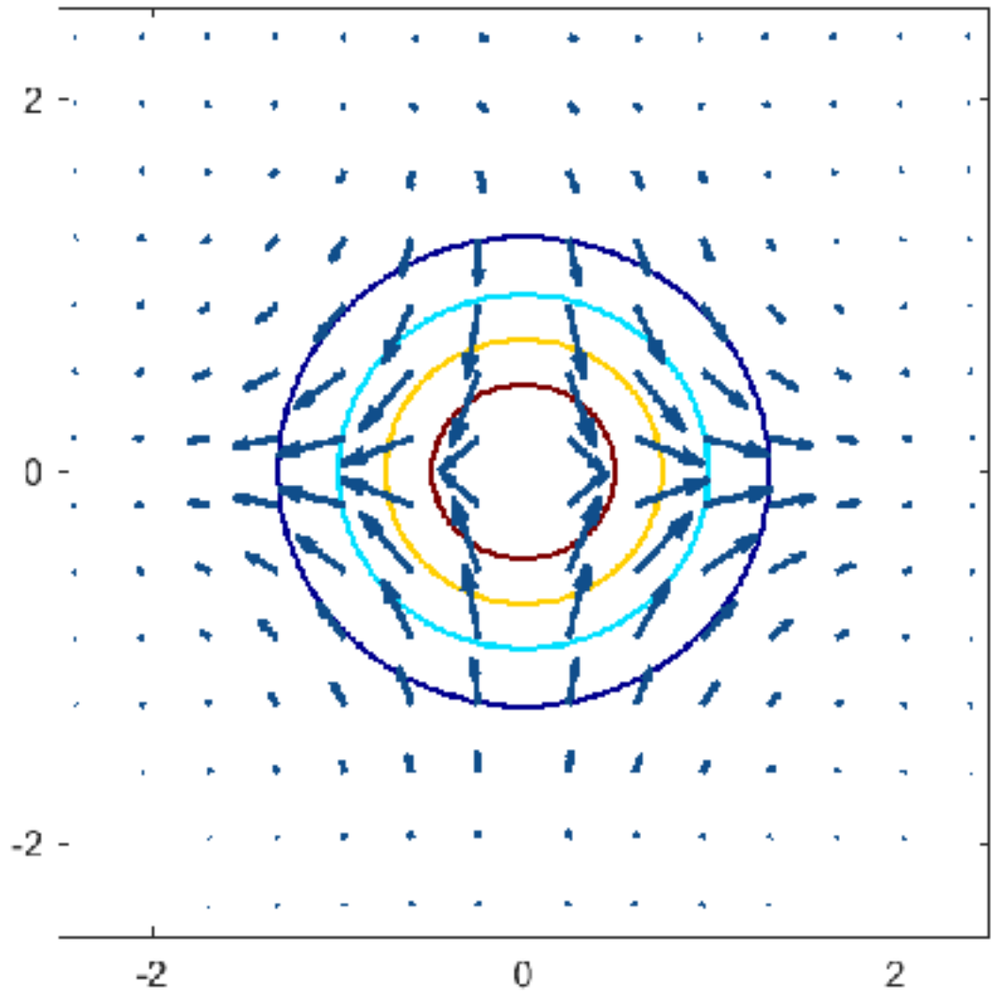
H.-Y. Hsieh, et al., Symmetry 14, 874(2022);
Special Issue "Quantum Optimization & Machine Learning";

Dynamics of Squeezers

Simulation

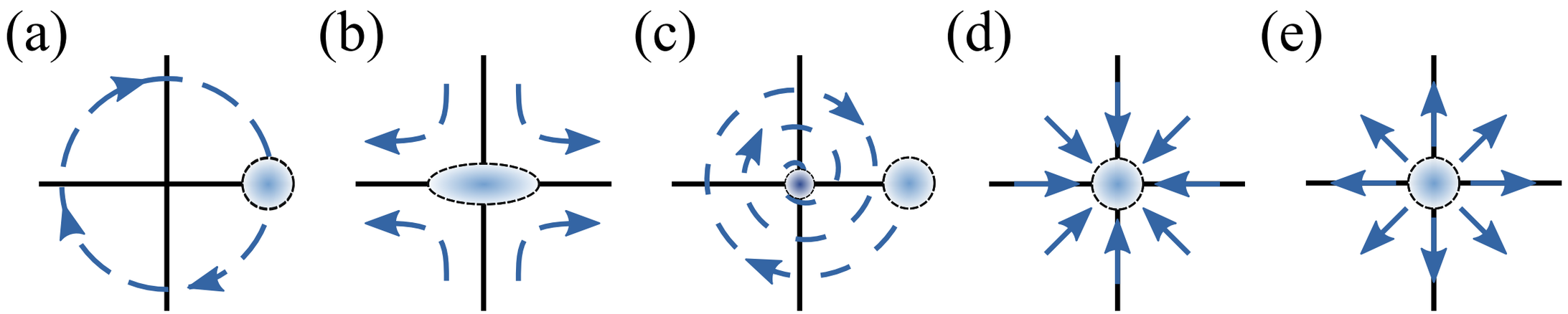


Exp. Reconstruction

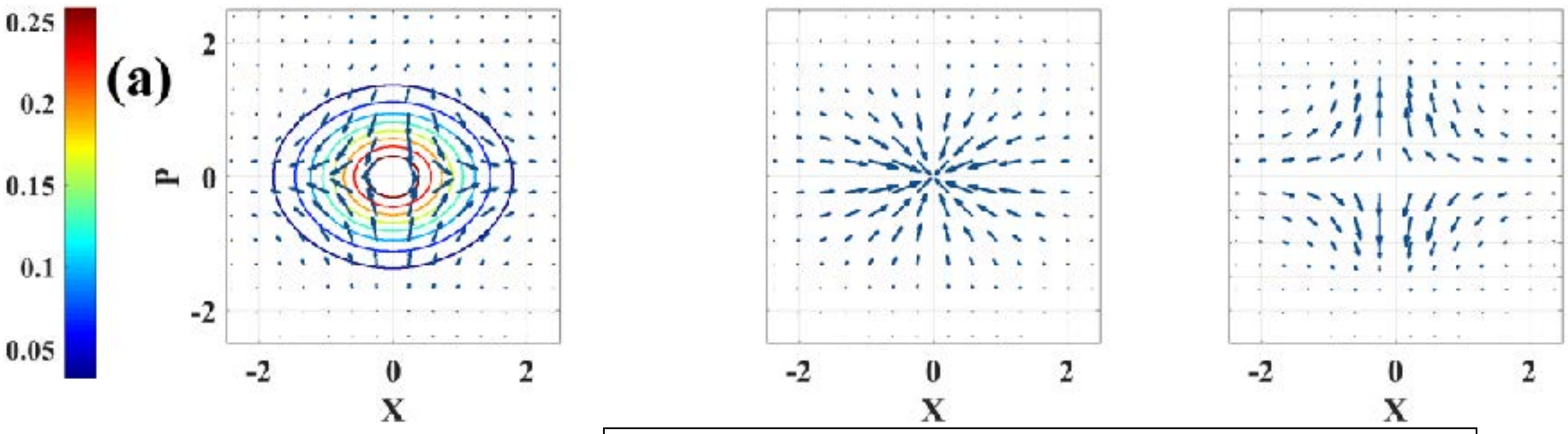


Yi-Ru Chen et al., Phys. Rev. A 108, 023729 (2023).

Topological Charges:



$\omega = +1$ $\omega = -1$ $\omega = +1$ $\omega = +1$ $\omega = +1$

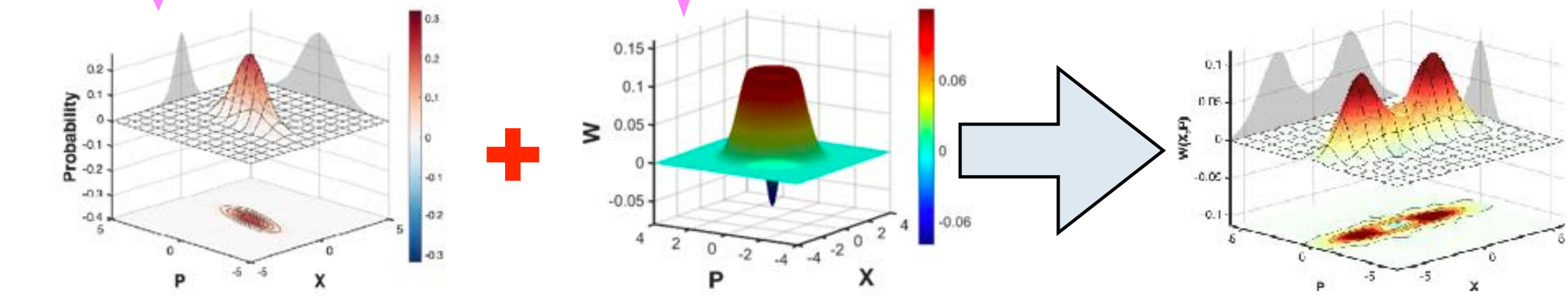


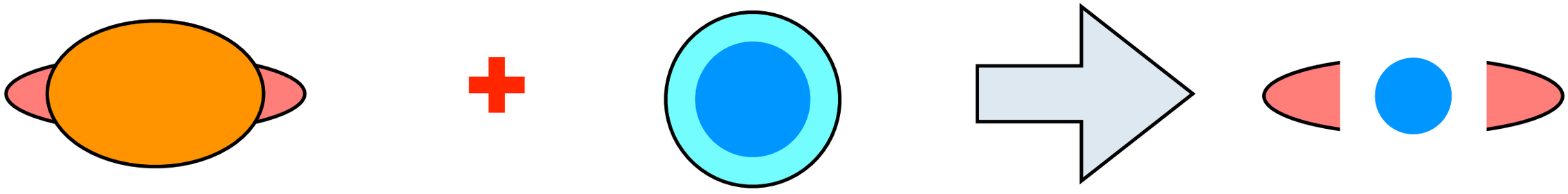
Yi-Ru Chen et al., Phys. Rev. A 108, 023729 (2023).

Photon-Addition

SQZ, |ξ>

Single-photon, |n=1>





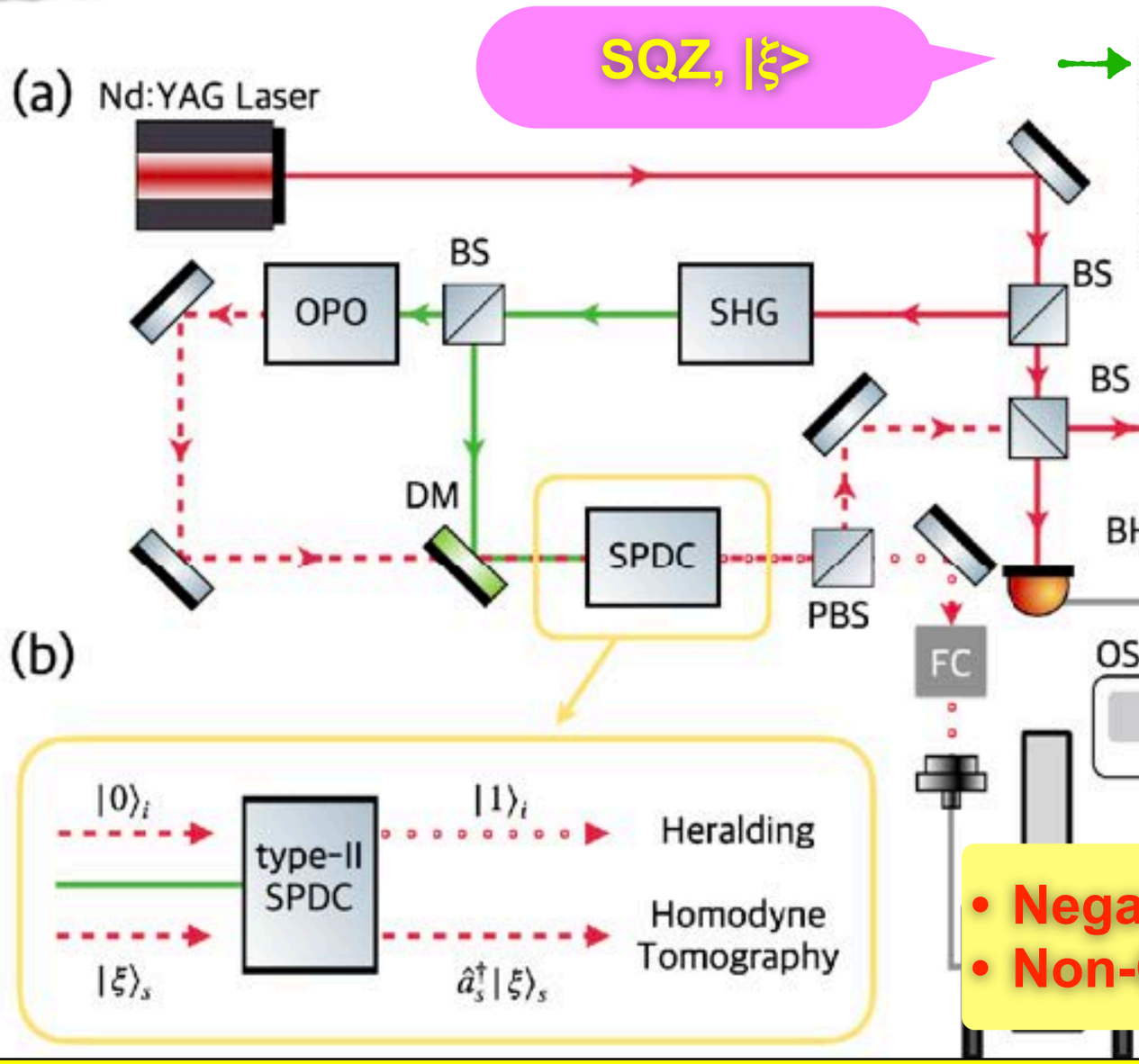
$\hat{a}^\dagger \hat{S}|0\rangle$

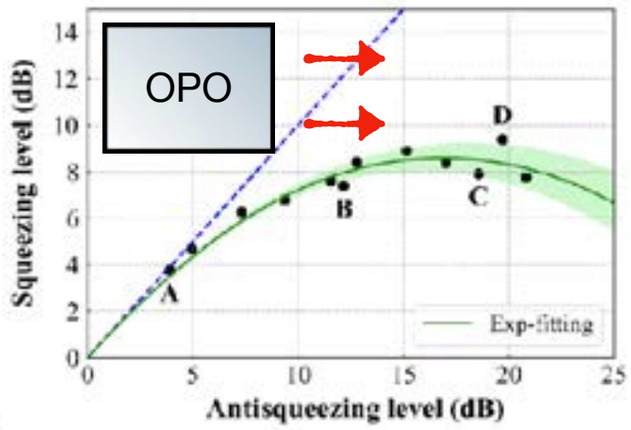
SPDC

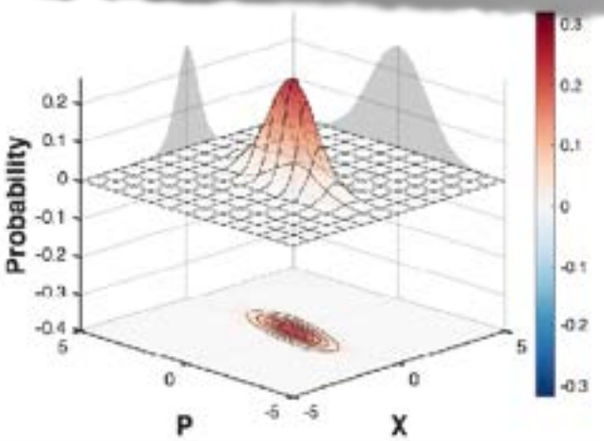
$$\hat{S}(g) = e^{g(\hat{a}_1\hat{a}_2 - \hat{a}_1^\dagger\hat{a}_2^\dagger)} \approx 1 + g(\hat{a}_1\hat{a}_2 - \hat{a}_1^\dagger\hat{a}_2^\dagger)$$

$$\hat{S}(g)\hat{S}|0\rangle_1|0\rangle_2 \approx \hat{S}|0\rangle_1|0\rangle_2 - g\hat{a}_1^\dagger\hat{S}|0\rangle_1|1\rangle_2$$

Optical Cat states: by photon-addition

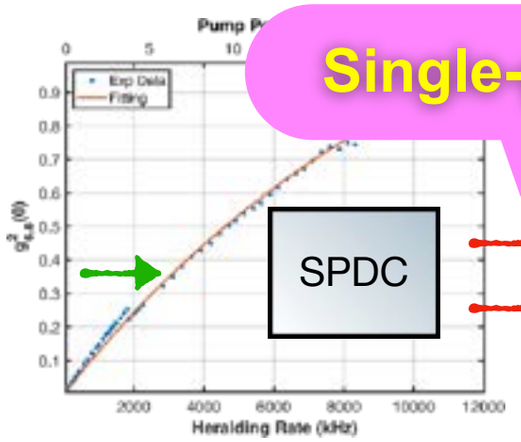


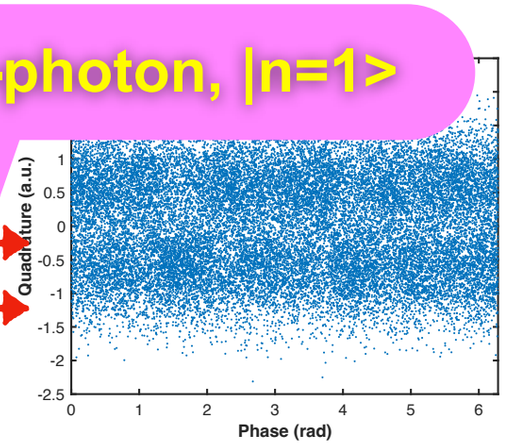




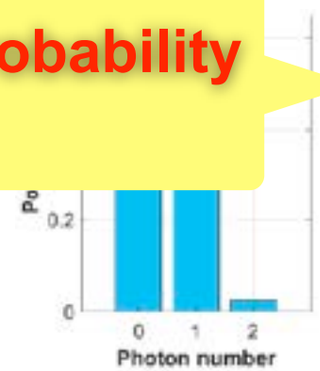
Hsieh-Yi Hsieh, et al., PRL 128, 073604 (2022).

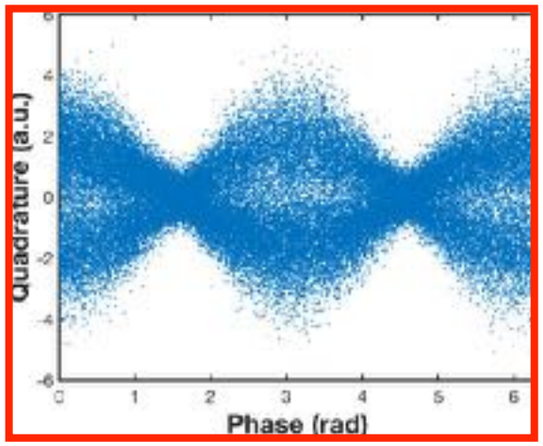
Single-photon, |n=1>





- **Negativity in Probability**
- **Non-Gaussian**





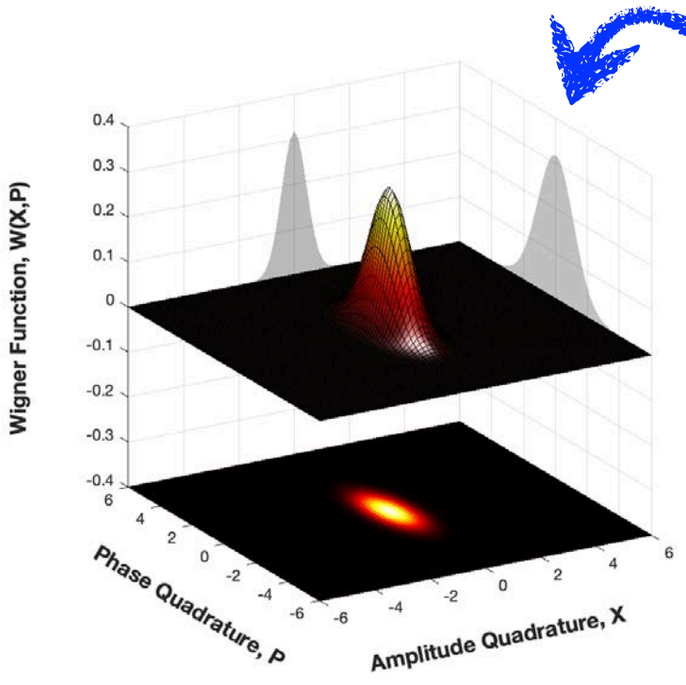
The First Experimental Realization with photo-addition.

Yi-Ru Chen et al., arXiv:2306.13011 (2023).

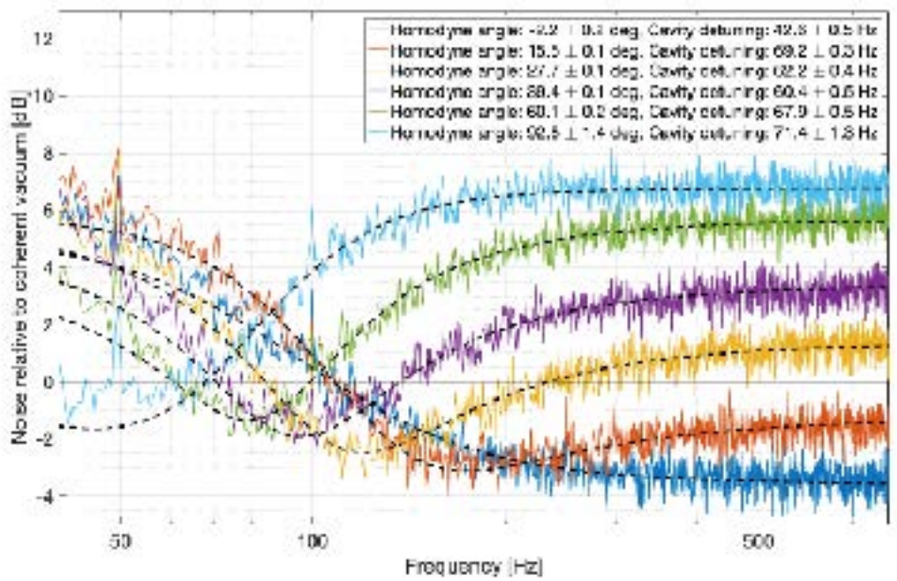
Neural network enhanced single-photon Fock state tomography, Invited paper to Adv. Quant. Tech. (2024).

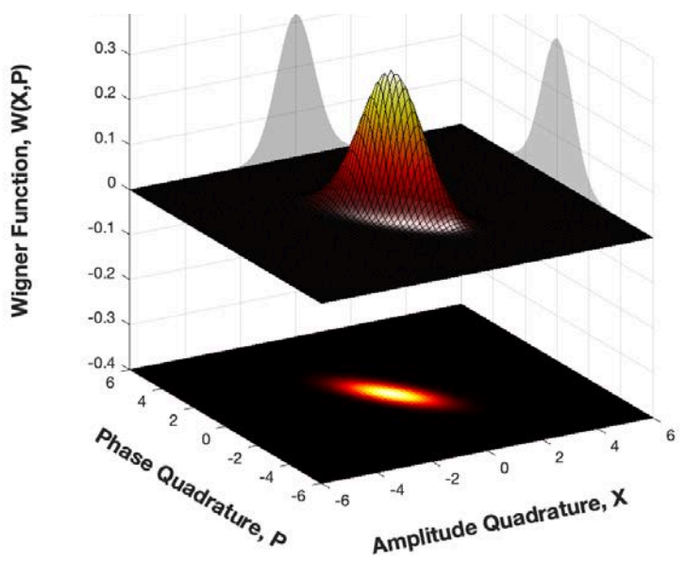
Quantum State Tomography:

Can we Monitor the purity of the quantum state?

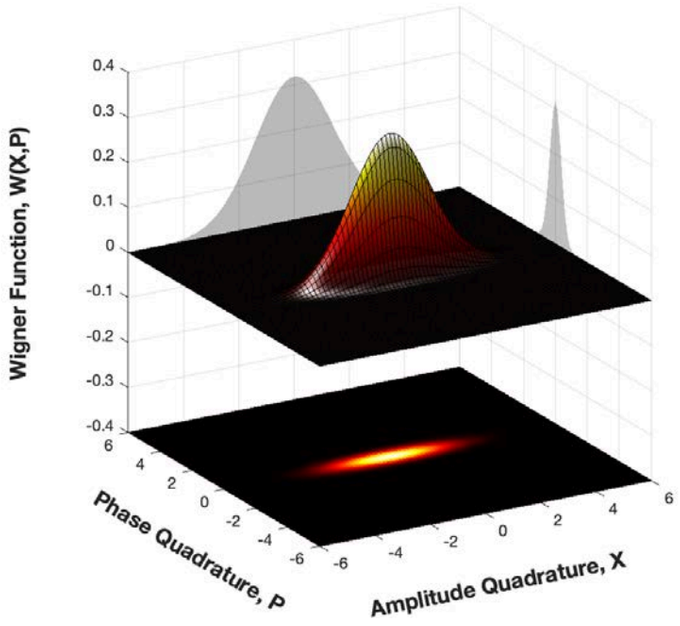


Low frequency region





Middle frequency region



High frequency region

Frequency dependent squeezing experiment

フリクエンシー

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Dr. Marc Eisenmann (NAOJ)

Prof. Yoichi Aso (NAOJ)

Miss Hua Li Chen (NTHU)

Miss Yi-Ru Chen (NTHU)

KAGRA

NAOJ, Feb. 2023

TSING HUA UNIVERSITY

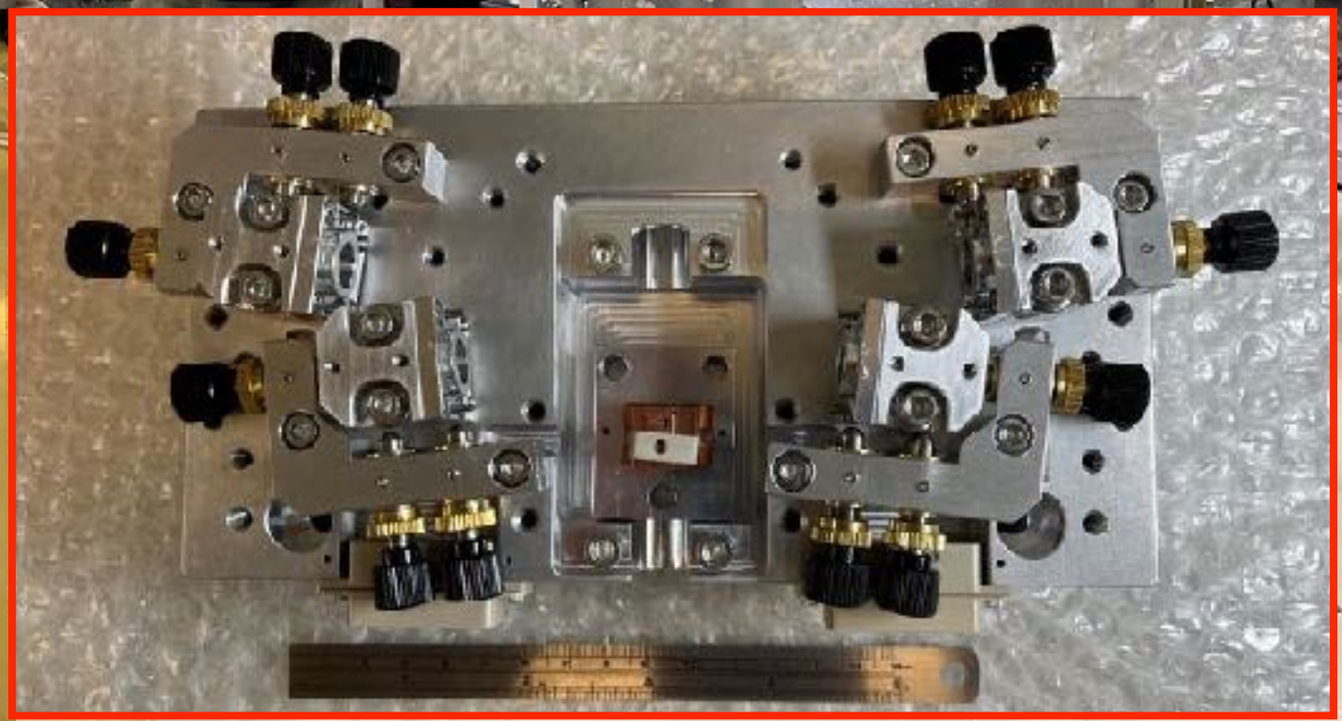
Zi-Hao Shi (NTHU)

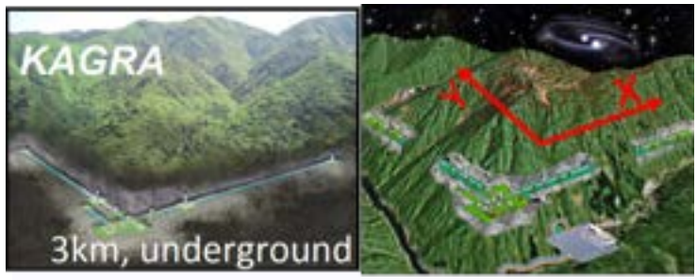
Dr. Yi-Ru Chen (NTHU)

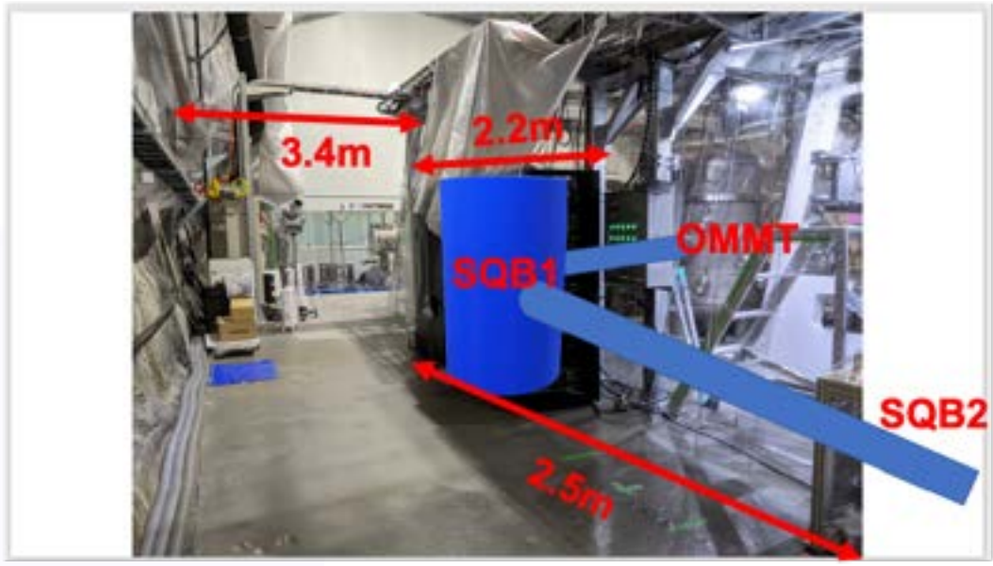
Dr. Marc Eisenmann (NAOJ)

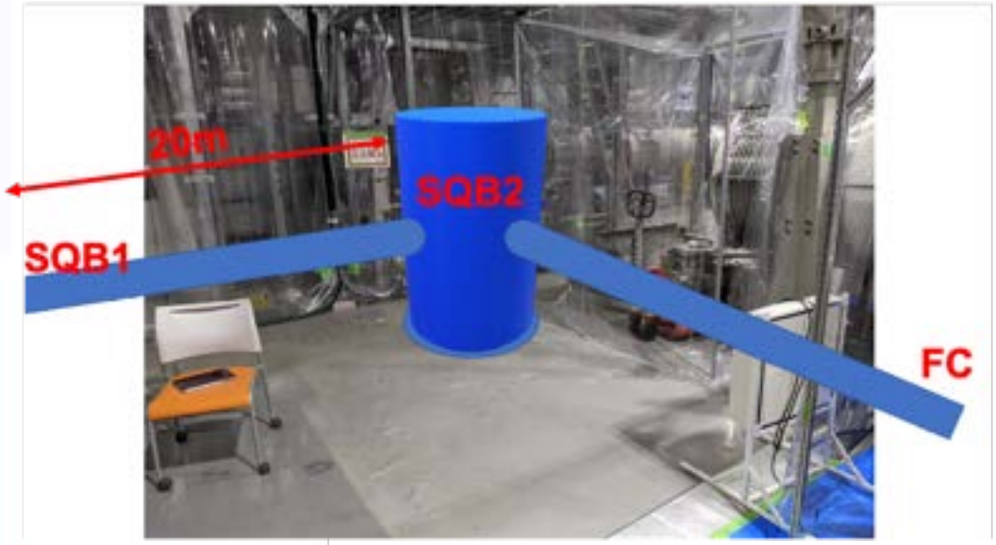
Dr. Yuhang Zhao (APC, U. Paris-7)

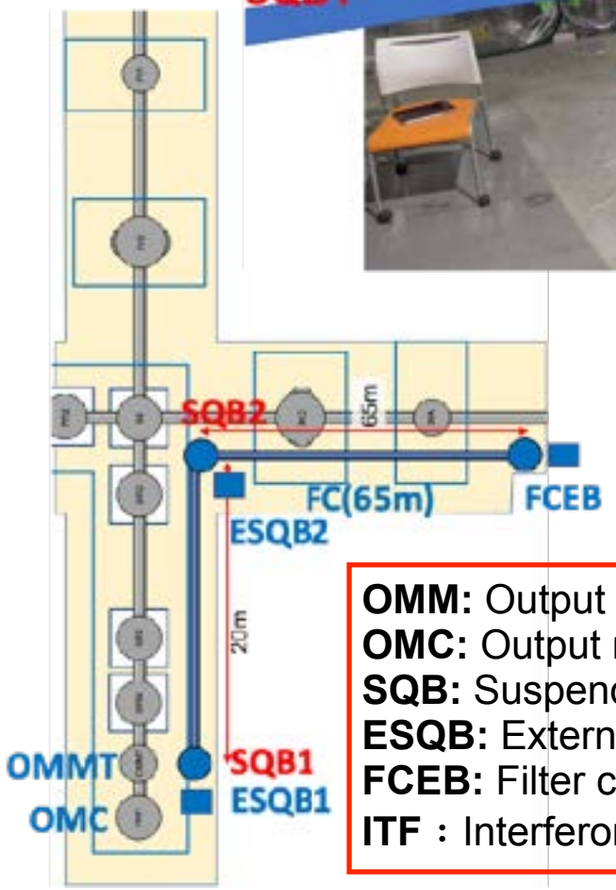
NAOJ, Dec. 2023









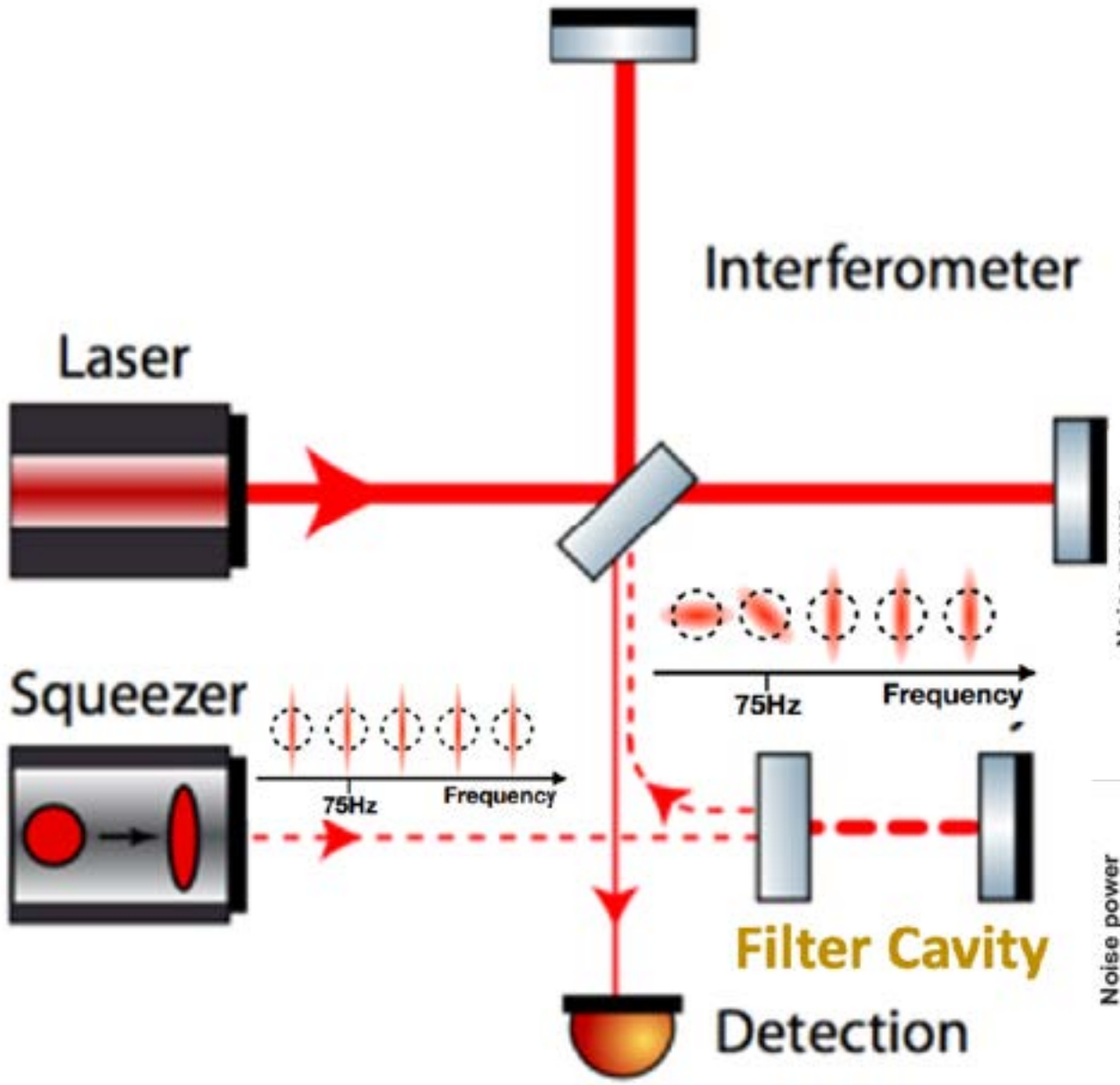


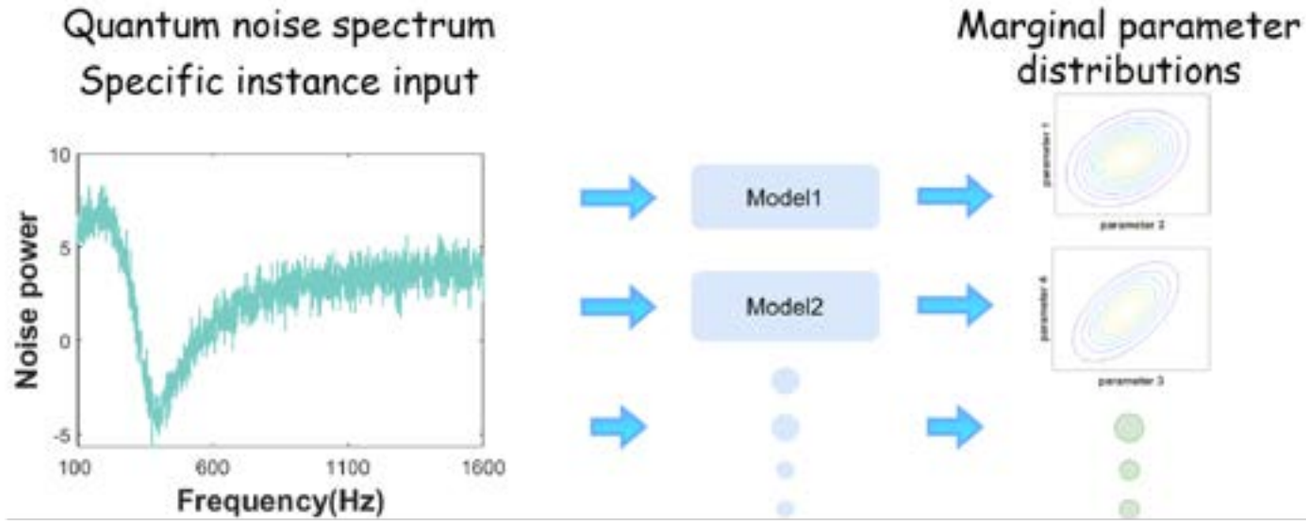
by Hua Li Chen

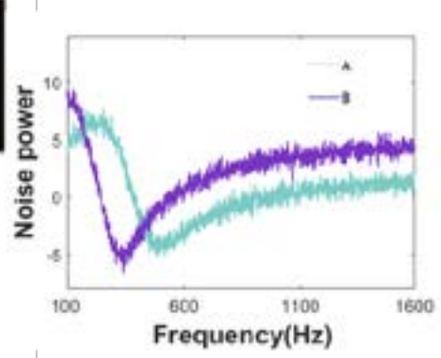
OMM: Output mode matching
OMC: Output mode cleaner
SQB: Suspended squeezing Bench
ESQB: External Suspended squeezing Bench
FCEB: Filter cavity external bench
ITF：Interferometer

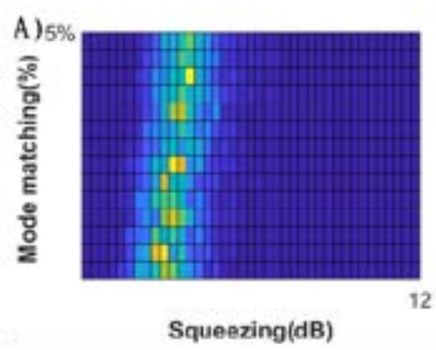
Machine-Learning for FDS

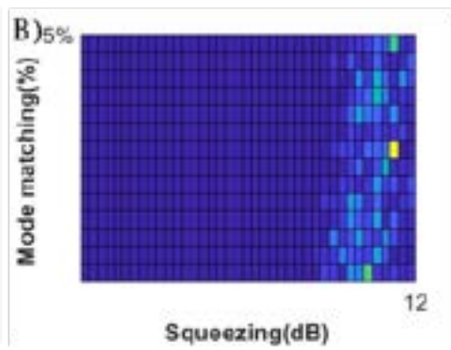
Multi-Parameters
Bayesian Estimation

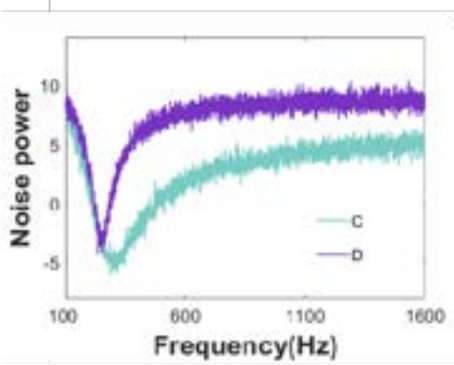


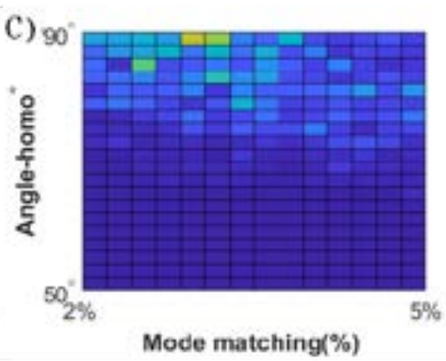


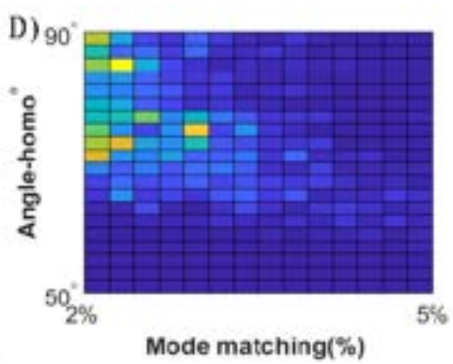




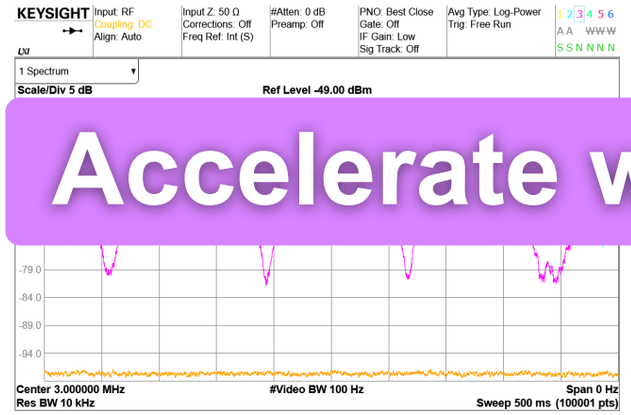








Summary



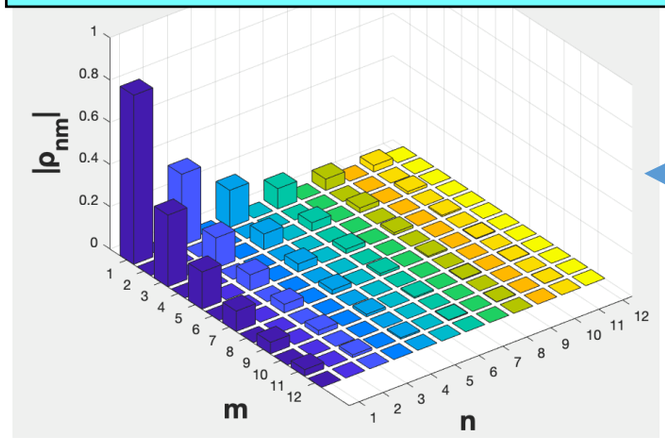
Accelerate with ML, but also Re-use training data

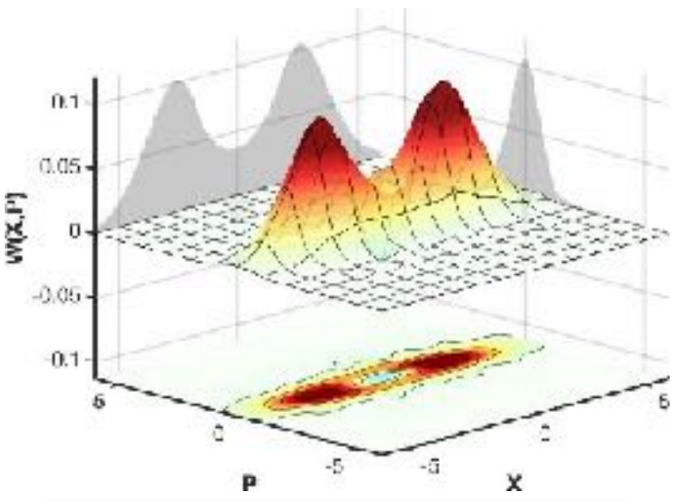
Local Oscillator

Max. Likelihood Estimation, MLE

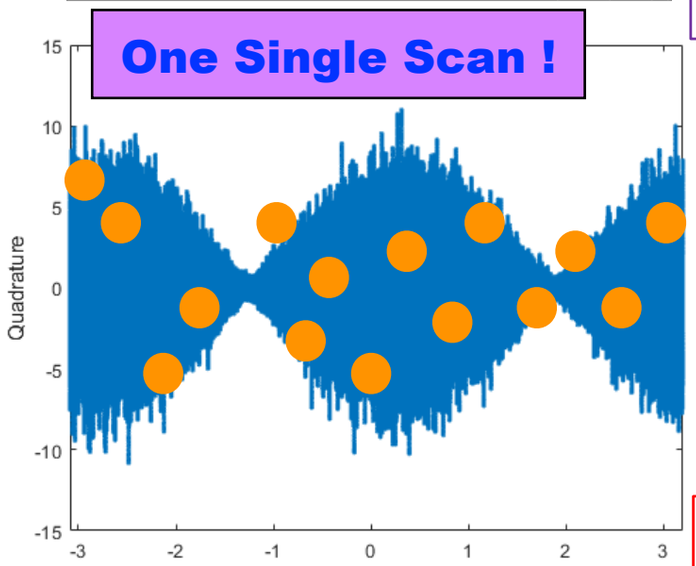
few minutes
to reconstruct

Density matrix in number basis





arXiv:2306.13011 (2023);



< 1s to
reconstruct

Machine Learning (SQ Learner), CNN

Phys. Rev. Lett. 128, 073604 (2022);

ADVANCES IN PHYSICS: X
2023, VOL. 8, NO. 1, 2165452
https://doi.org/10.1080/23746149.2023.2165452

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REVIEW

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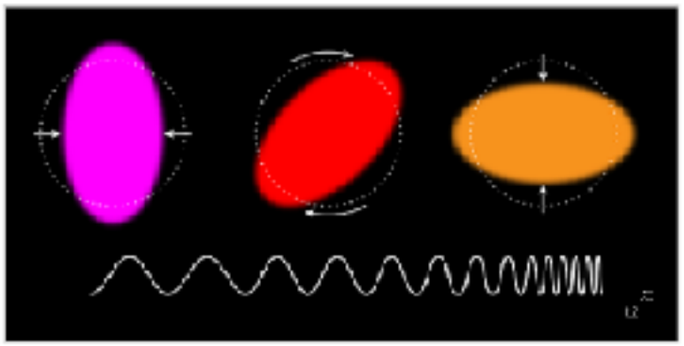
Quantum machine learning: from physics to software engineering

Alexey Melnikov[a], Mohammad Kordzanganeh[a], Alexander Alodjants[b] and Ray-Kuang Lee[c,d,e,f]



Machine-Learning for FDS

ありがとうございました

Thanks for your attentions ^.^