

Filter cavity experiments

for Frequency Dependent Squeezed light source for KAGRA

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National Tsing Hua University (NTHU), Taiwan

Shinji Miyoki (ICRR)

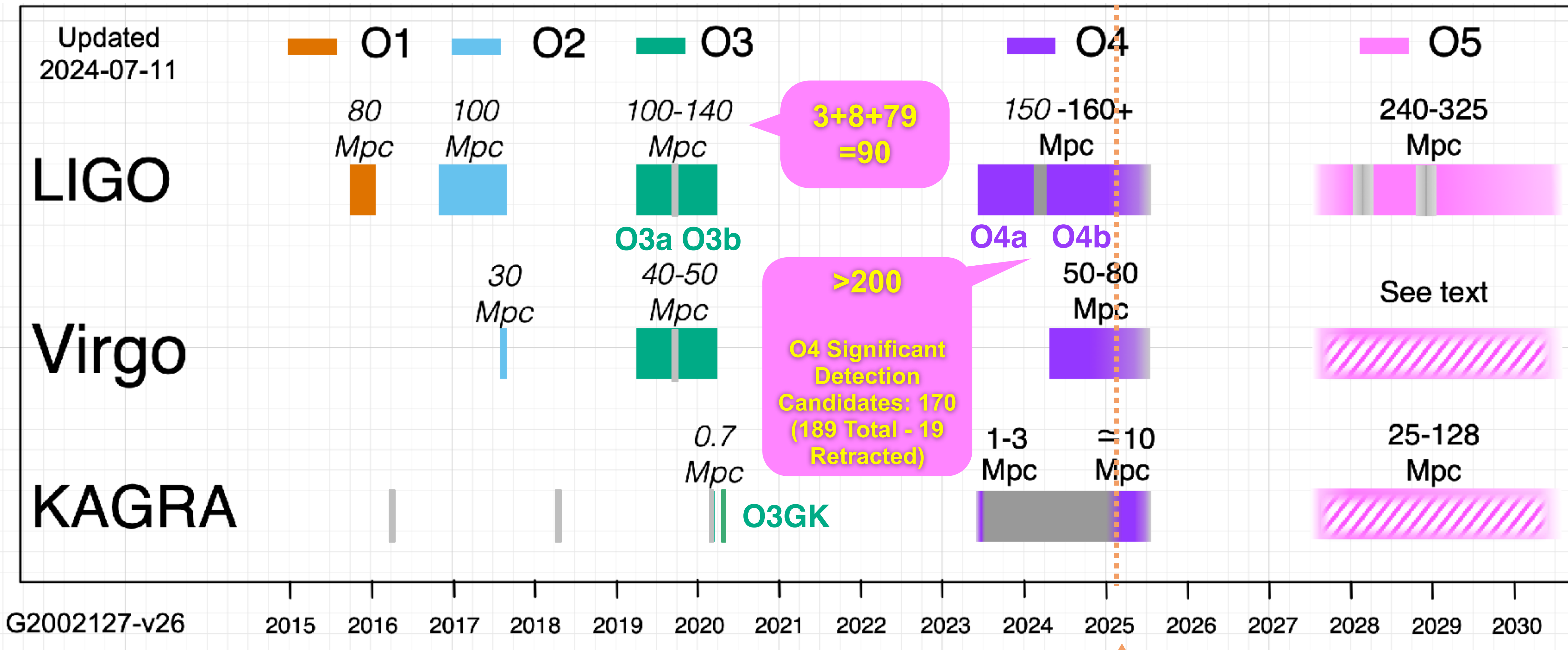
(+Marc Eisenmann, Michael Page, Yoichi Aso, Takayuki Tomaru, NAOJ)





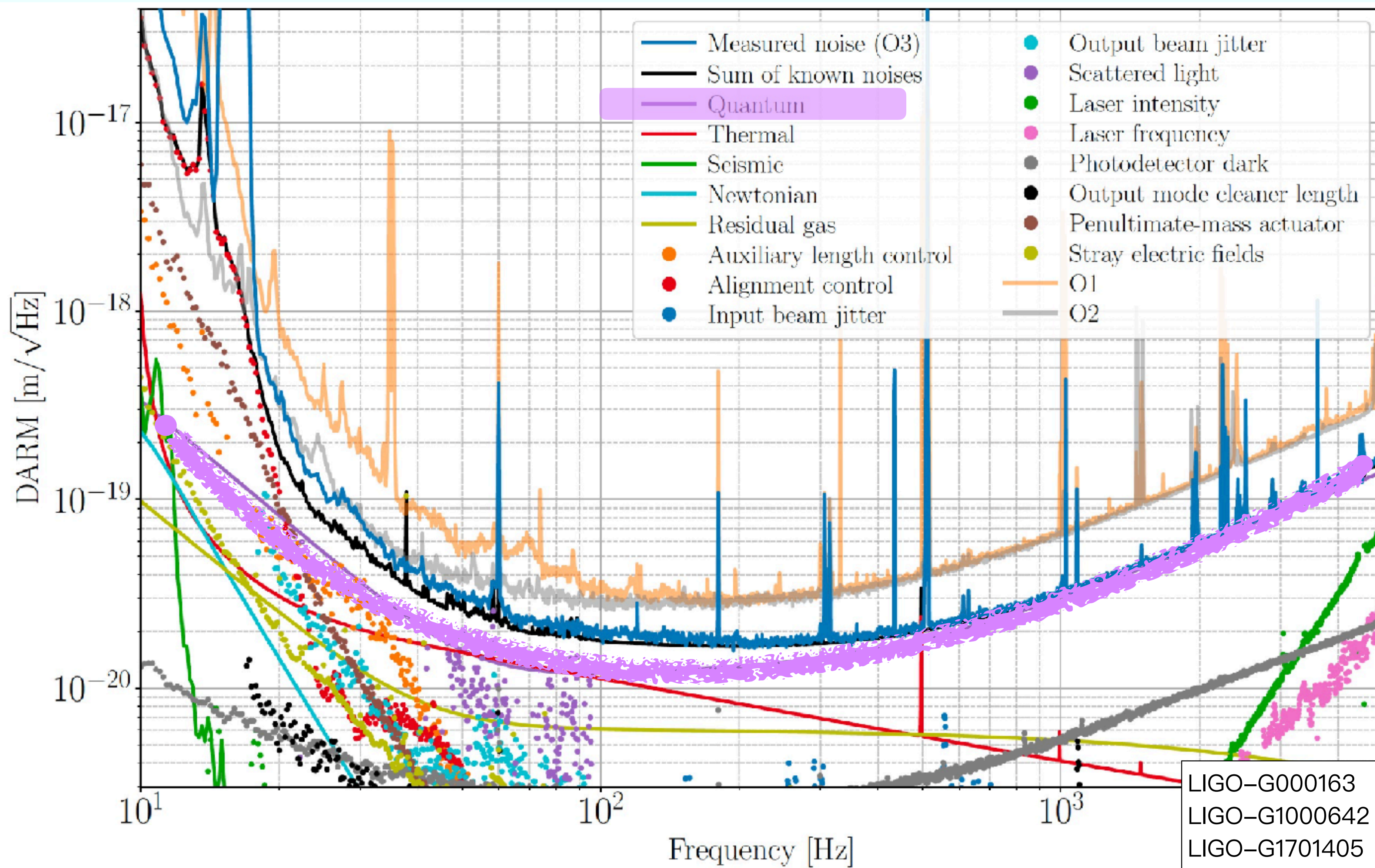
Observing Run Plans

<https://observing.docs.ligo.org/plan/>



KAGRA is going to join O4b in Spring, 2025

Noise Budget:



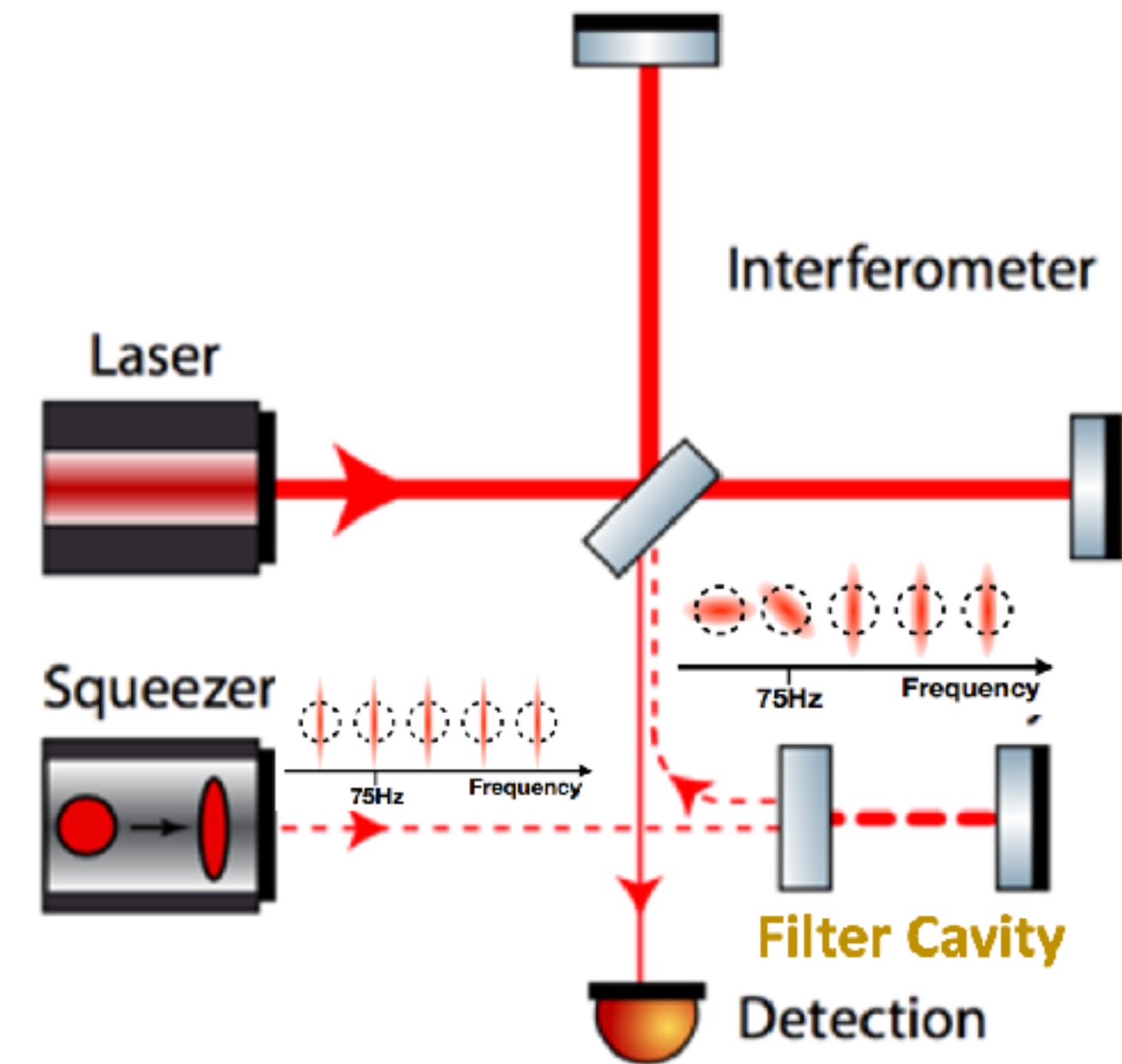
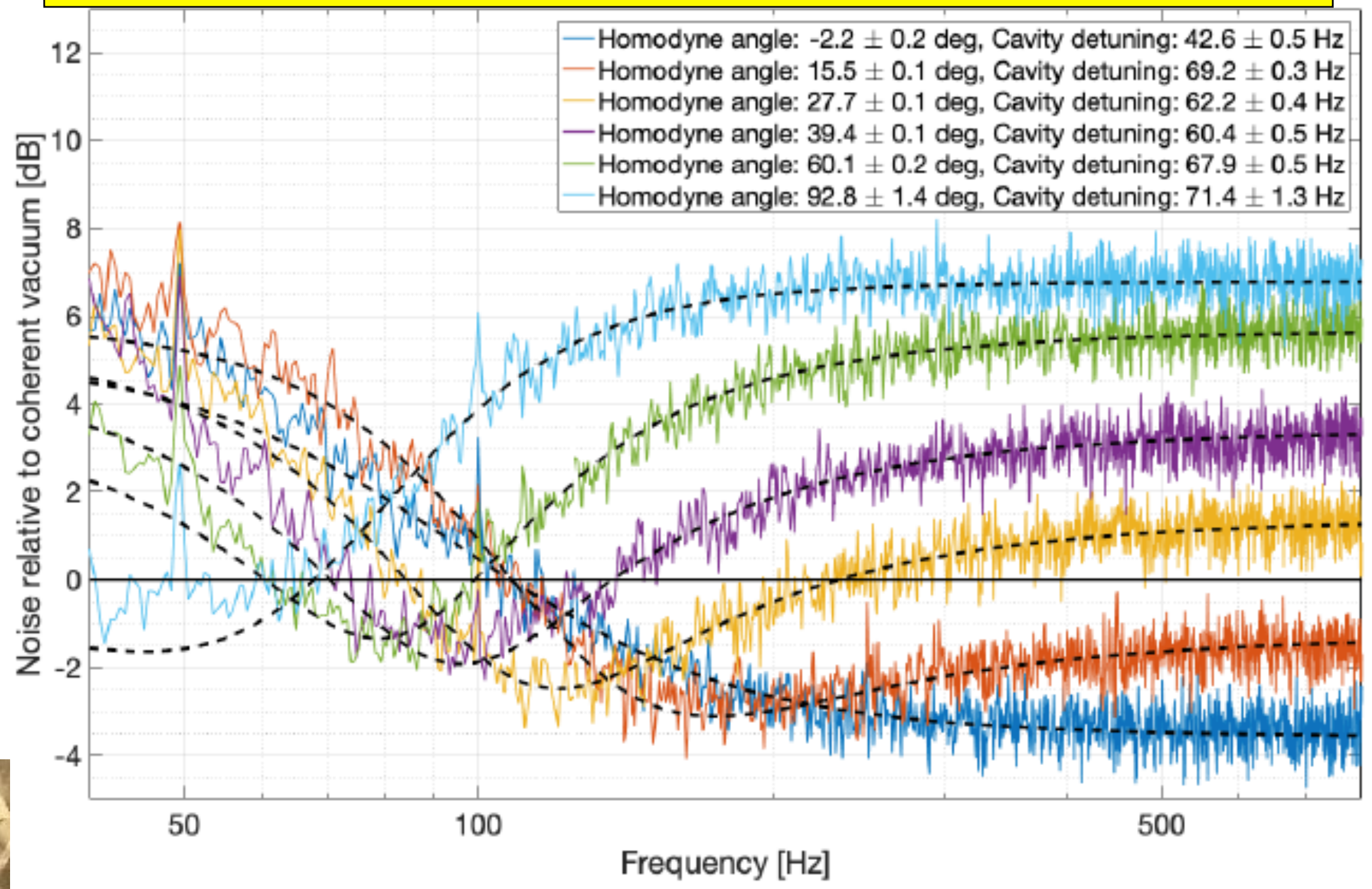
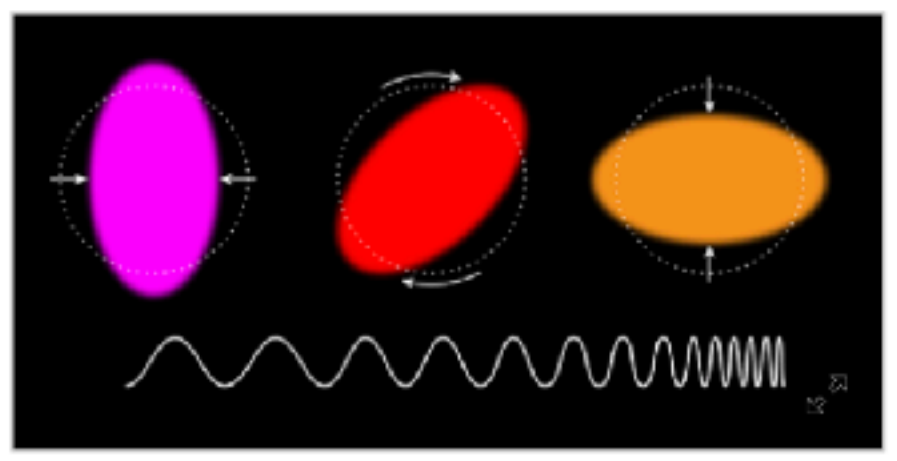
Frequency Dependent Squeezing (FDS)

The First Experimental Realization of FDS at 70 Hz.

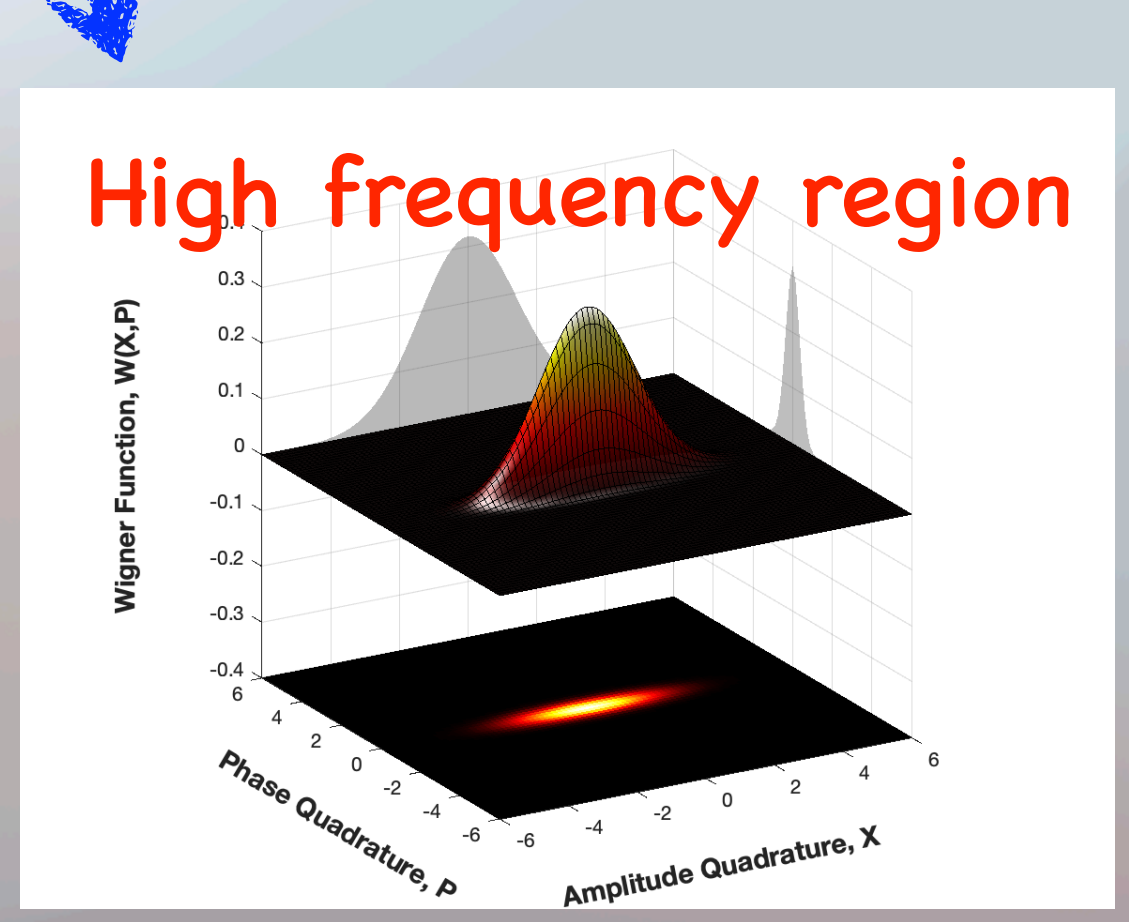
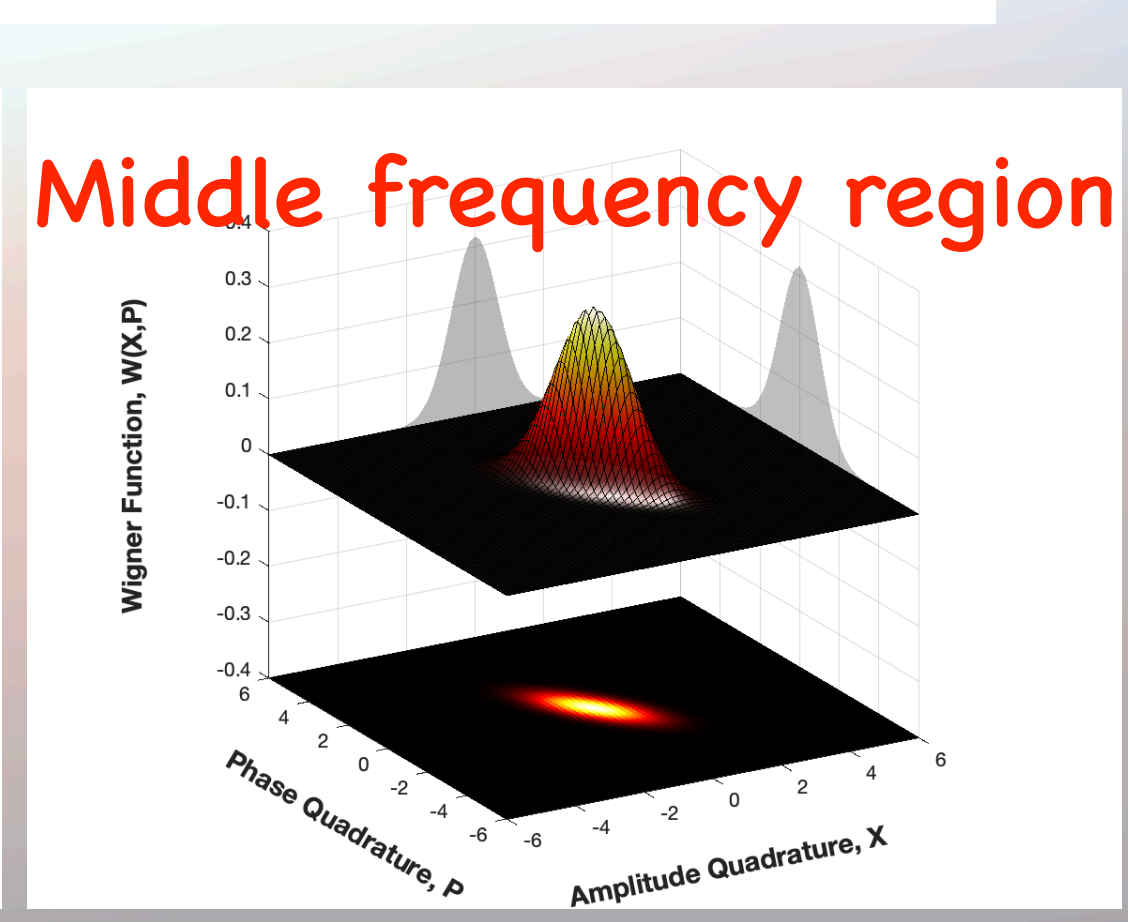
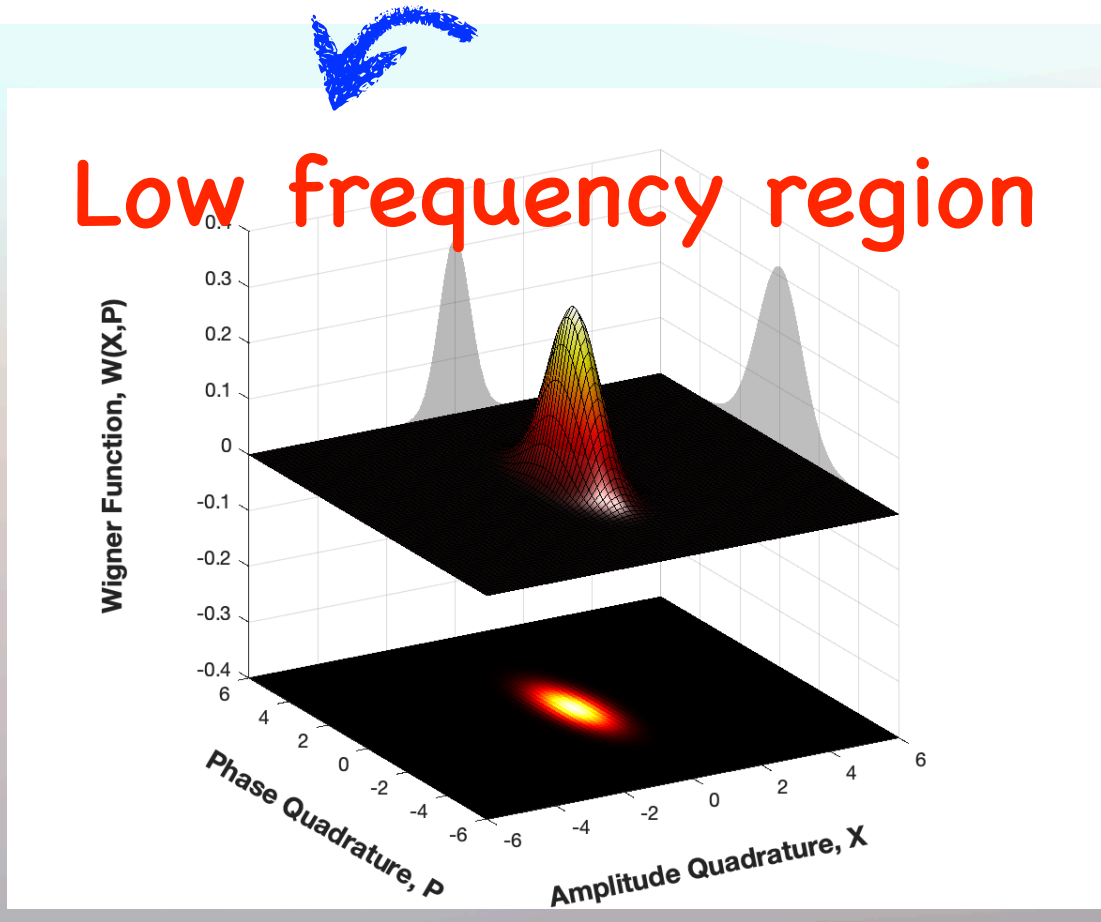
Physics ABOUT BROWSE PRESS COLLECTIONS

Synopsis: Feeling the Squeeze at All Frequencies

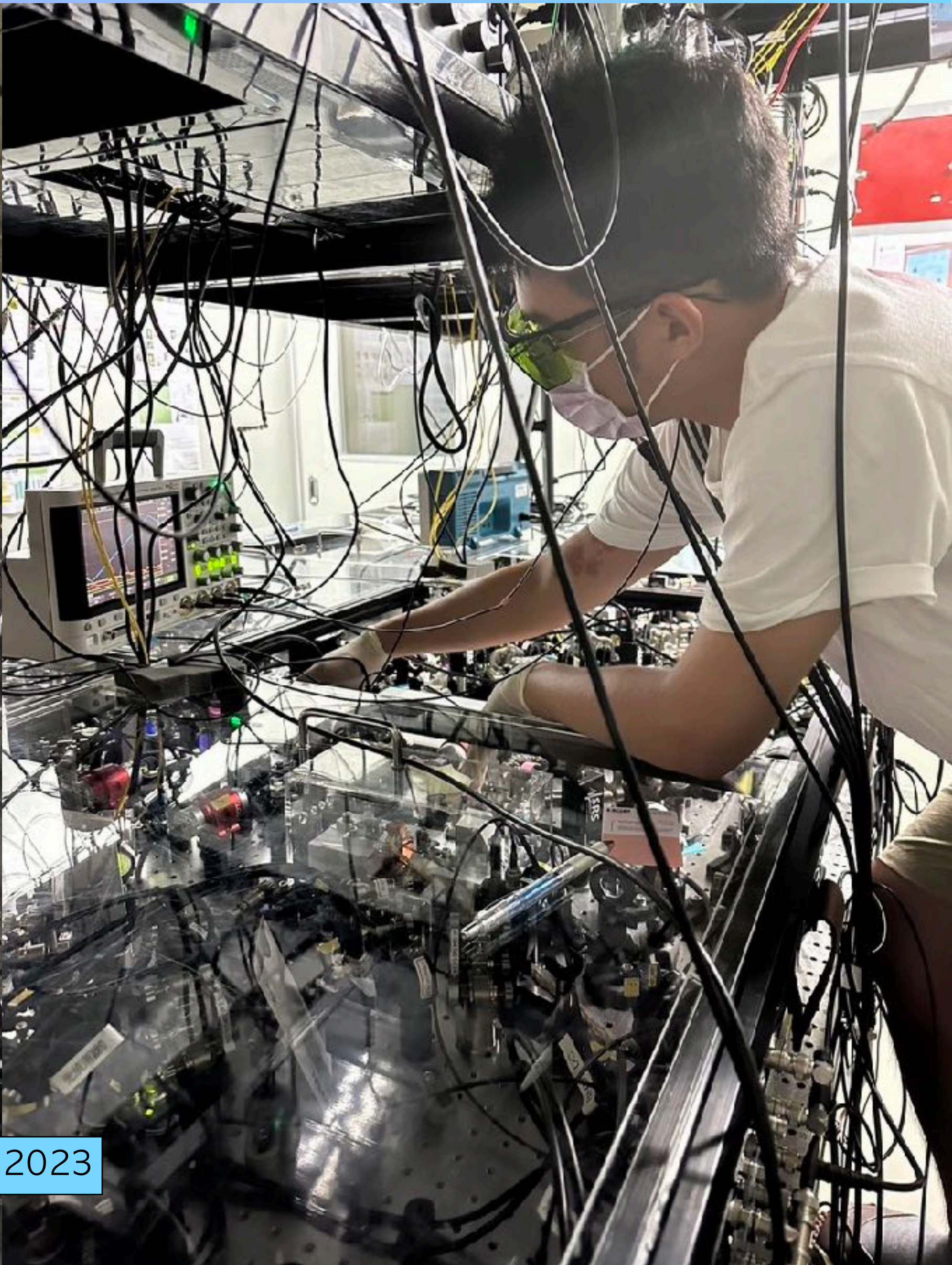
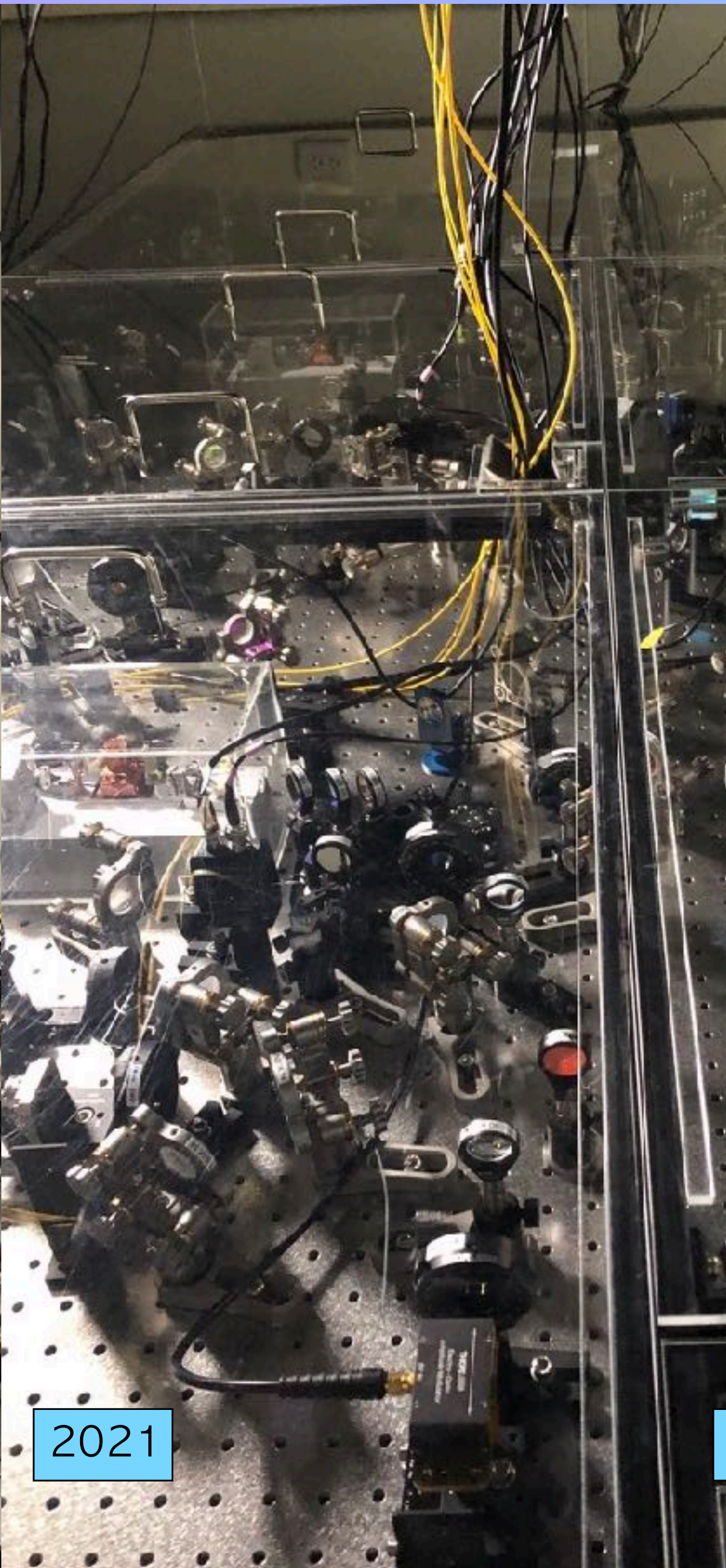
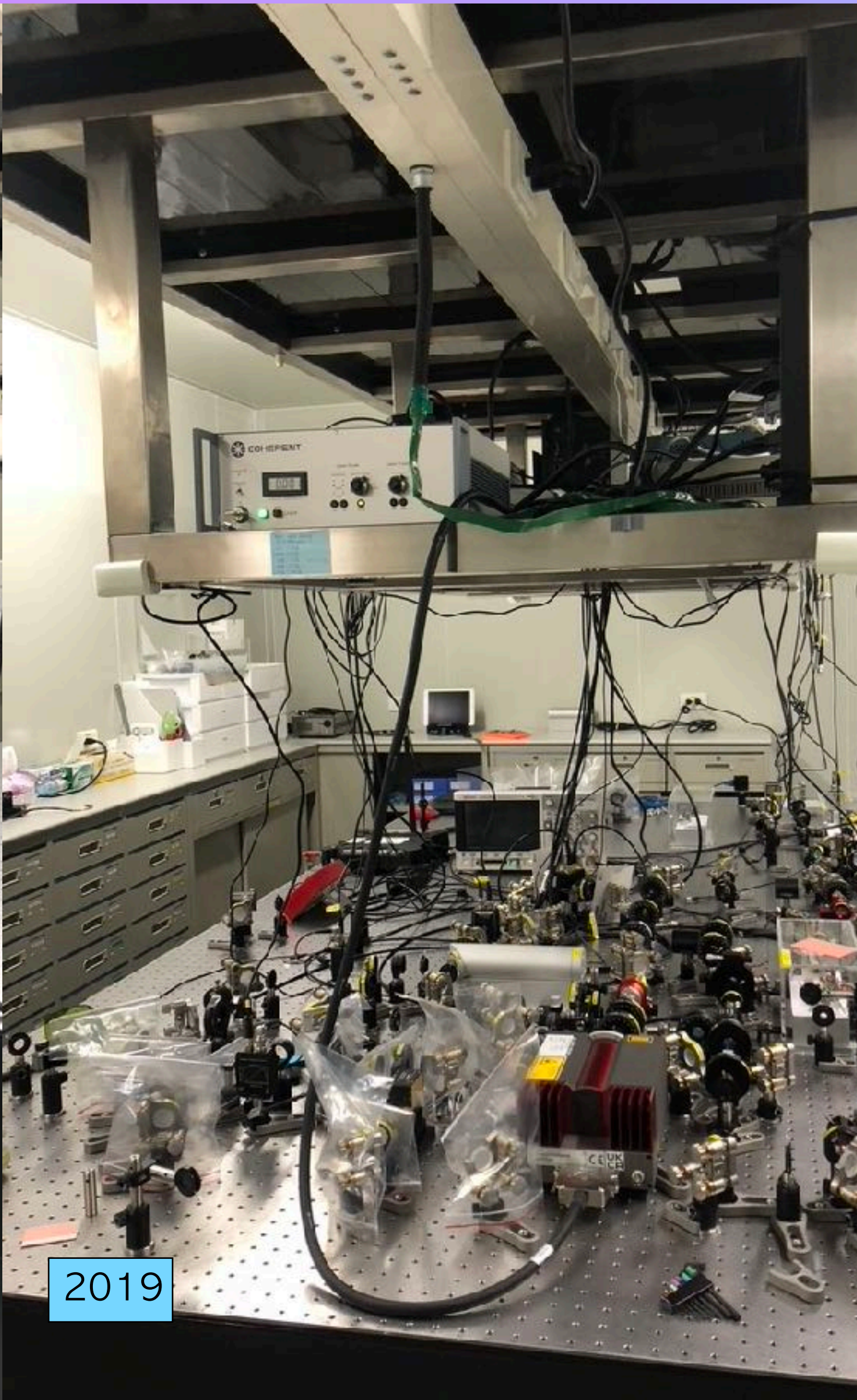
April 28, 2020 • Physics 13, s55
Two teams demonstrate frequency-dependent quantum squeezing, which could double the sensitivity of gravitational-wave detectors.



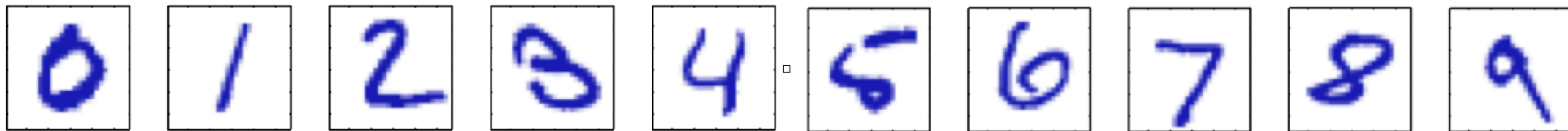
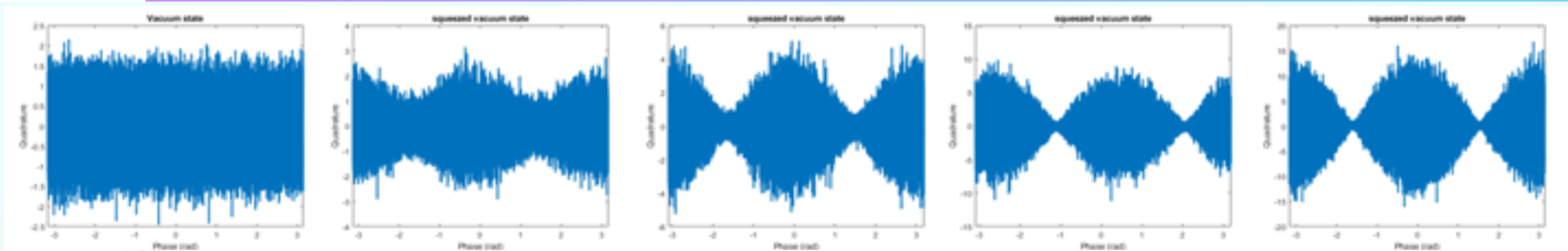
Yuhang Zhao et al.,
Phys. Rev. Lett. 124, 171101 (2020).



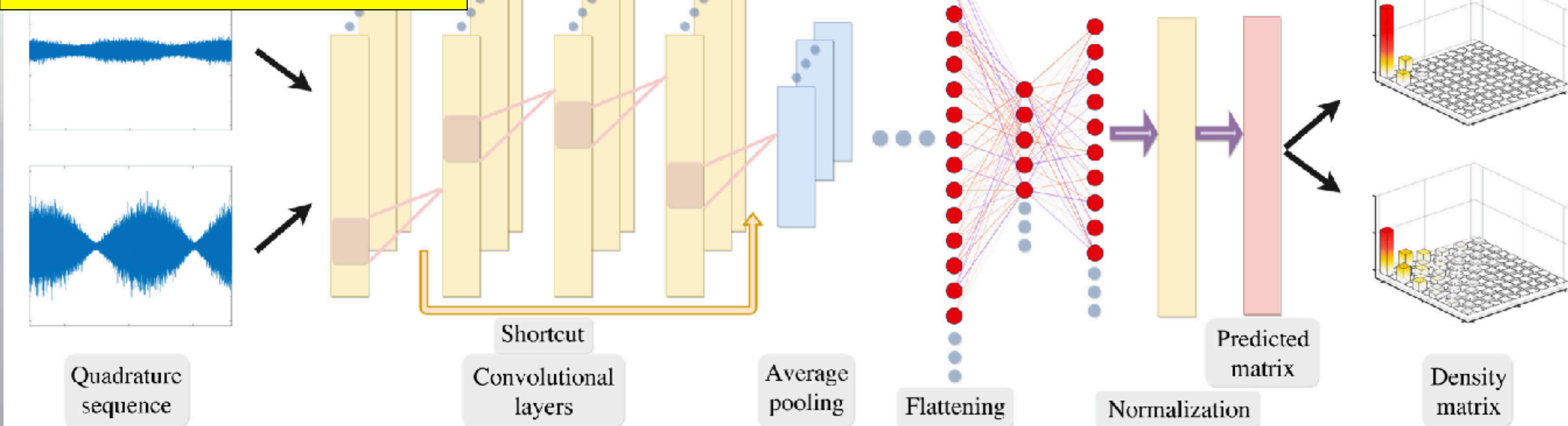
Squeezer @ NTHU, Taiwan



Pattern Recognition & Machine Learning:



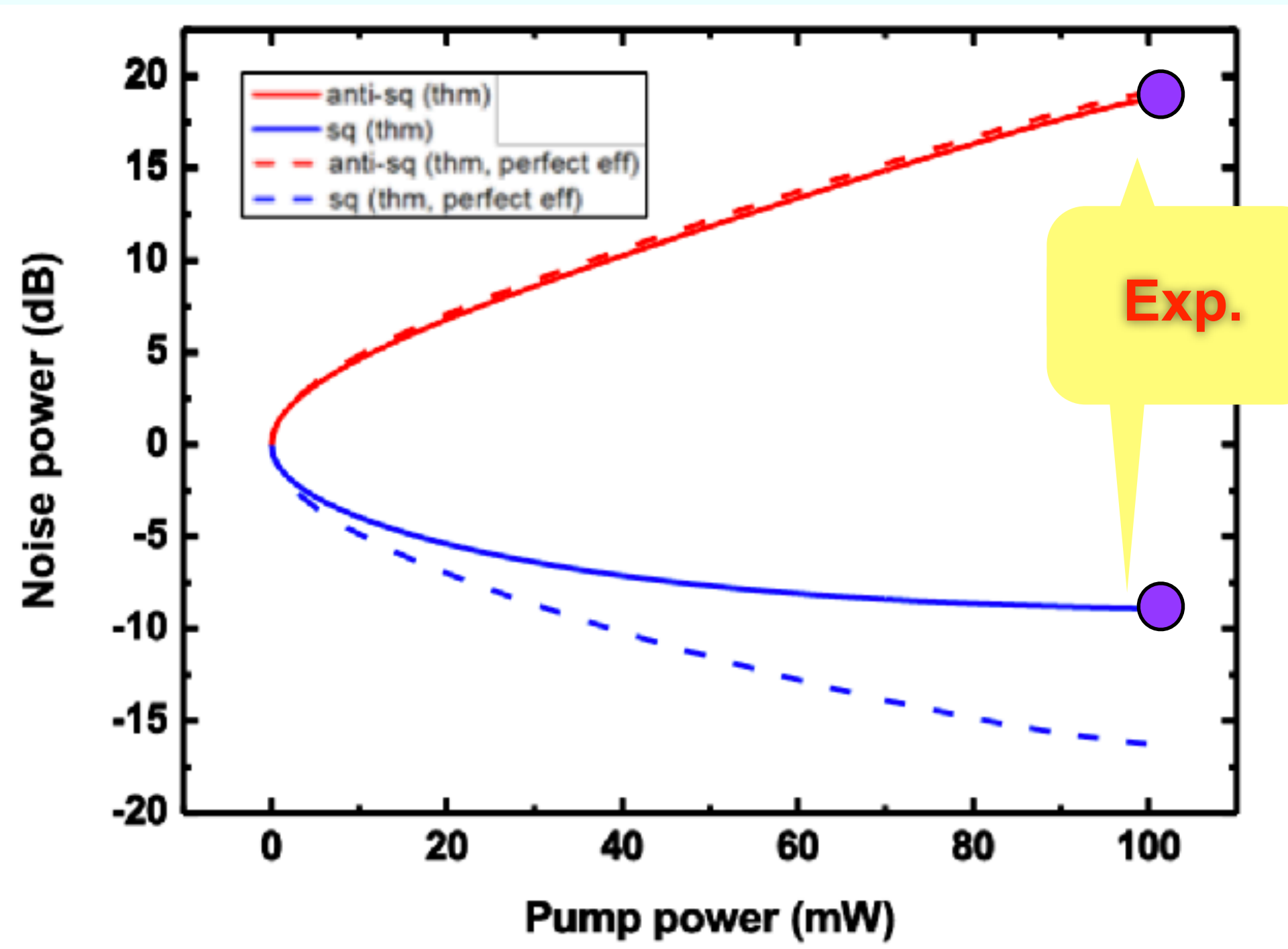
Convolution Neural Network (CNN)



by Yi-Ru Chen, Hsieh-Yi Hsieh

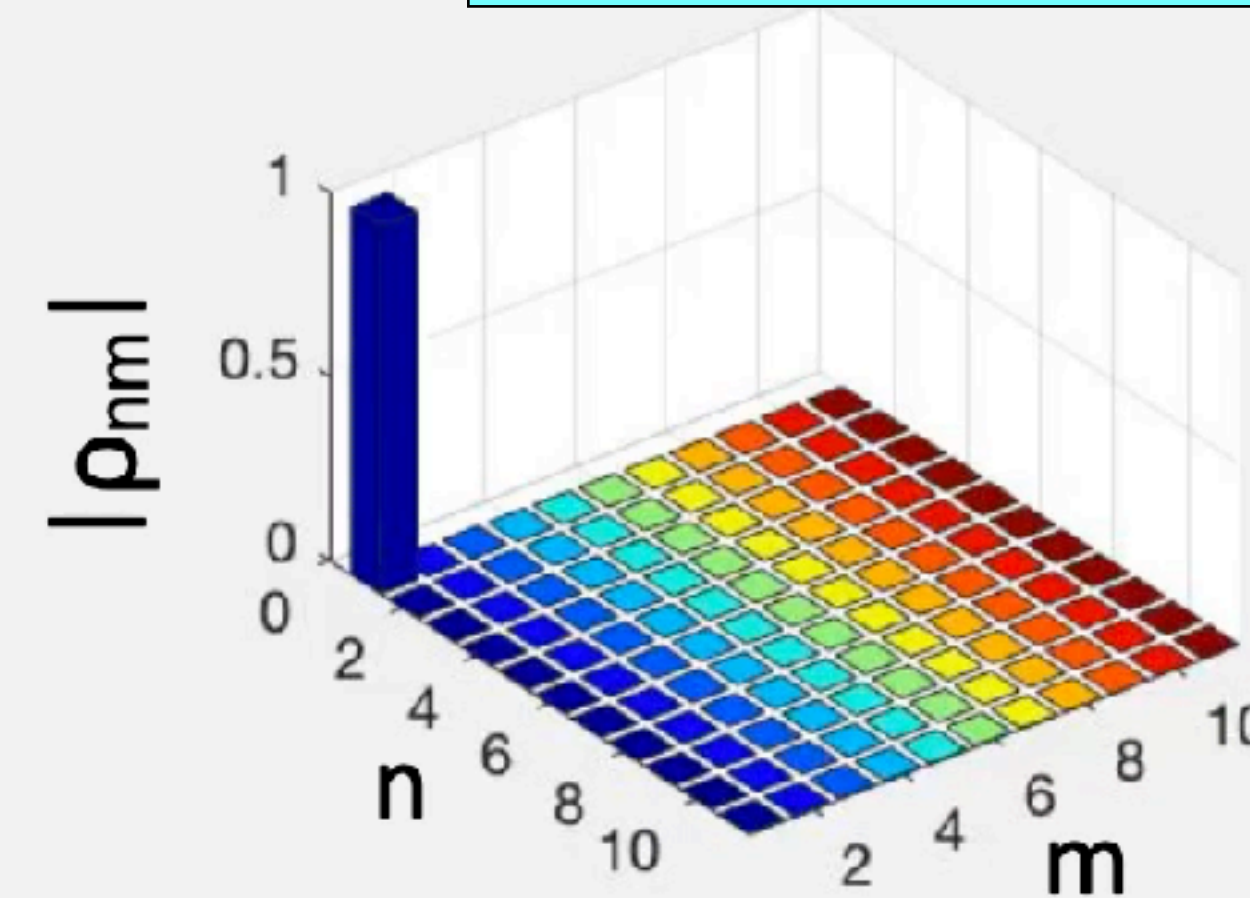
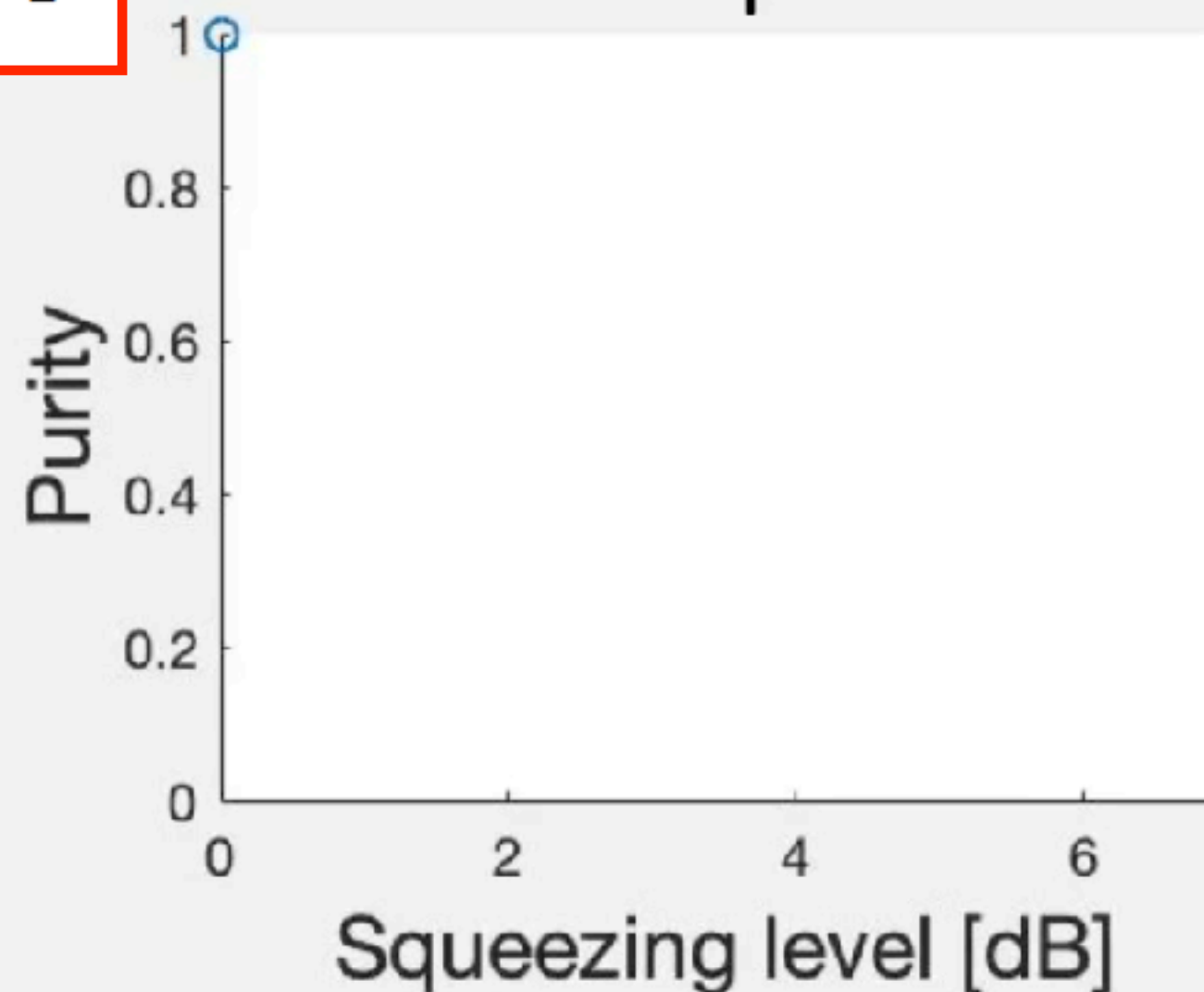
Toward **Real-Time** QST to Extract Degradation information

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

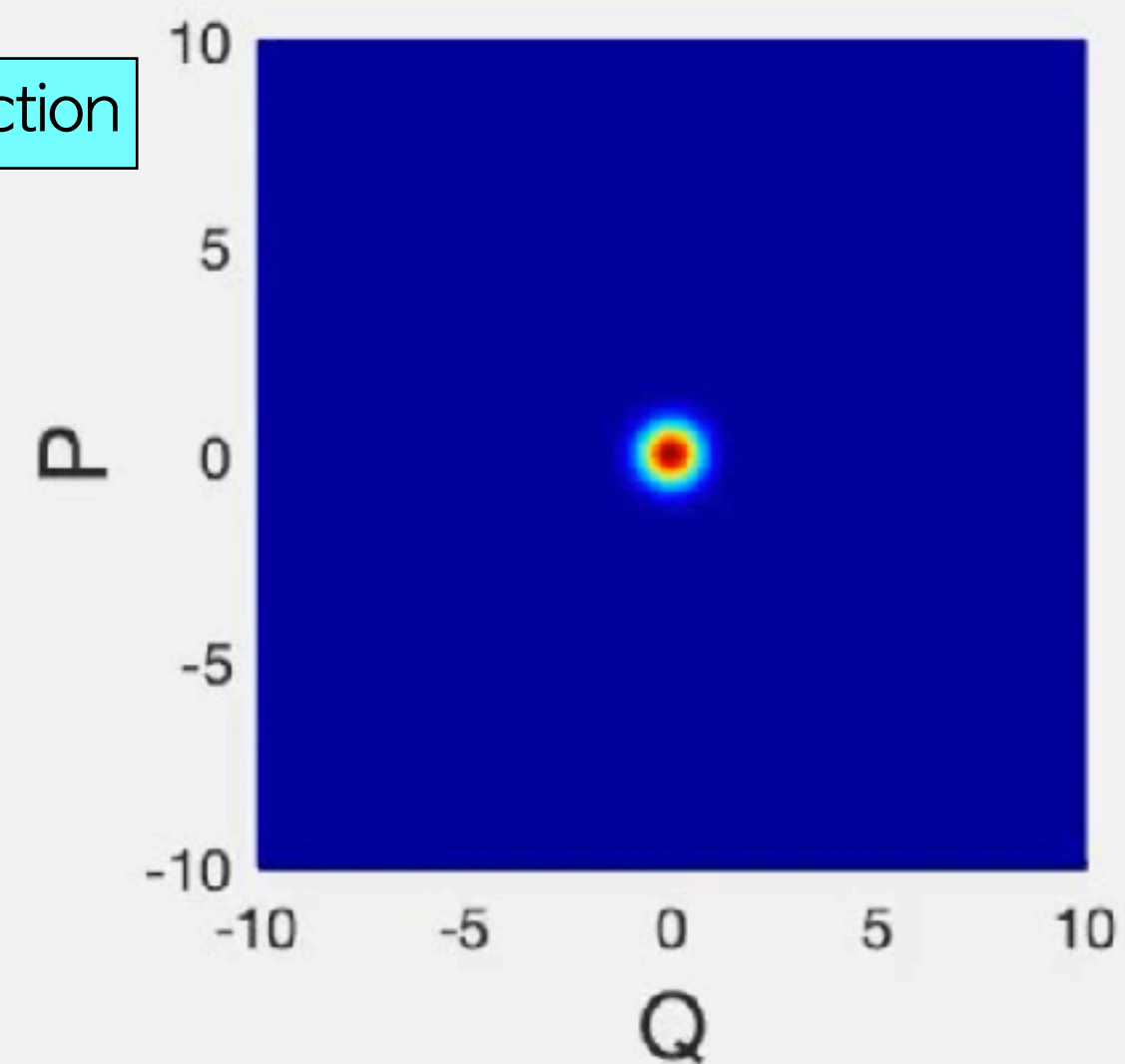
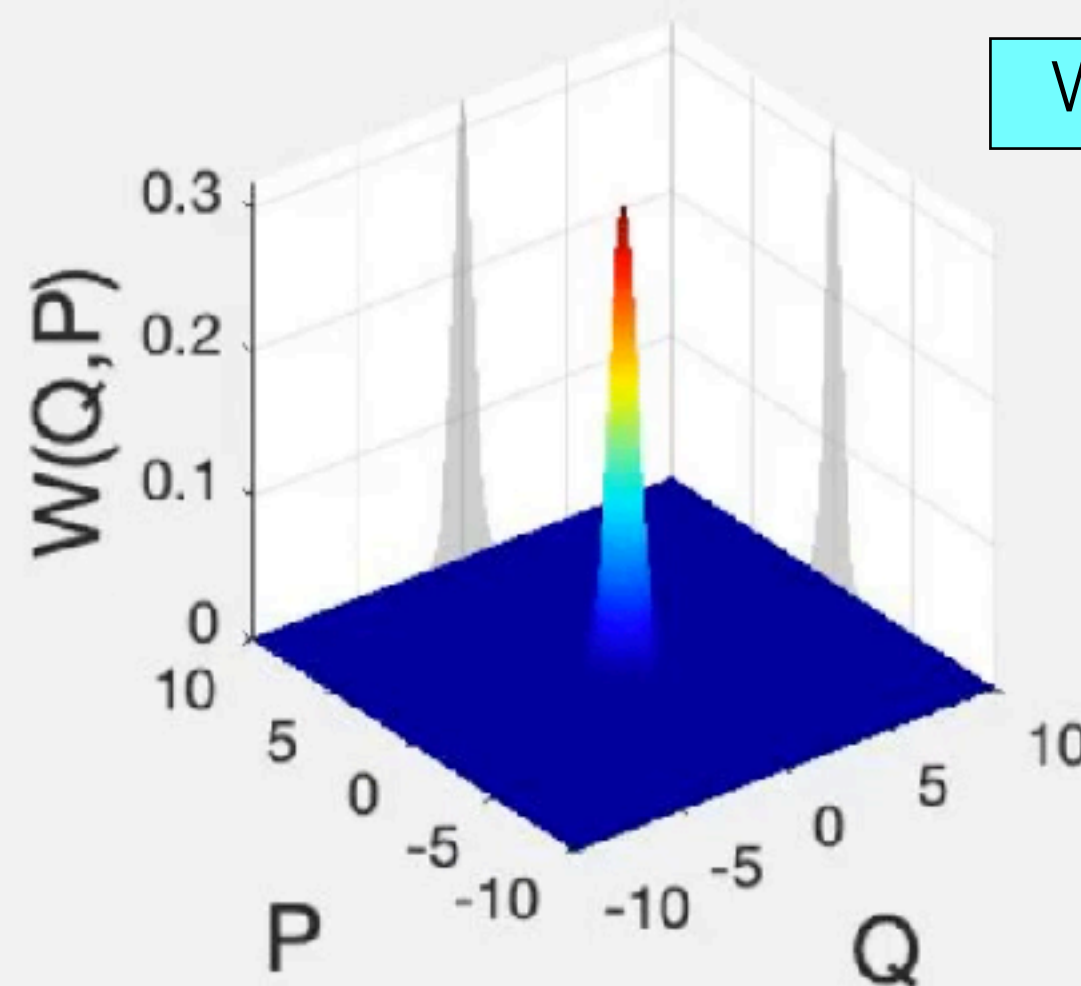


Squeezed state with loss

Density matrix in number basis



Wigner function

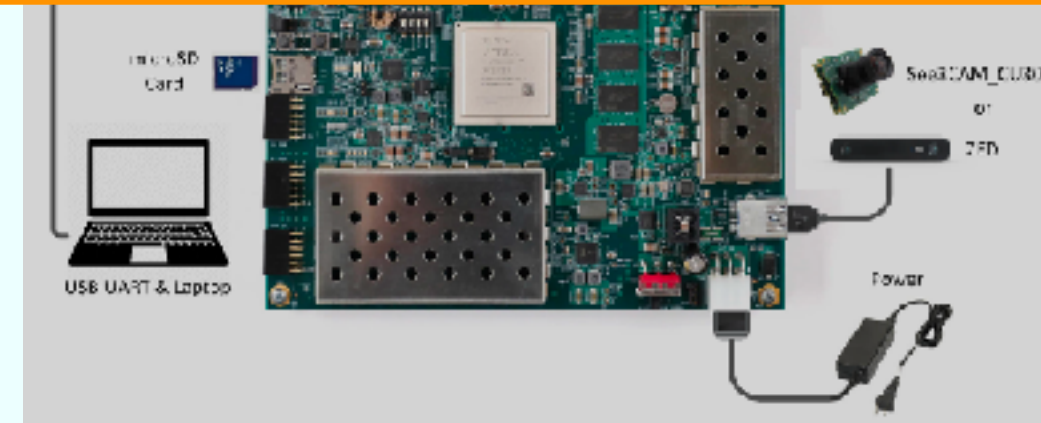
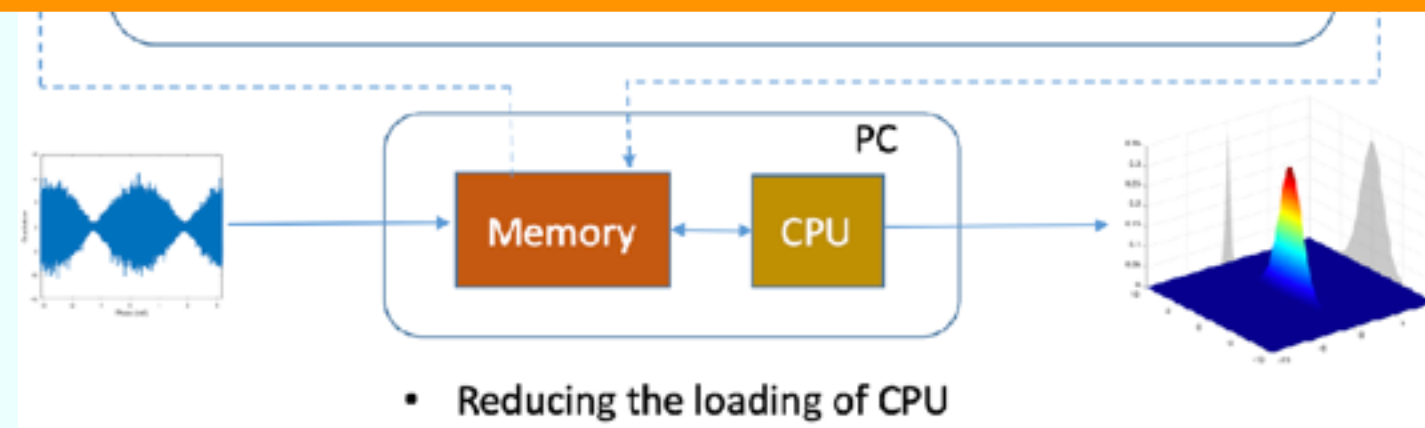


Real-time QST: with **FPGA** Acceleration

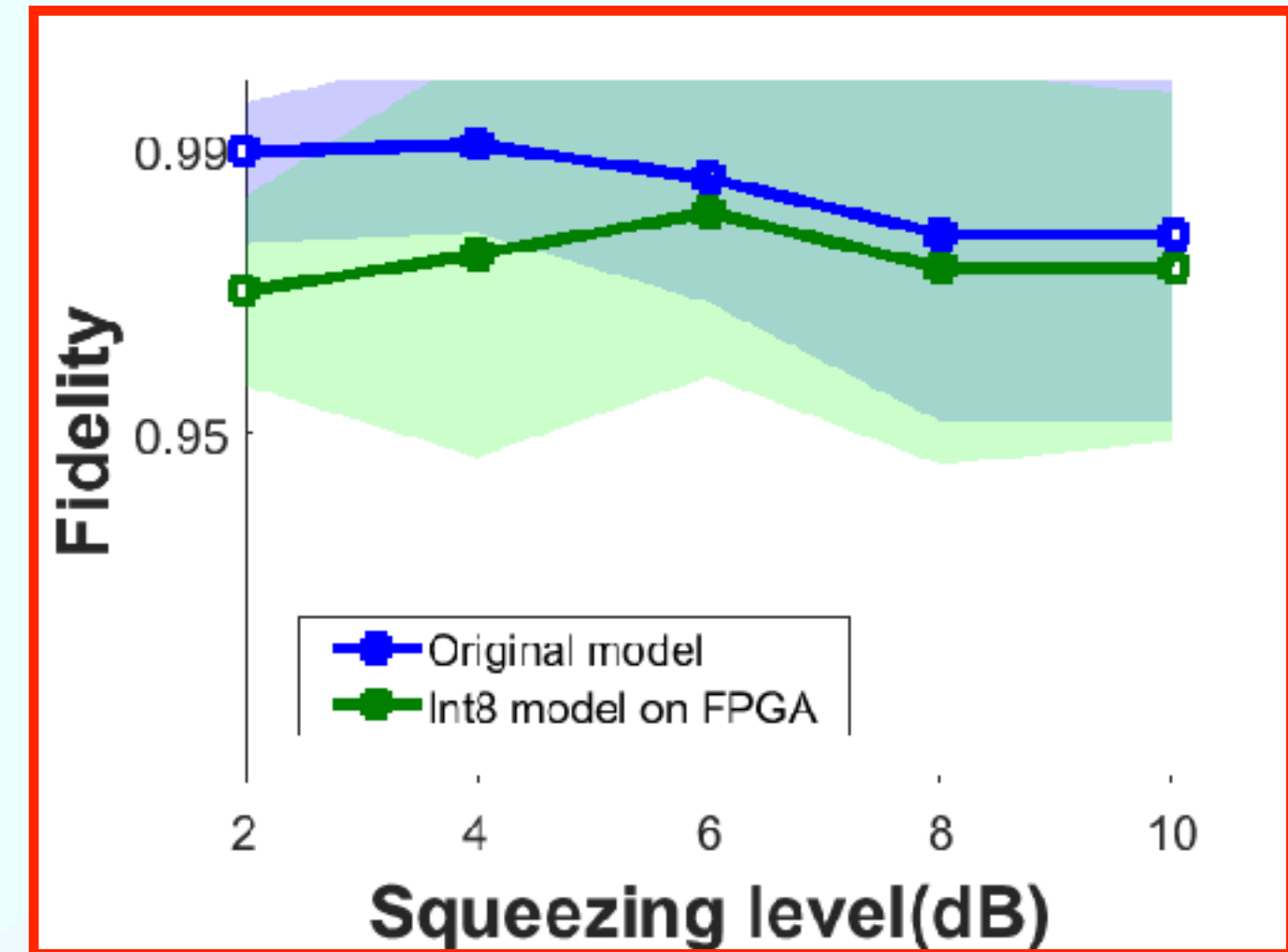
Software + Hardware 軟硬兼施



by Hsun-Chung Wu

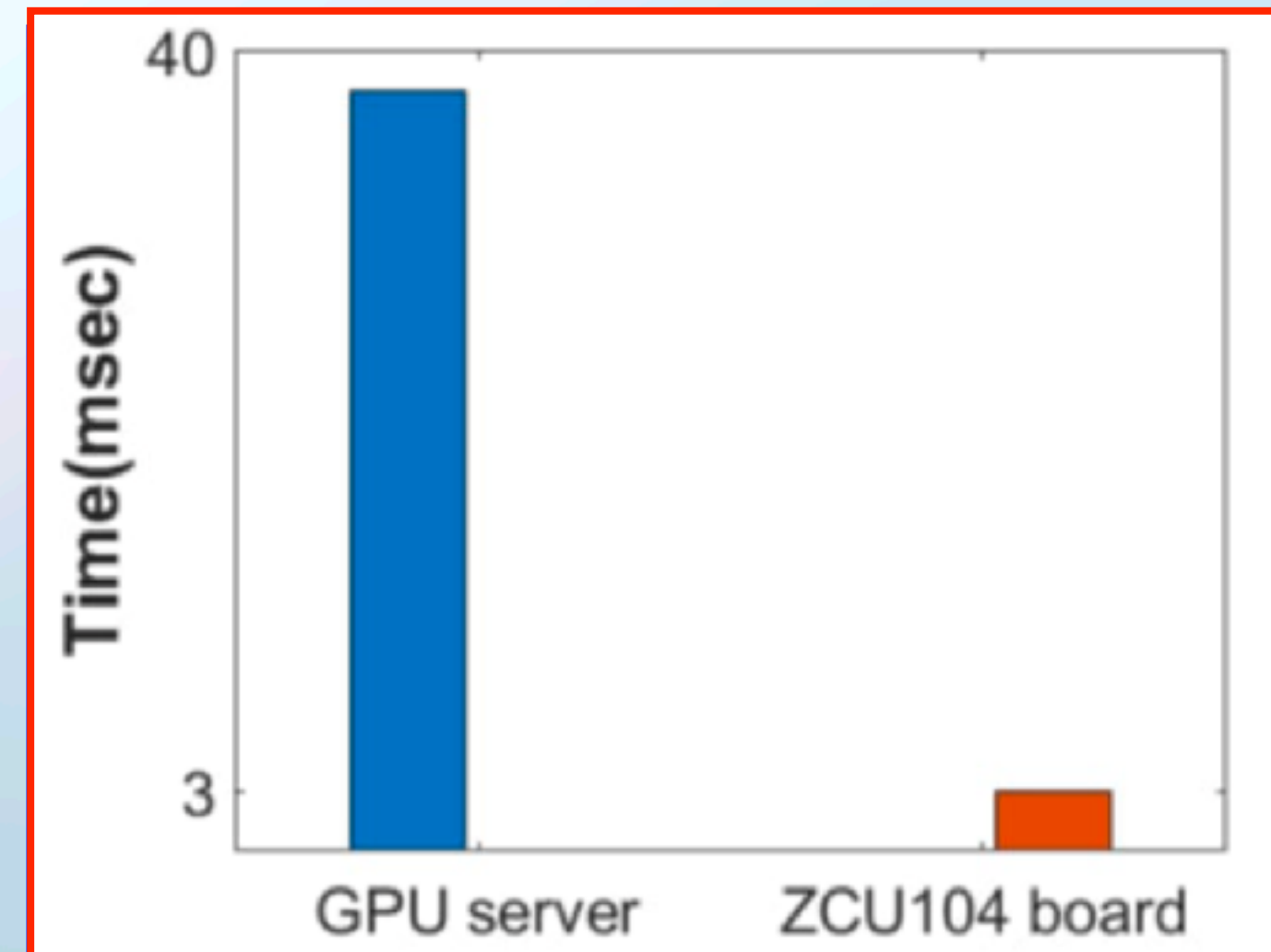
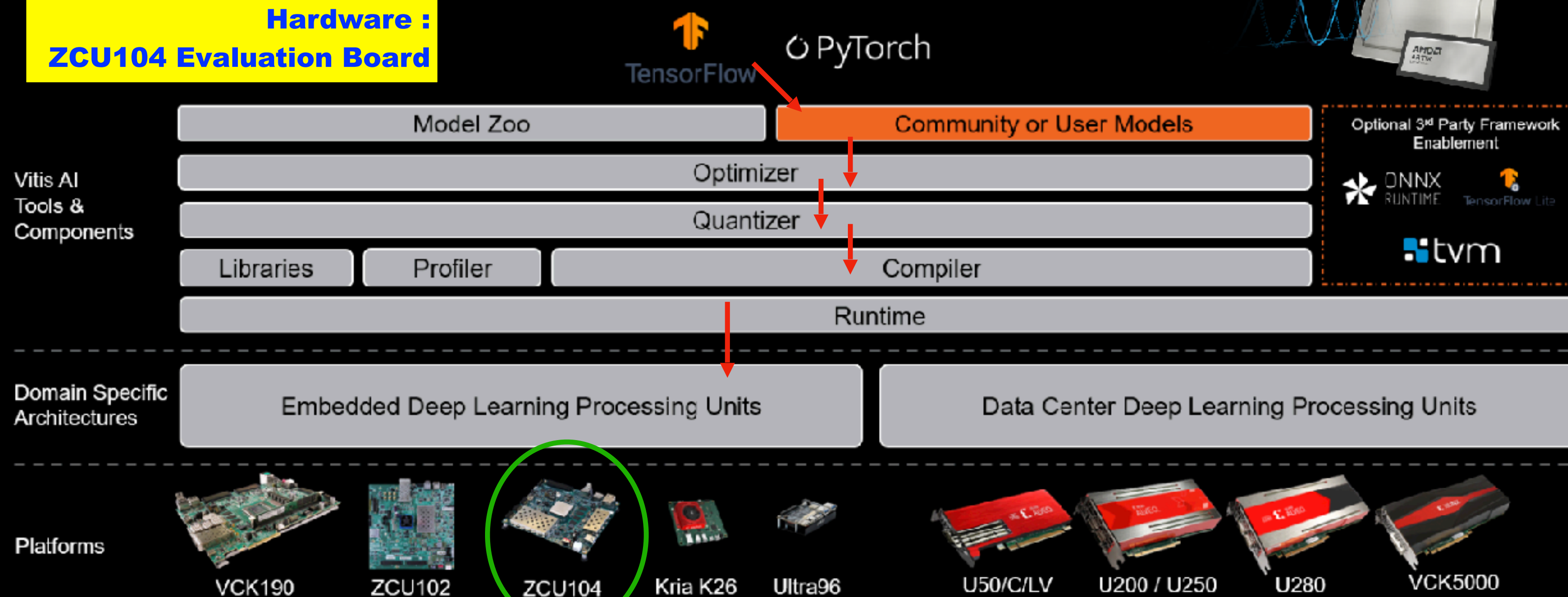


Hsun-Chung Wu et al., arXiv:2501.04327 (2025).



Vitis™ AI Integrated Development Environment

Hardware :
ZCU104 Evaluation Board



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

ML-enhanced QST: Gravitational Wave Detectors

Hsieh-Yi Hsieh et al., (in preparation).

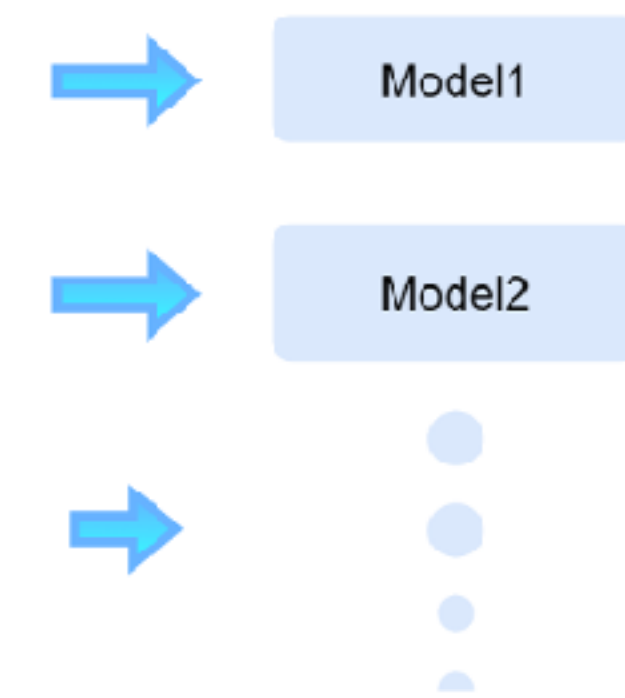
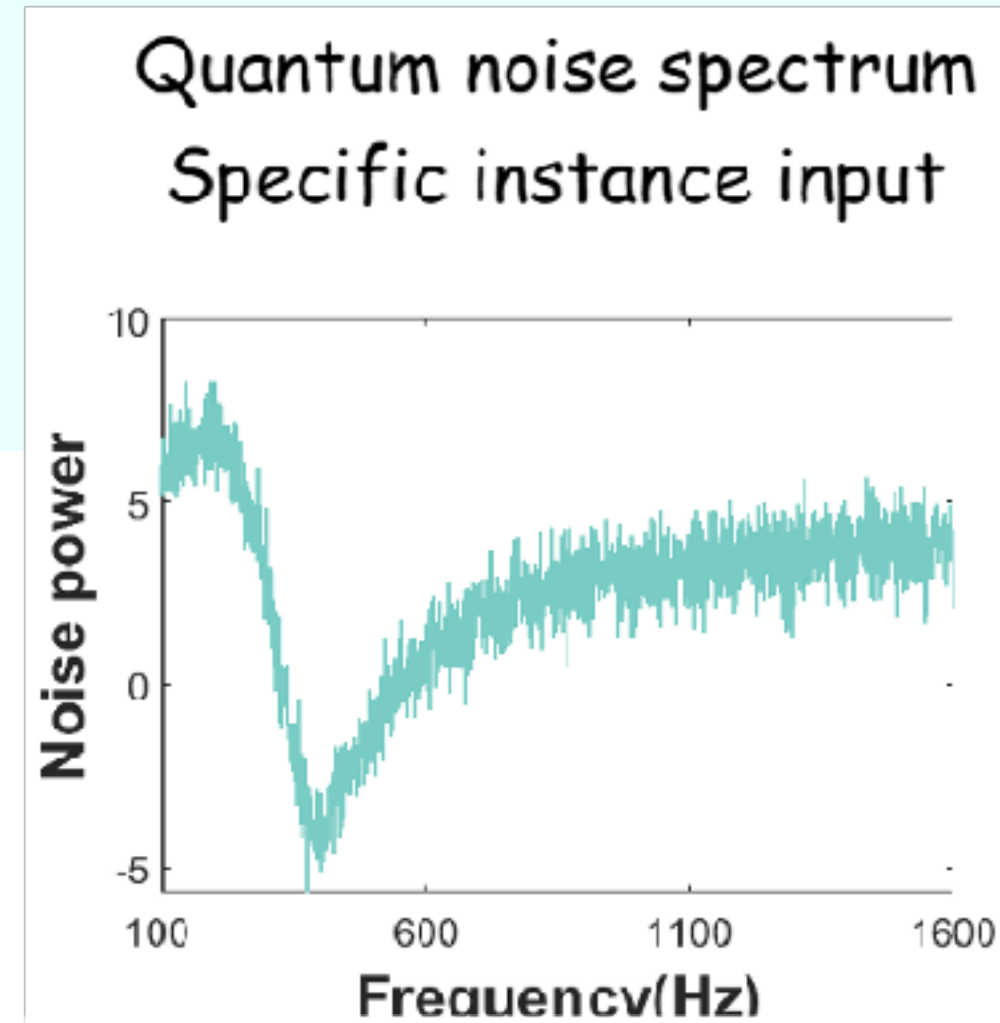
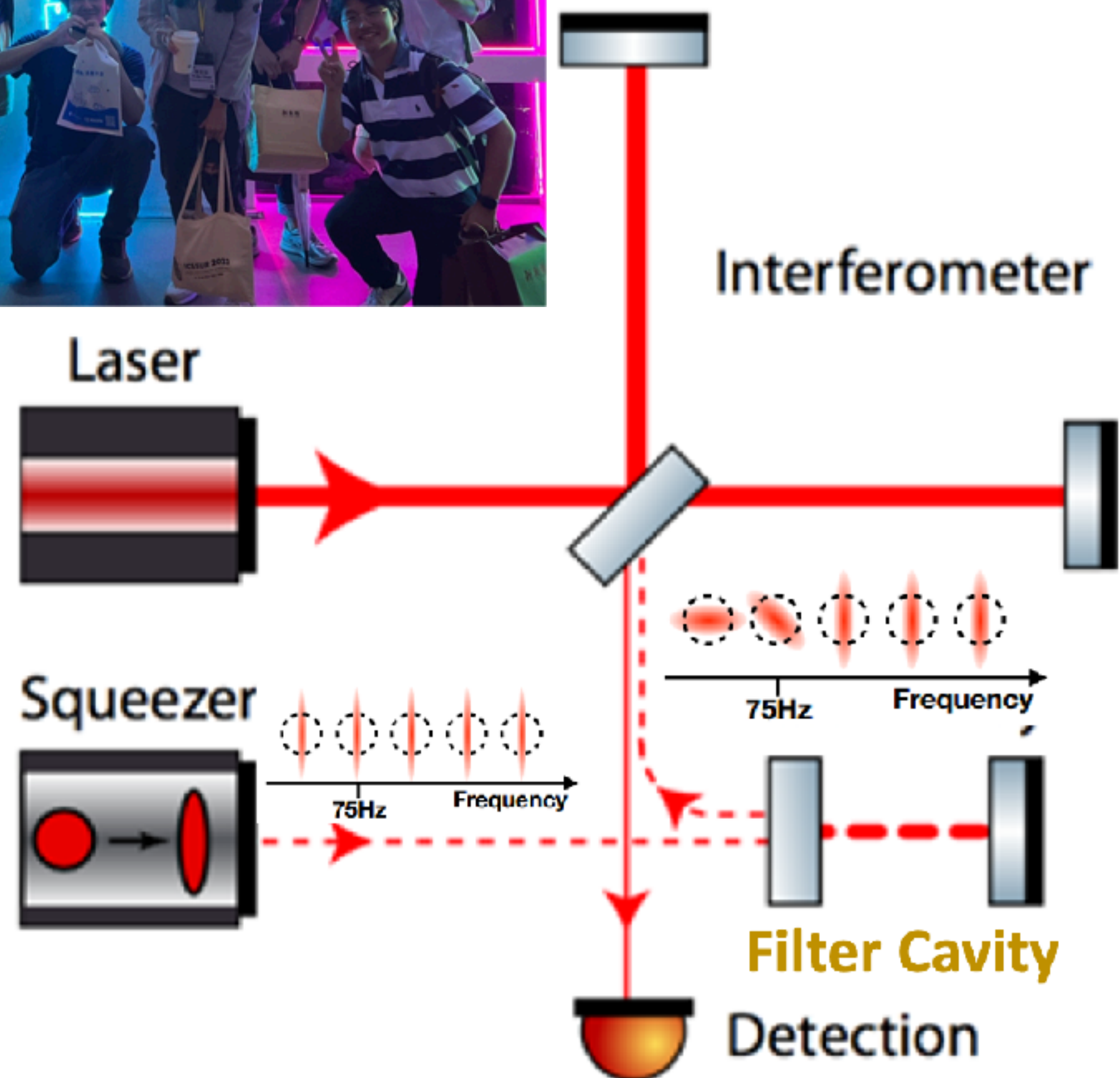


Multi-Parameters Bayesian Estimation

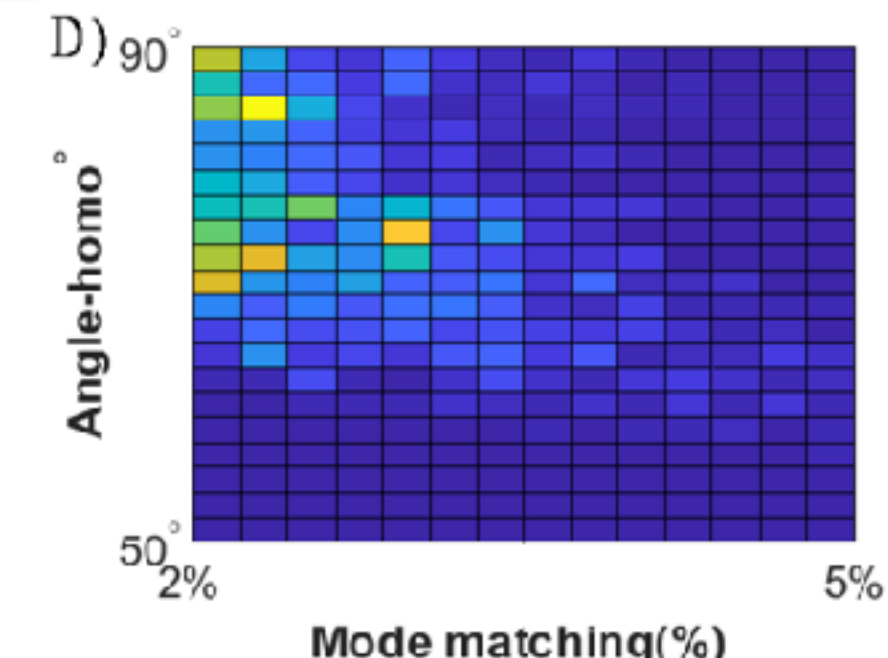
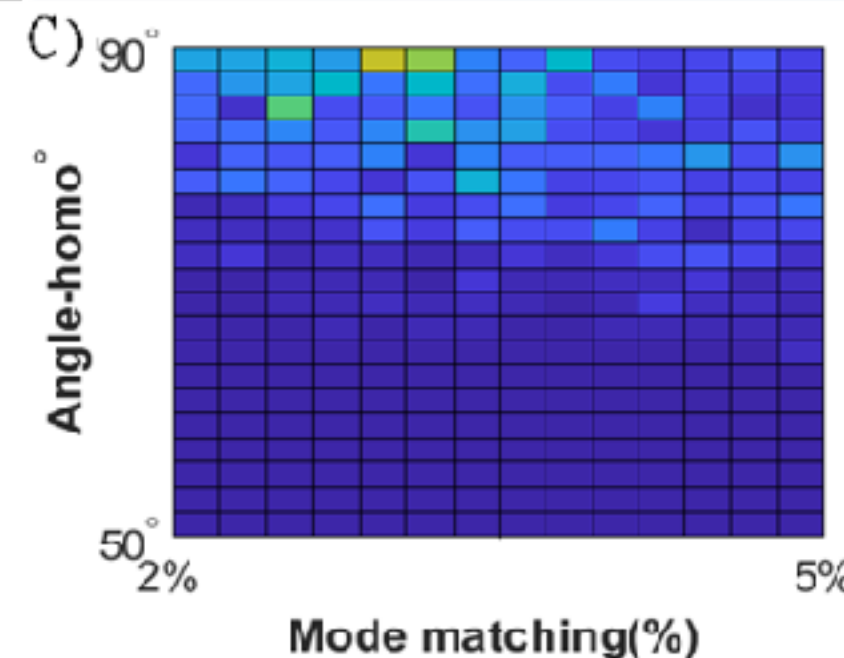
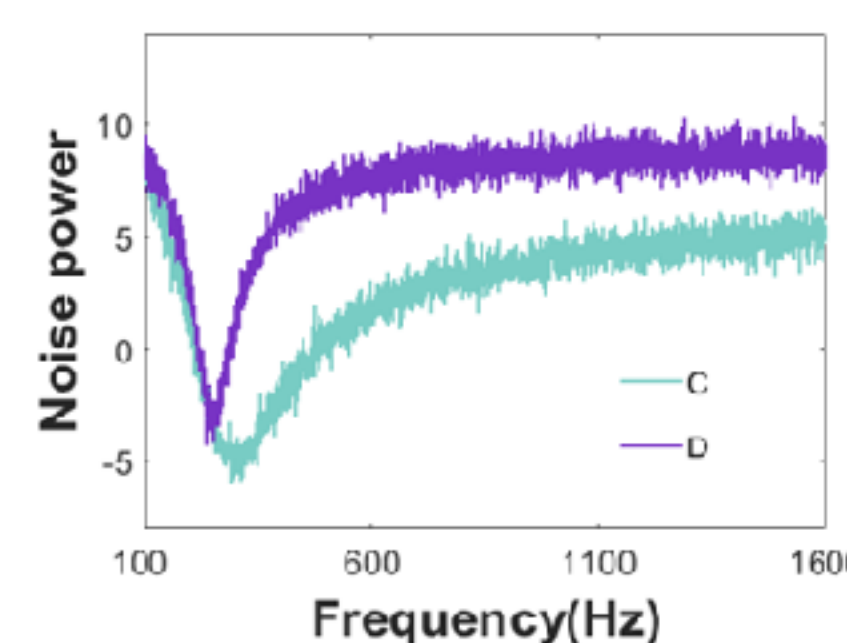
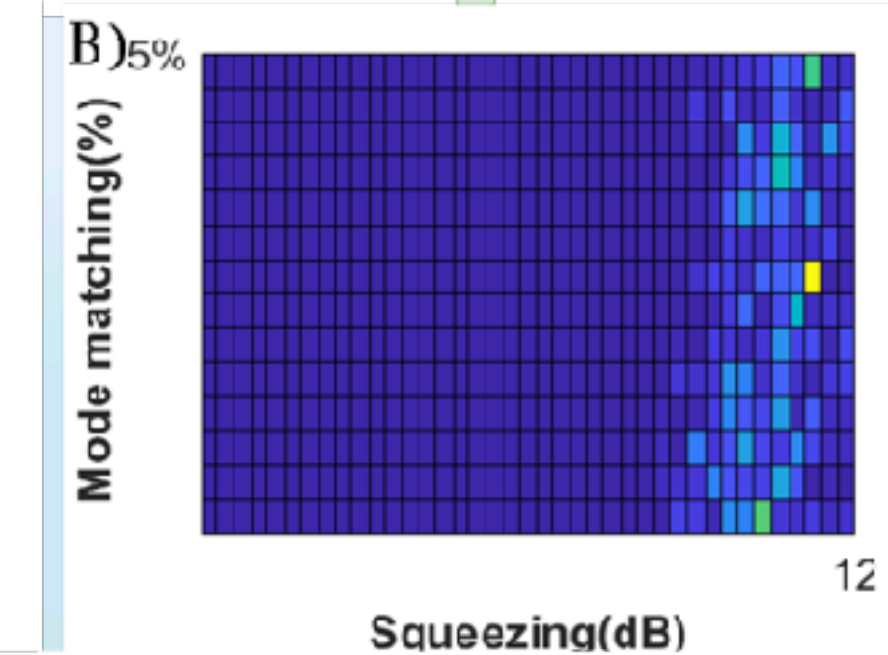
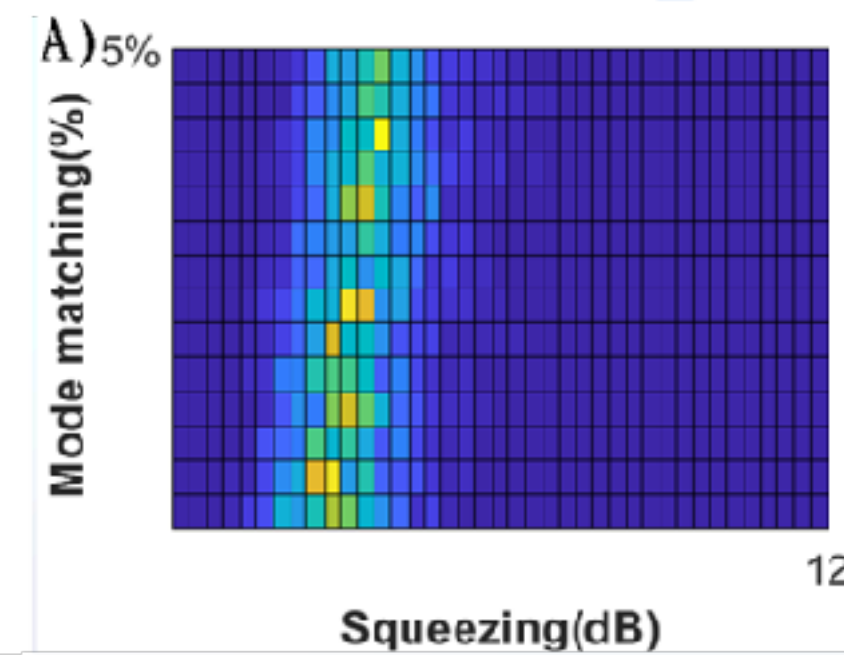
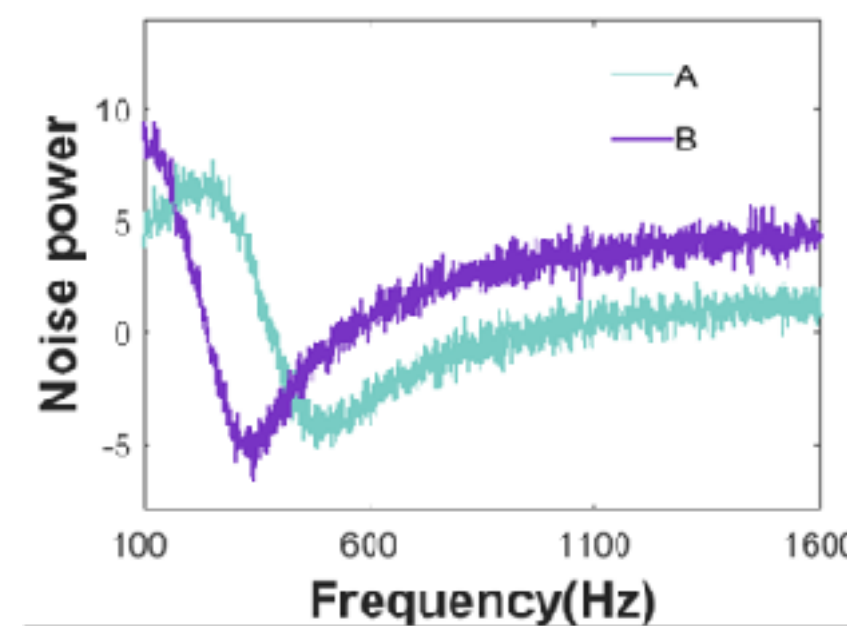
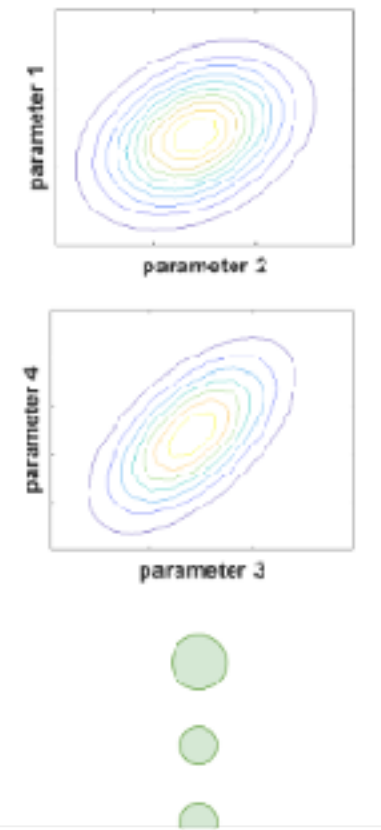
with Michael Page, Y. Aso, T. Tomaru (NAOJ)



by Hsieh-Yi Hsieh

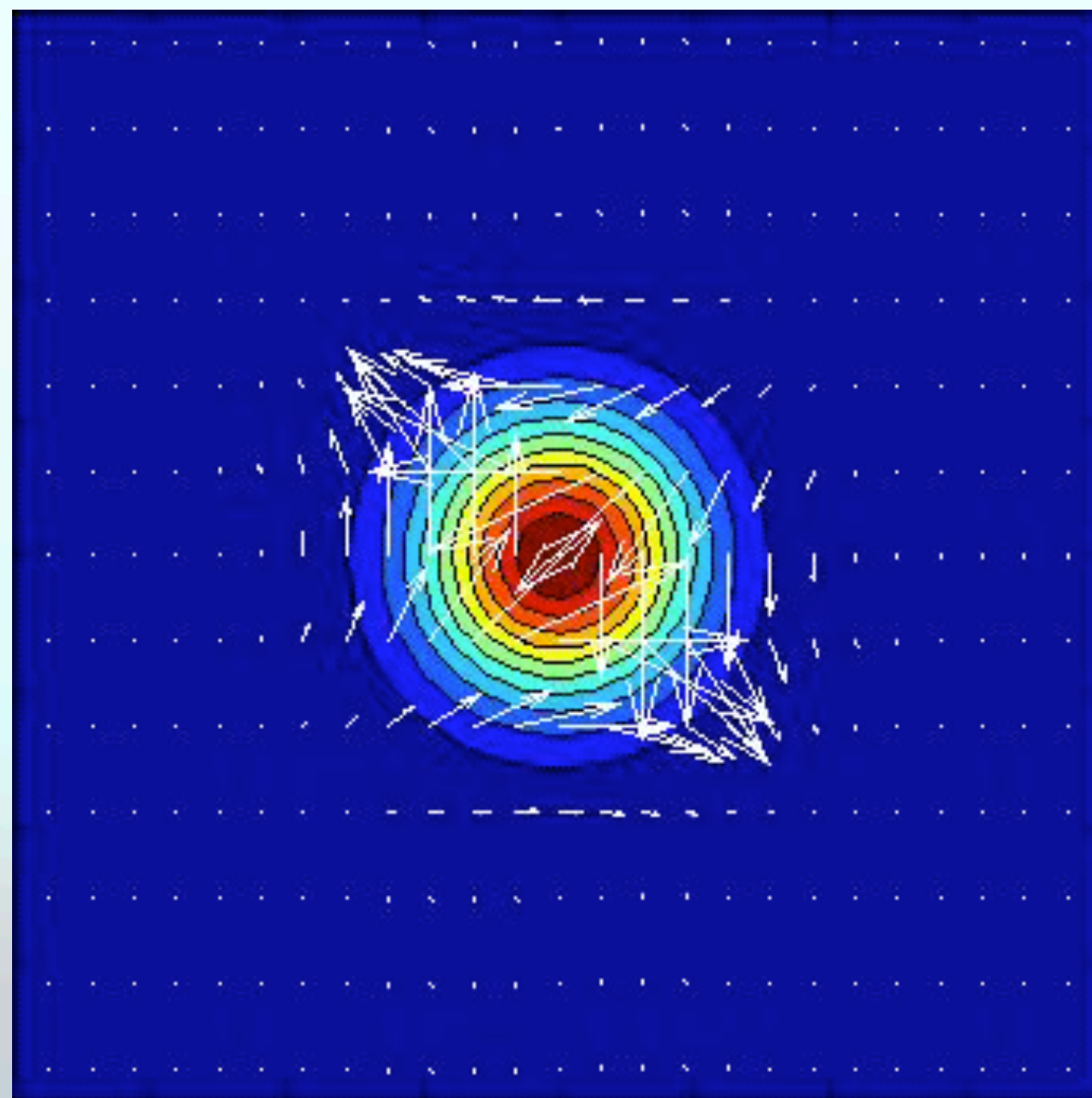


Marginal parameter distributions



More than Non-Classicality:

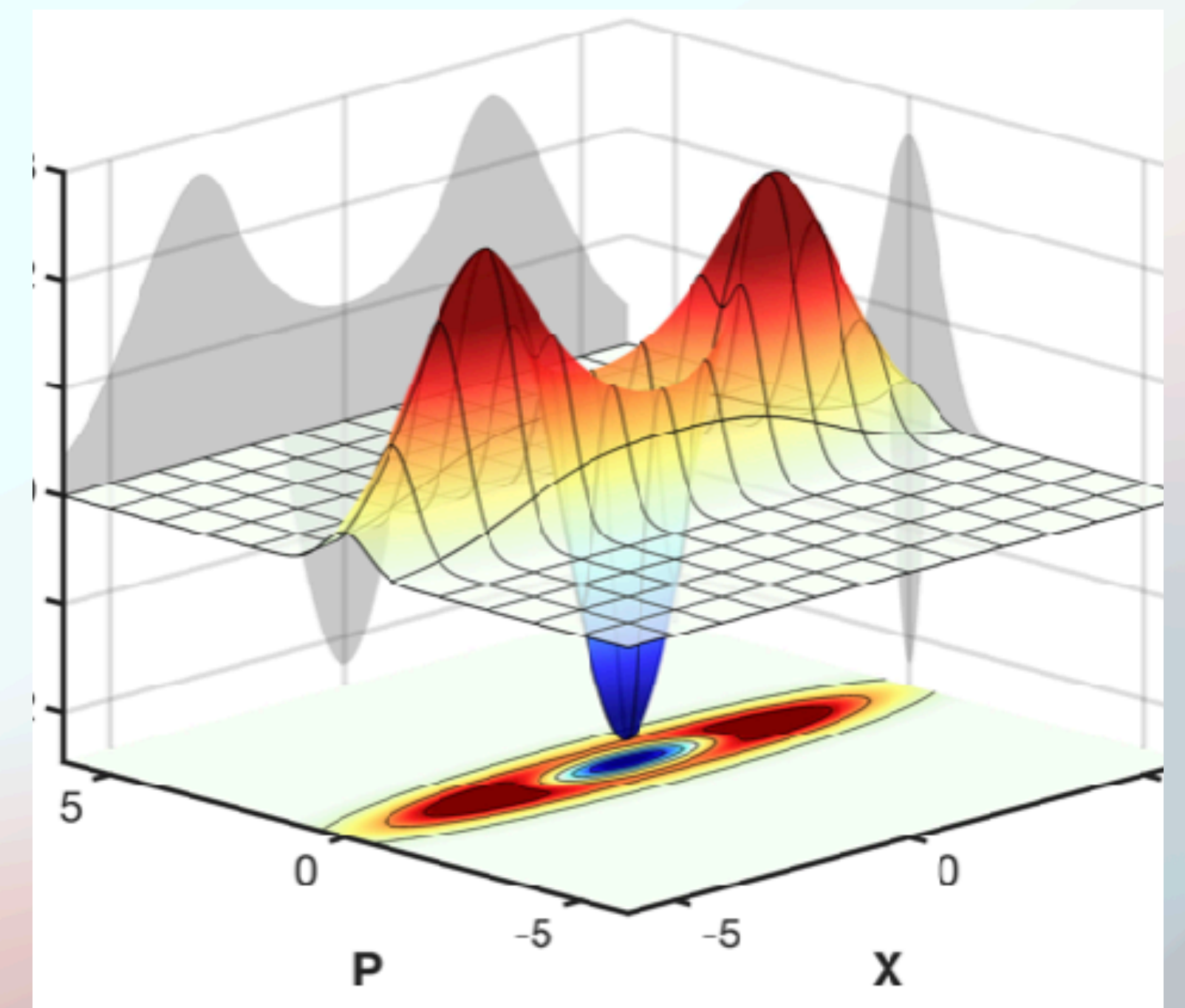
Squeezed State in Taiwan



Machine-Learning Quantum State Tomography



Non-Gaussian: Fock and Cat States

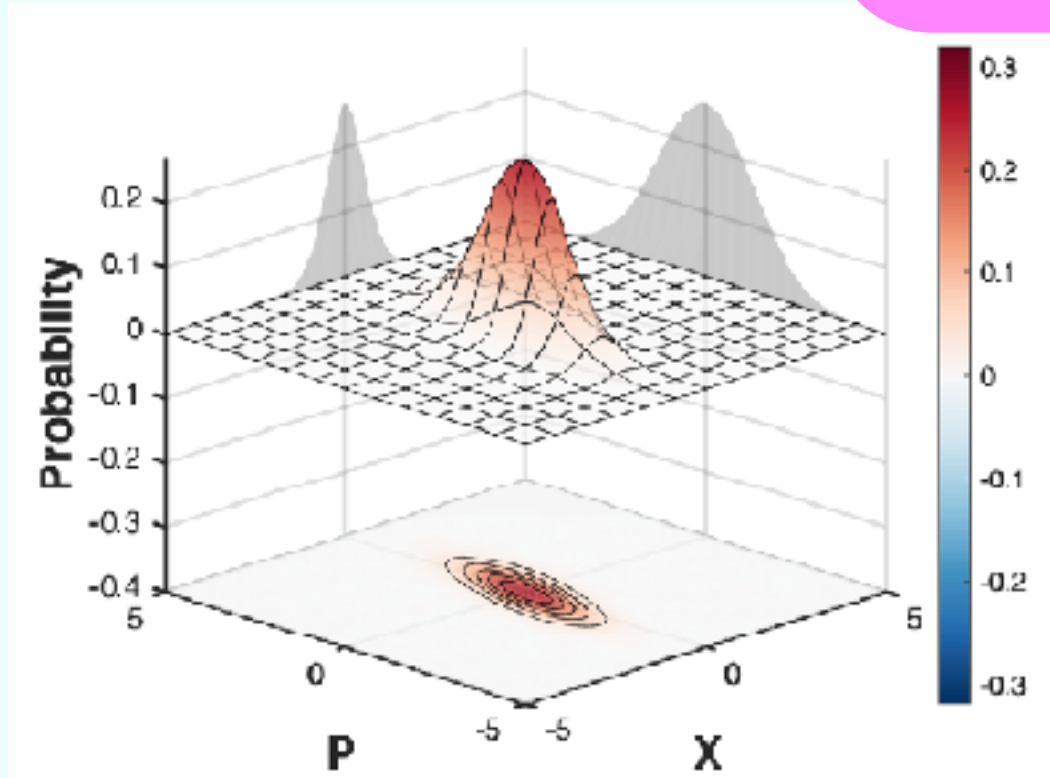
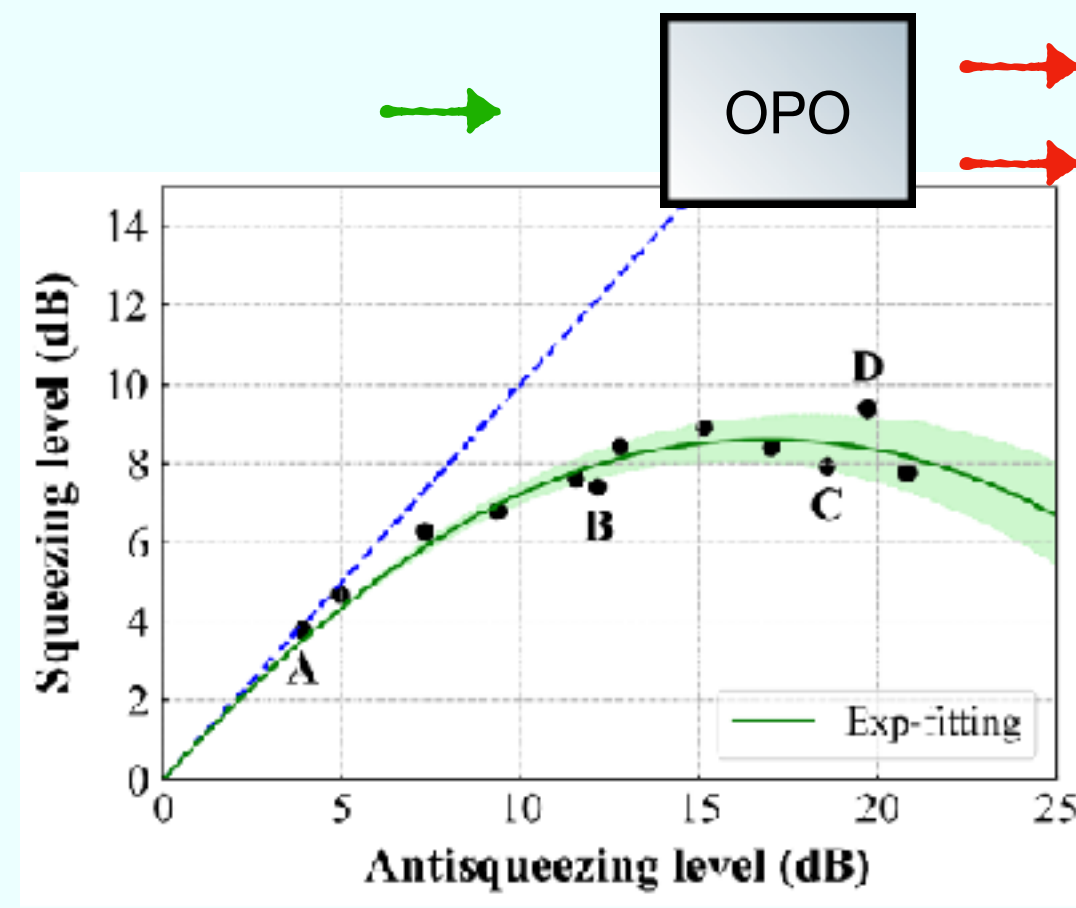


ML-Quant. State Tomography, Phys. Rev. Lett. 128, 073604 (2022);
Wigner Current, Phys. Rev. A 108, 023729 (2023);

Optical cat states by photon-addition, Phys. Rev. A 110, 023703 (2024);
ML-Fock State Tomography, Phys. Rev. A 110, 053705 (2024);
Quantumness Measure from phase space distributions, [arXiv: 2311.17399];

Review on Quantum ML, Advances in Phys. X 8, 2165452 (2023);

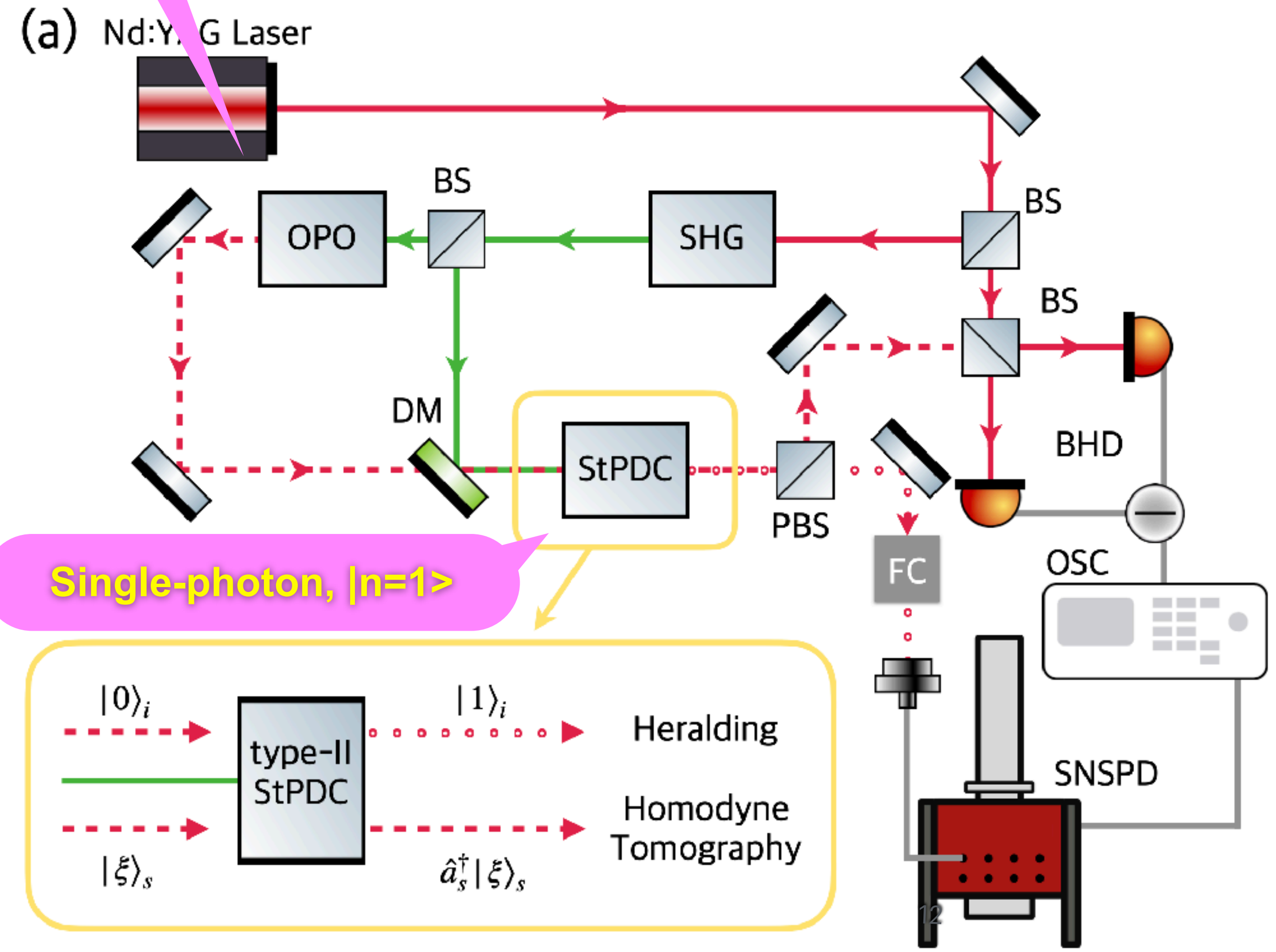
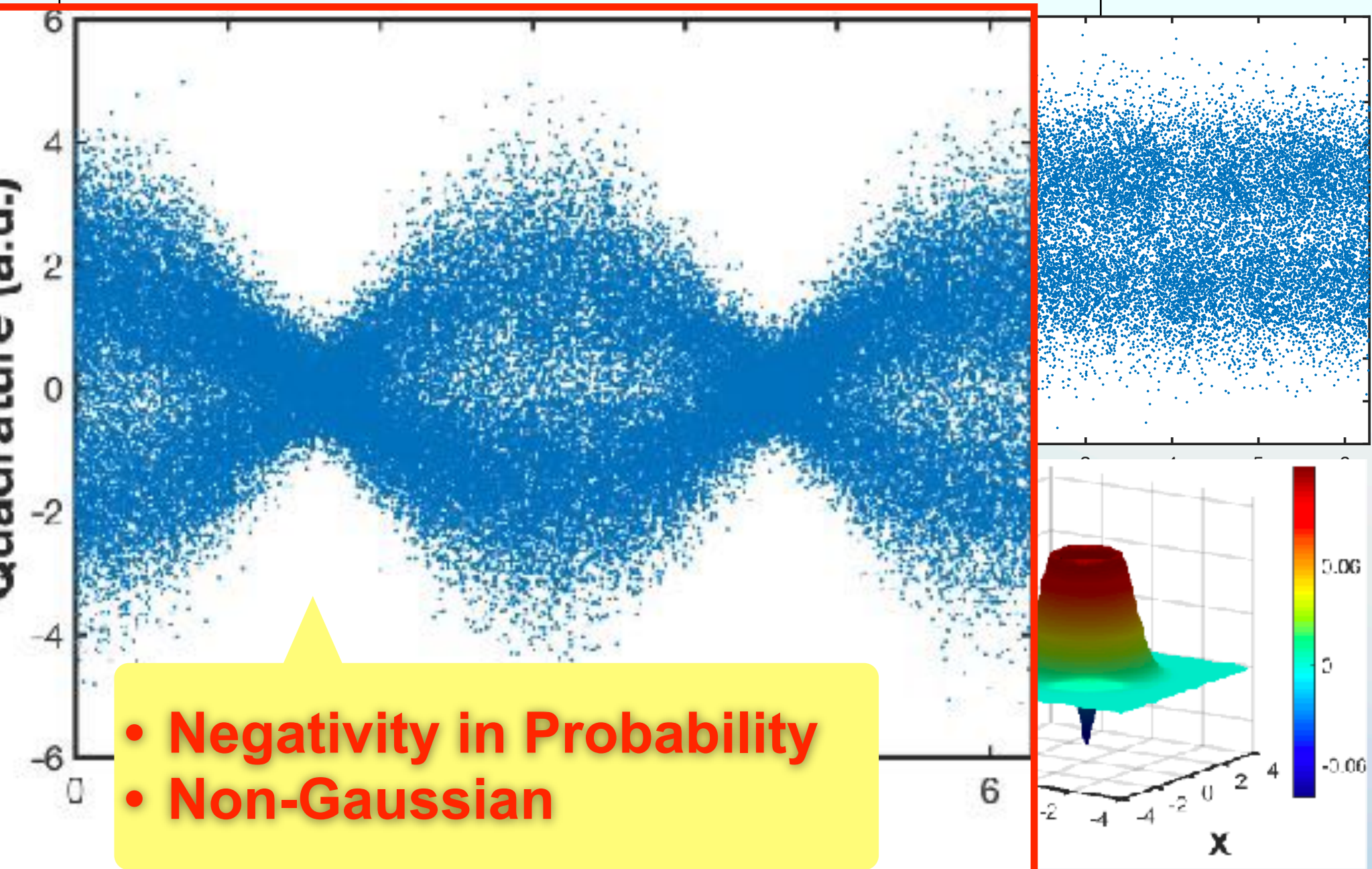
Optical Cats: Photon-Addition



SQZ, $|\xi\rangle$

The First Experimental Realization with photo-addition.

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



Hsien-Yi Hsieh et al., PRA 110, 053705 (2024).

Yi-Ru Chen et al., PRA 110 023703 (2024).

Optical Cats: Photon-Addition

Yi-Ru Chen et al., PRA 110 023703 (2024).

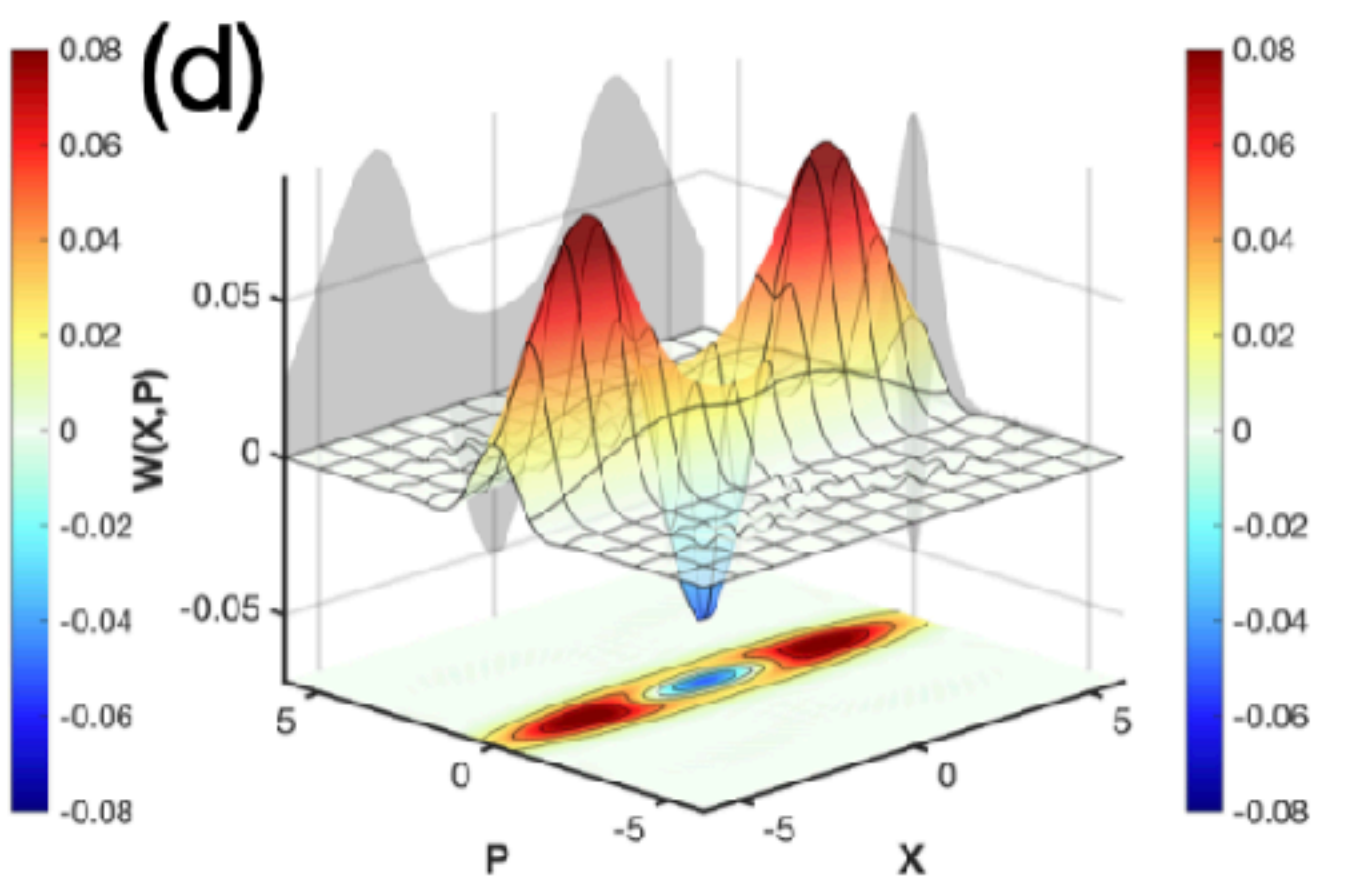
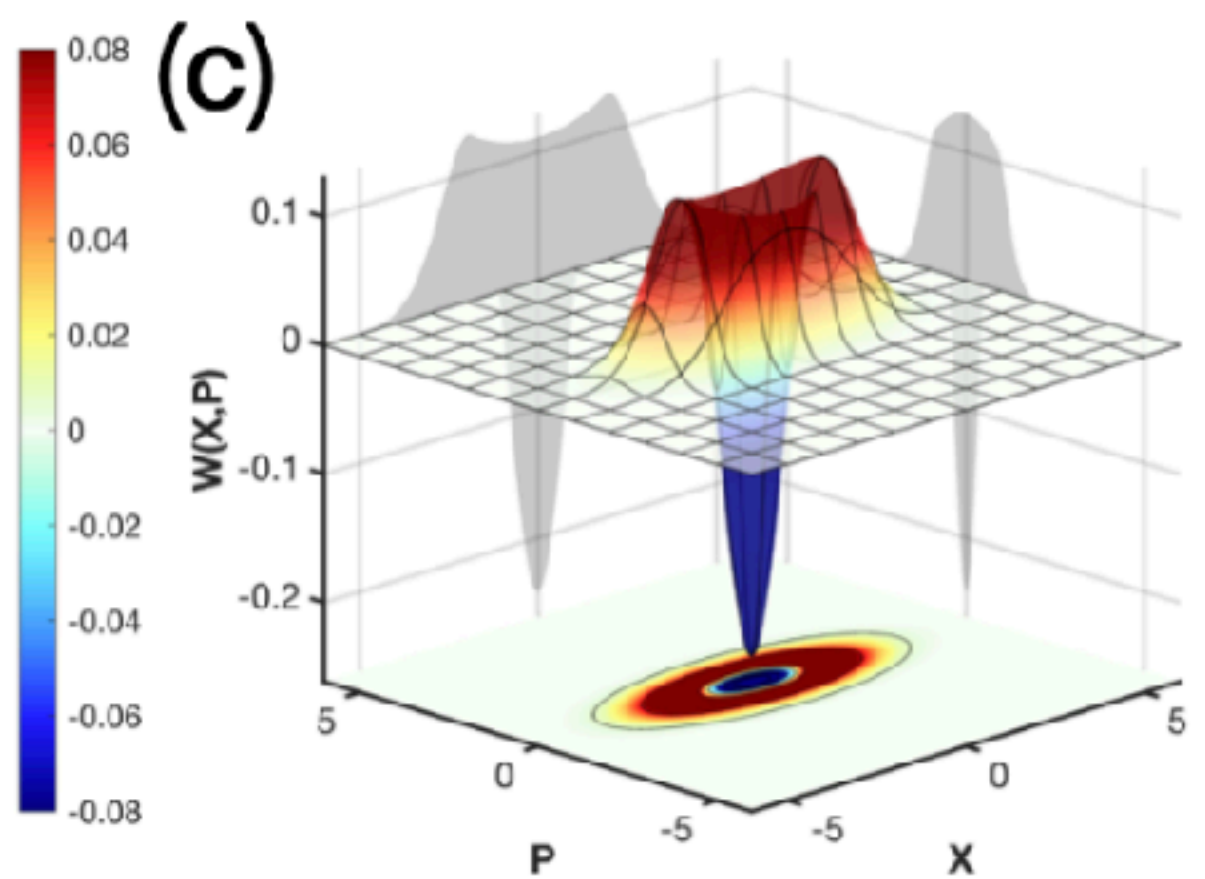
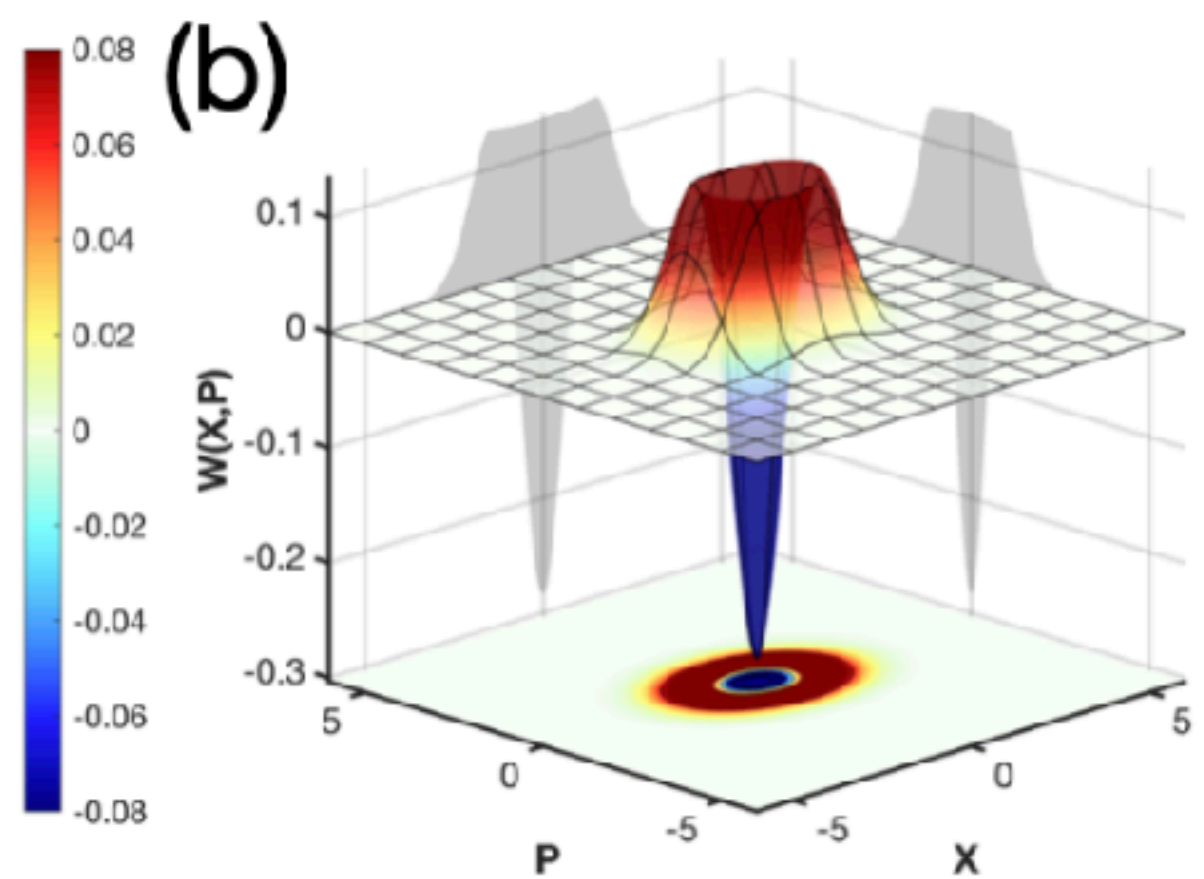
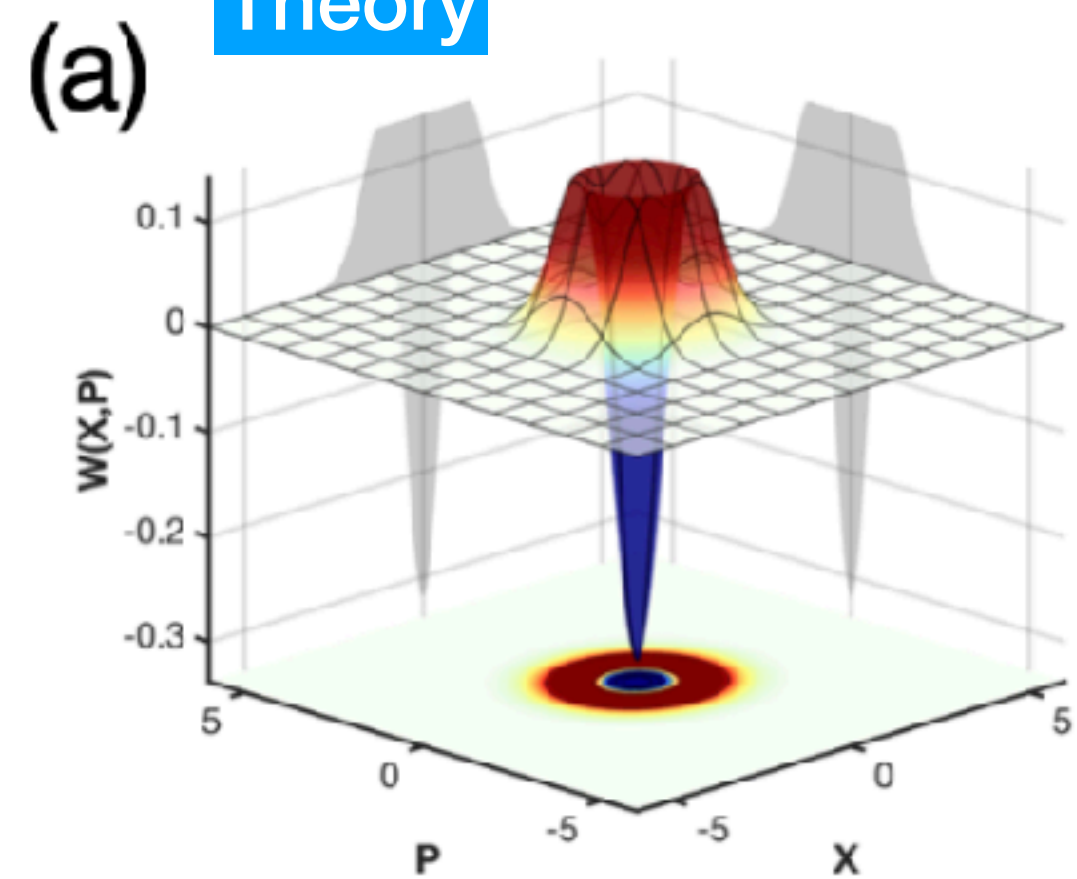
SQZ/ASQZ = -3.8:3.9 dB

-6.3:7.3 dB

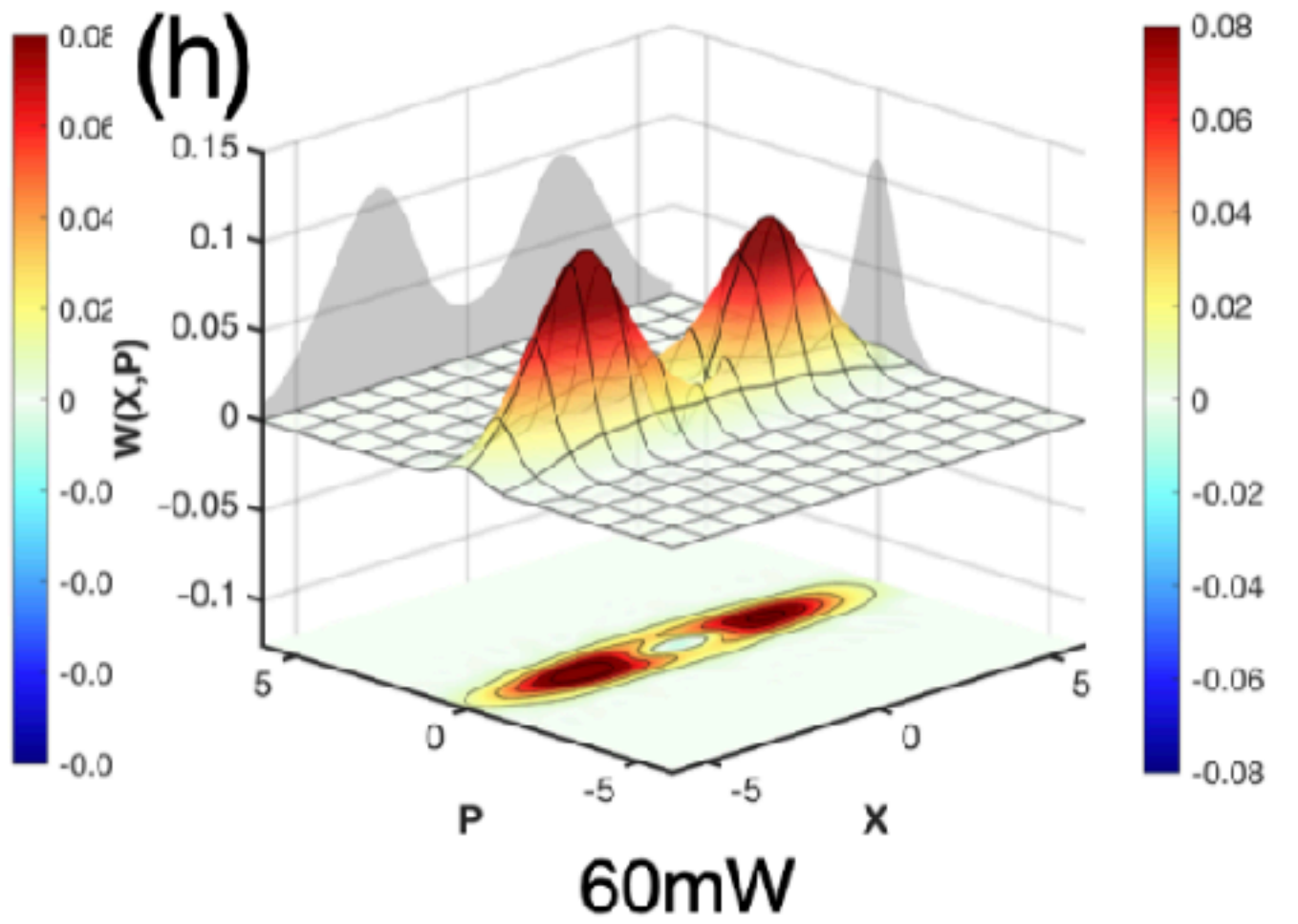
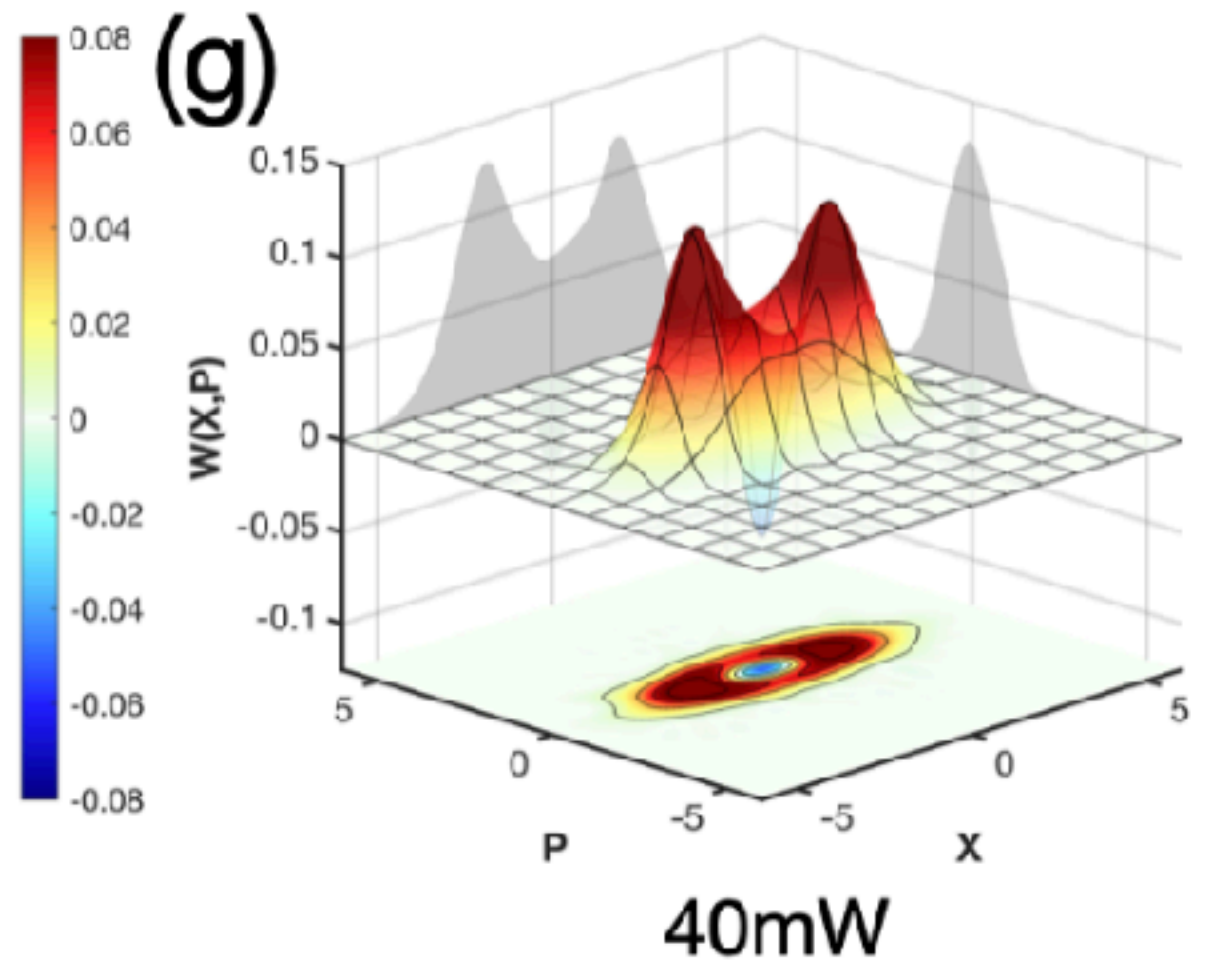
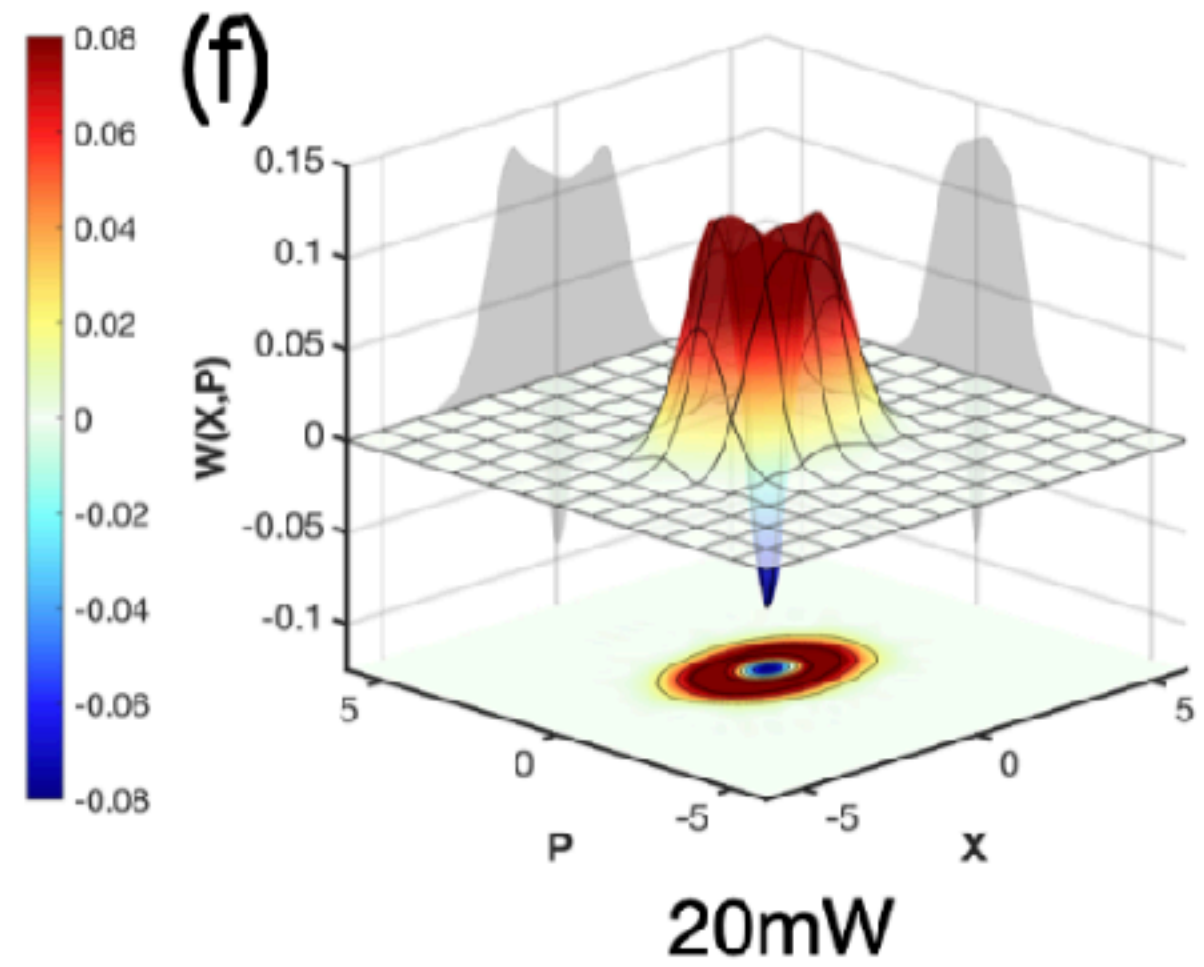
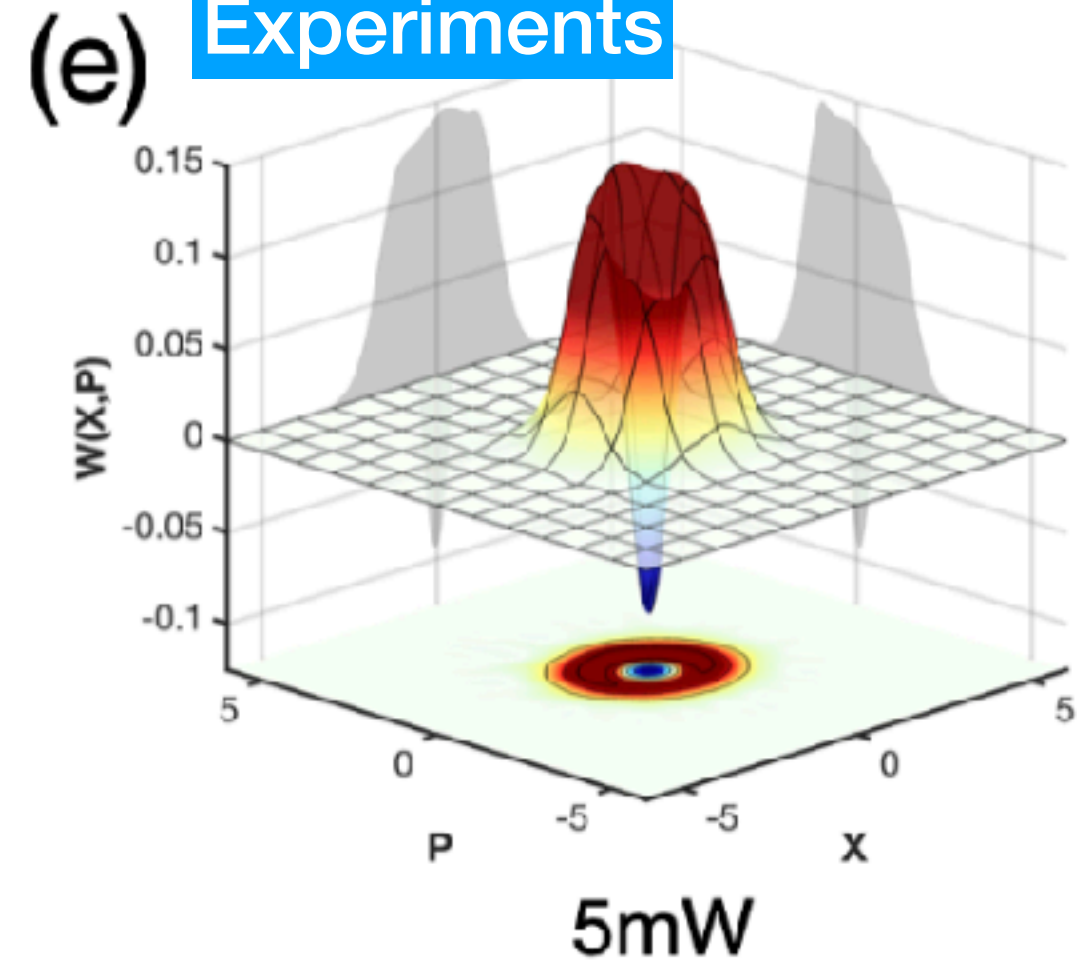
-7.6:11.6 dB

-8.9:15.1 dB

Theory



Experiments



photon number, $n = 0.16$

$n=0.55$

$n=1.54$

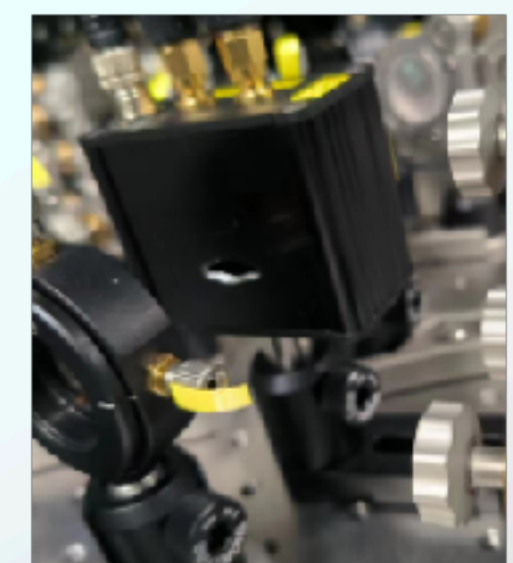
$n=3.13$

Entangled two-mode SQZ:

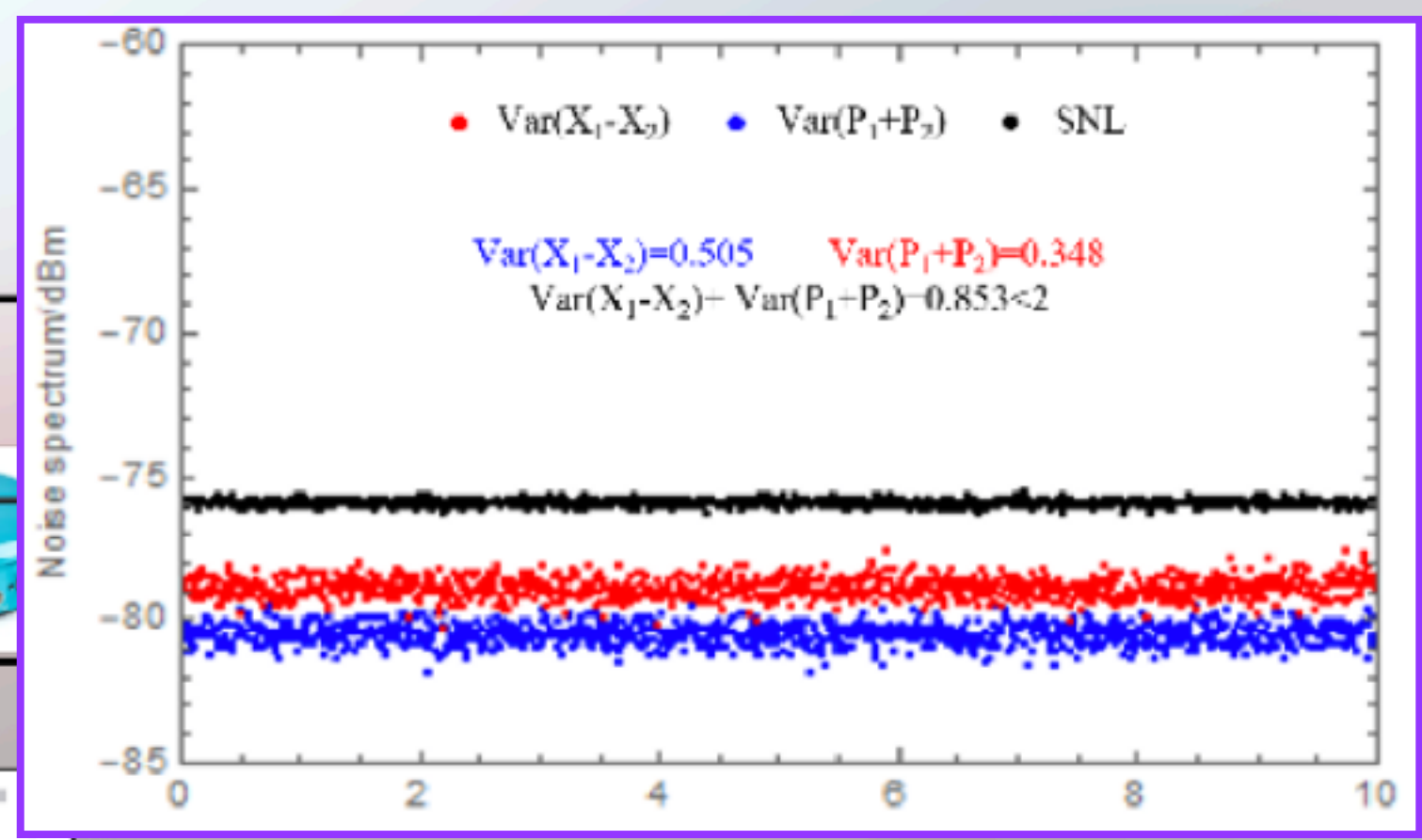
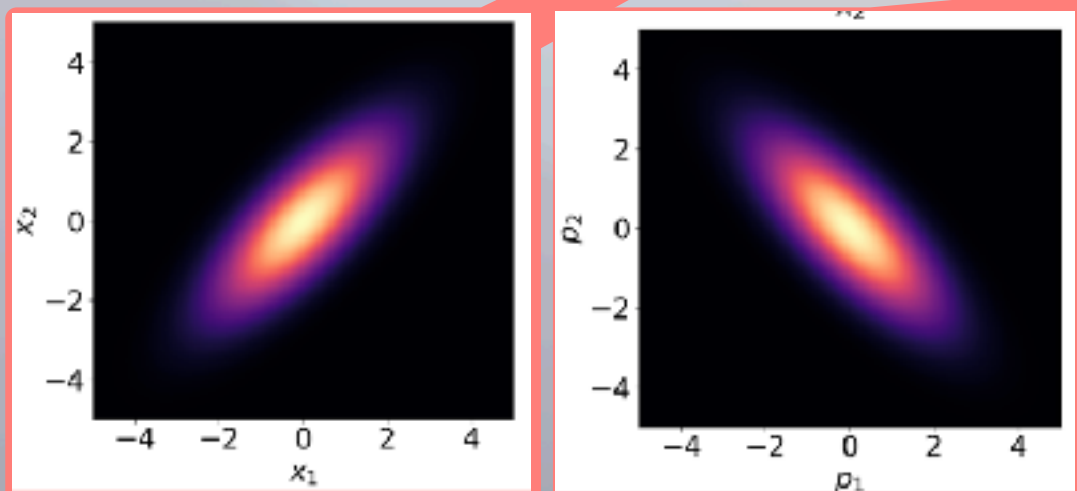
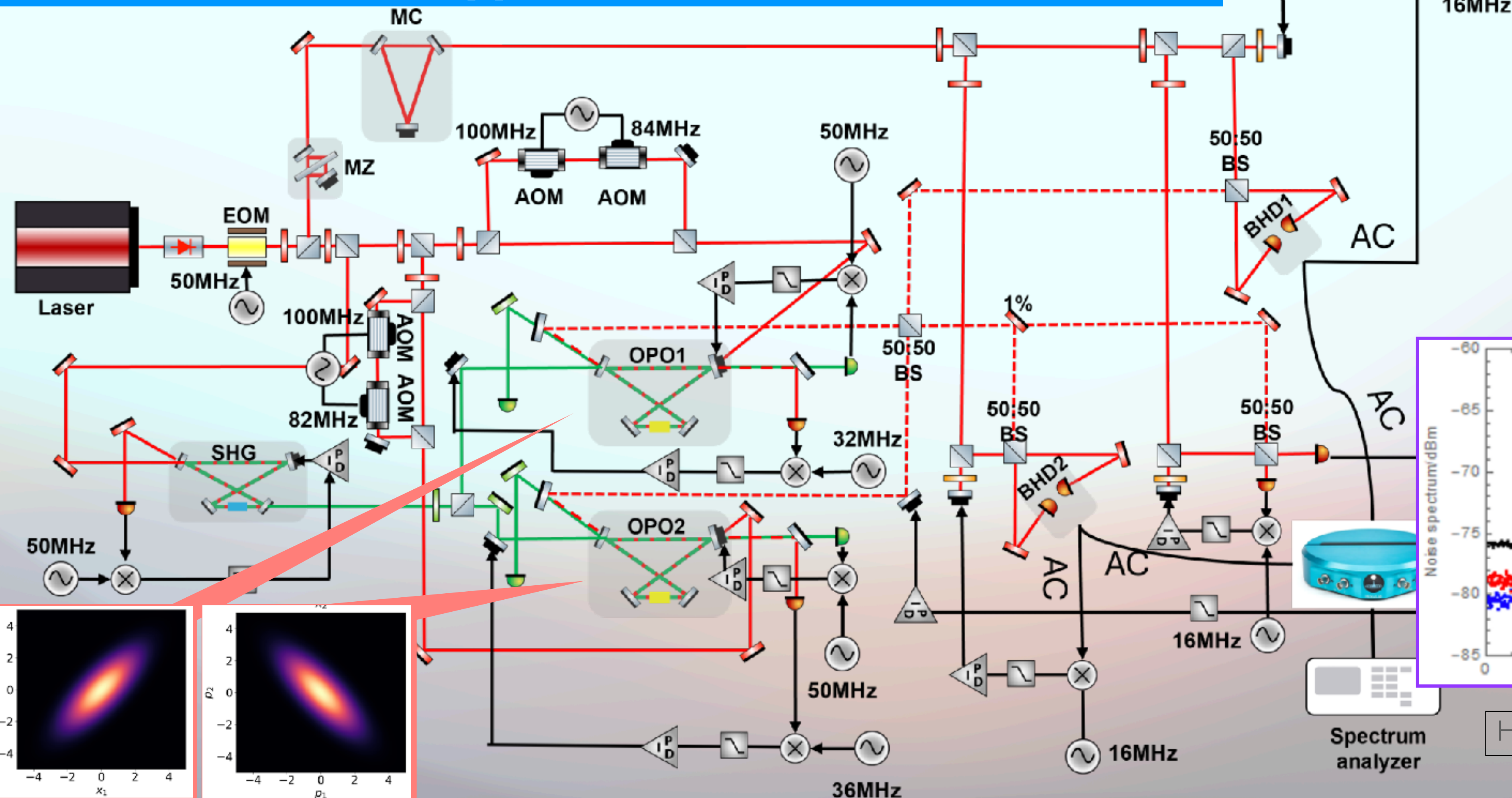


Machine Learning Enhanced Quantum State Tomography: A Covariance Matrix Approach

Juan Camilo Rodriguez Perez, et al.,
arXiv:2501.xxxxx (2025).



BHD



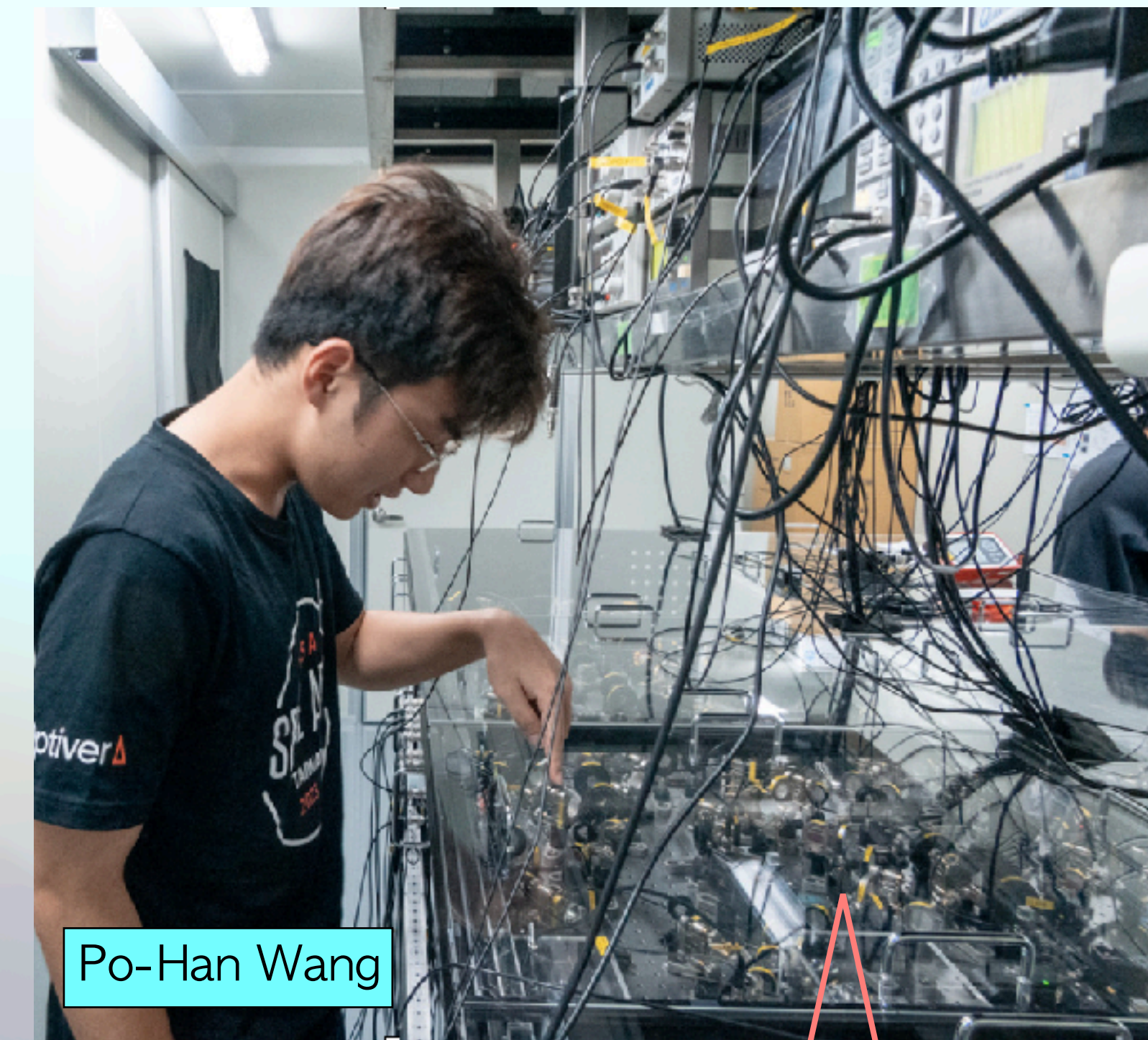
Hua Li Chen, et al., in preparation (2025).

Outlook: Bigger, Entangled, and to GWD

Optical Cat States: Non-Gaussianity

ML-QST: Entanglement

Quantum Sensors: Gravitational Wave Detector



- Largest Big Optical Cat (two-photon addition)
- GKP states as Error-Correcting Code
- Probe the Decoherence



- ML-QST for Entanglement in 2 mode SQZ
- Quantum Teleportation/Gate
- Entangled Cats



- EPR-SQZ, Teleportation
- Quantum Filter, $SU(1,1)$
- non-Gaussianity for GWD

日本巡展, BH-GW science exhibition, 2025-2029

“Black Hole and Gravitational Waves - - Attractive Attractive Force (2025-2028)”

ブラックホールと重力波 魅力的な引力

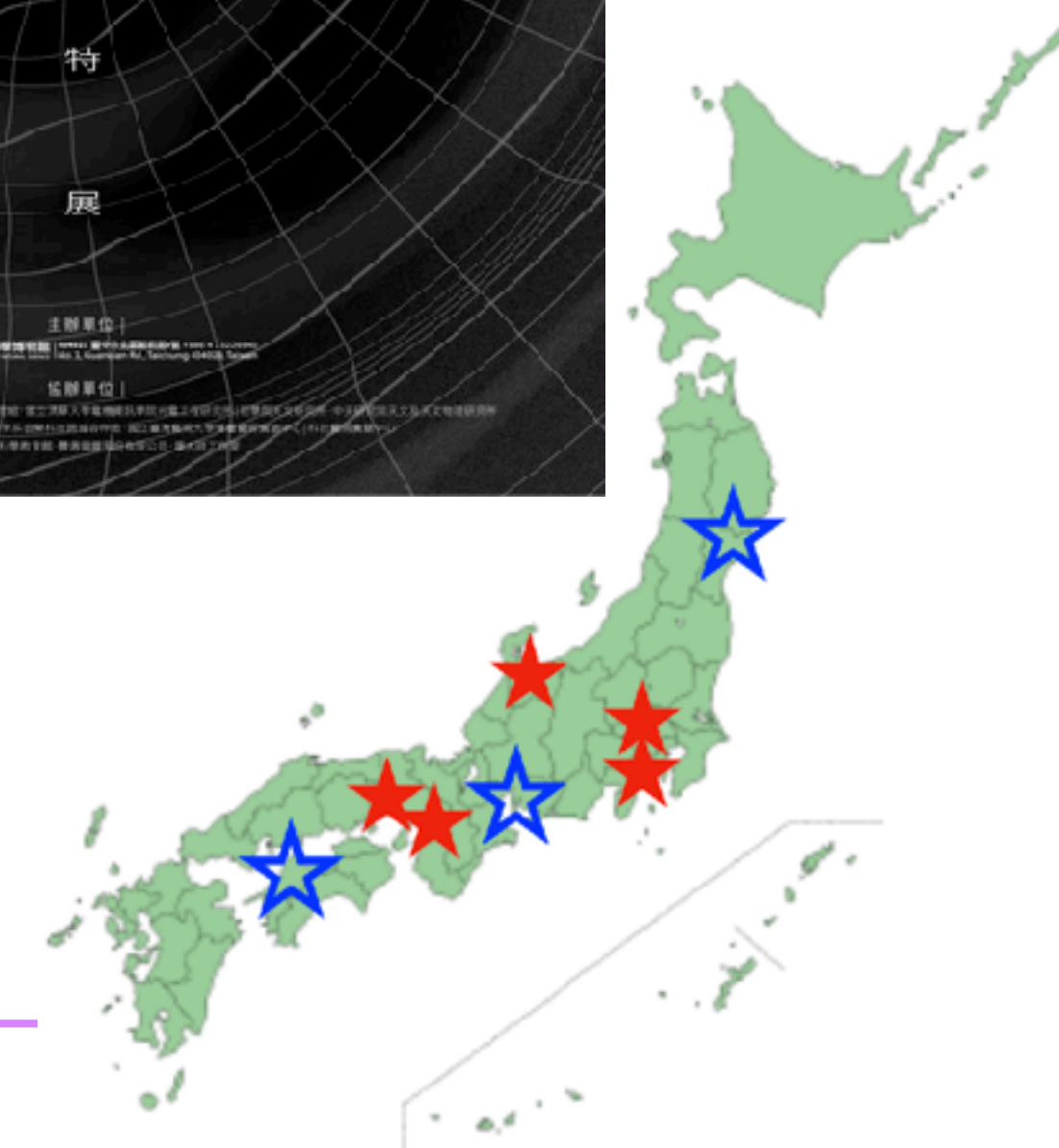
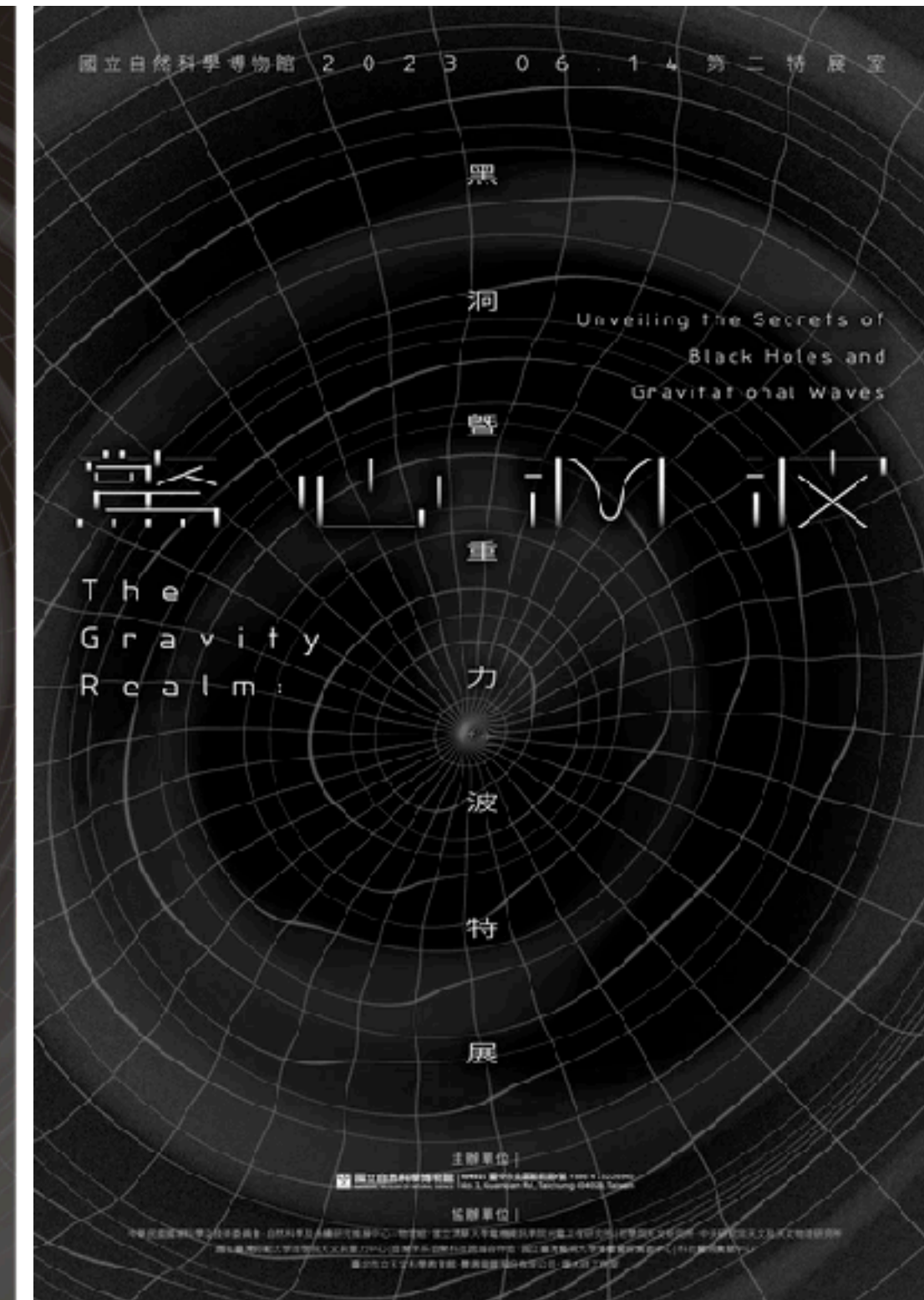
- ✓ 2025年7月19日～8月31日 Osaka 大阪市立科学館
- ✓ 2025年7月19日～9月7日 Akashi 明石市立天文科学館
- ✓ 2025年夏休みから秋 Sendai 仙台市天文台
- ✓ 2026年 Yokohama 宇宙科学館 (横浜) (TBD)
- ✓ 2027年 Spring Toyama 富山市科学博物館
- ✓ 2027年夏から秋 Ehime 愛媛県総合科学博物館 (TBD)

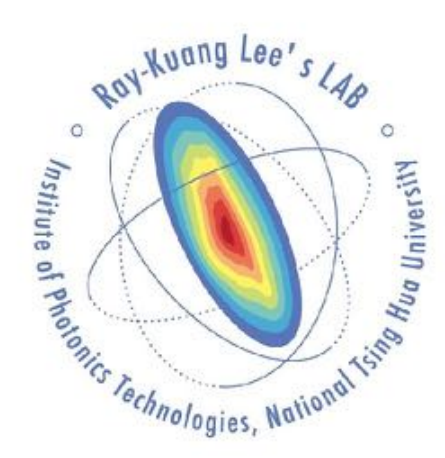
→ + three under consideration

✓ 2028年 Winter～2029年 Spring Tokyo 国立科学博物館

✓ 主催 国立科学博物館 (東京) 国立自然科学博物館 (台中)

✓ 協力 国立清華大學 (新竹) 大阪工業大学 東京大学宇宙線研究所 国立天文台 康木祥工作室





Thank you for your attention.