令和四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

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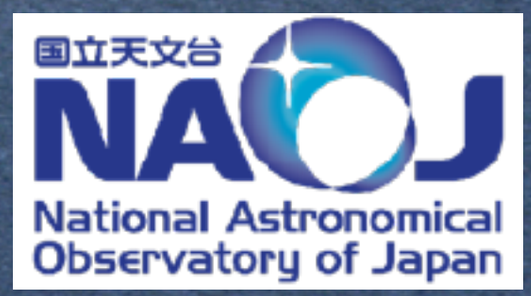
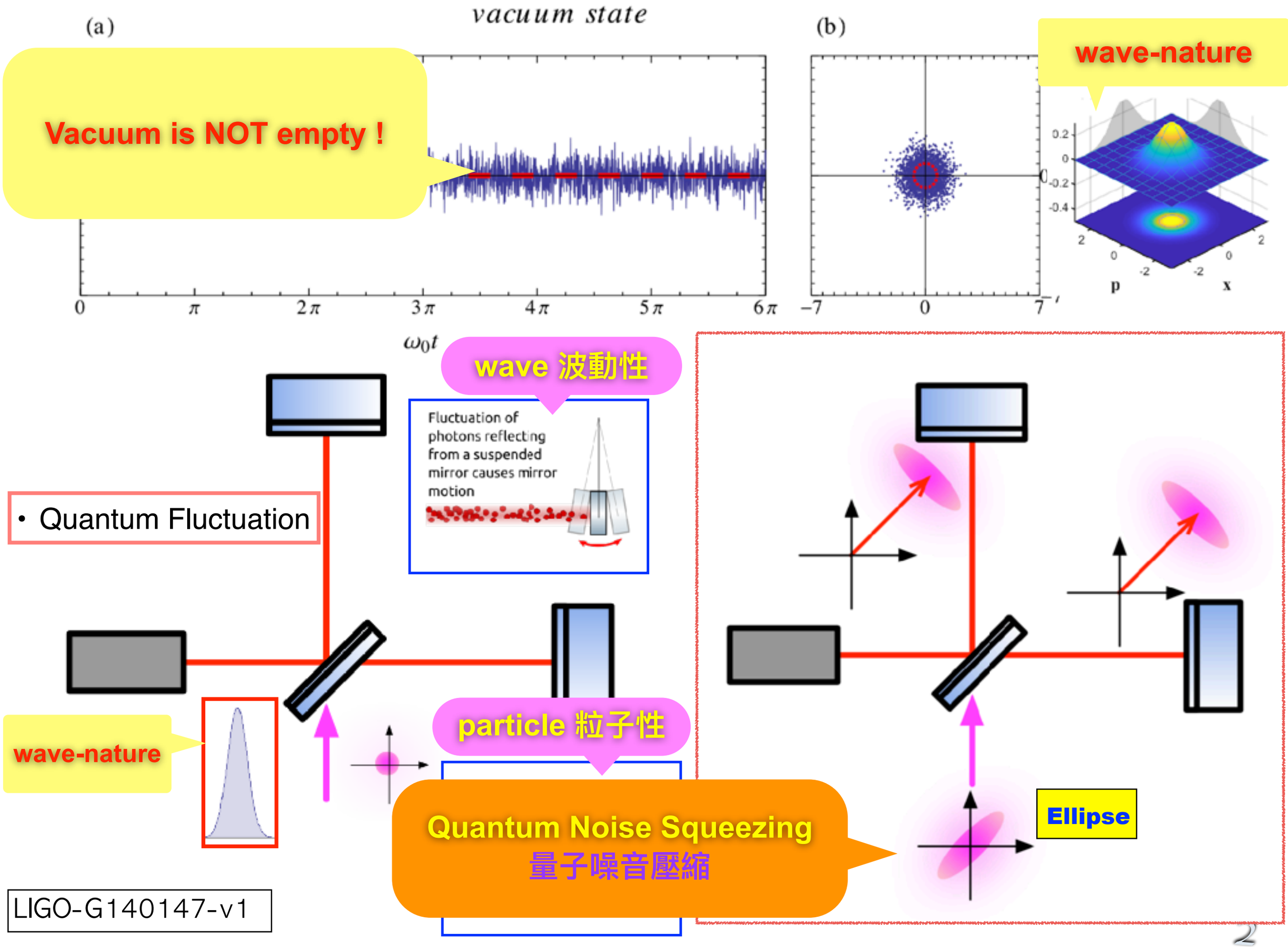
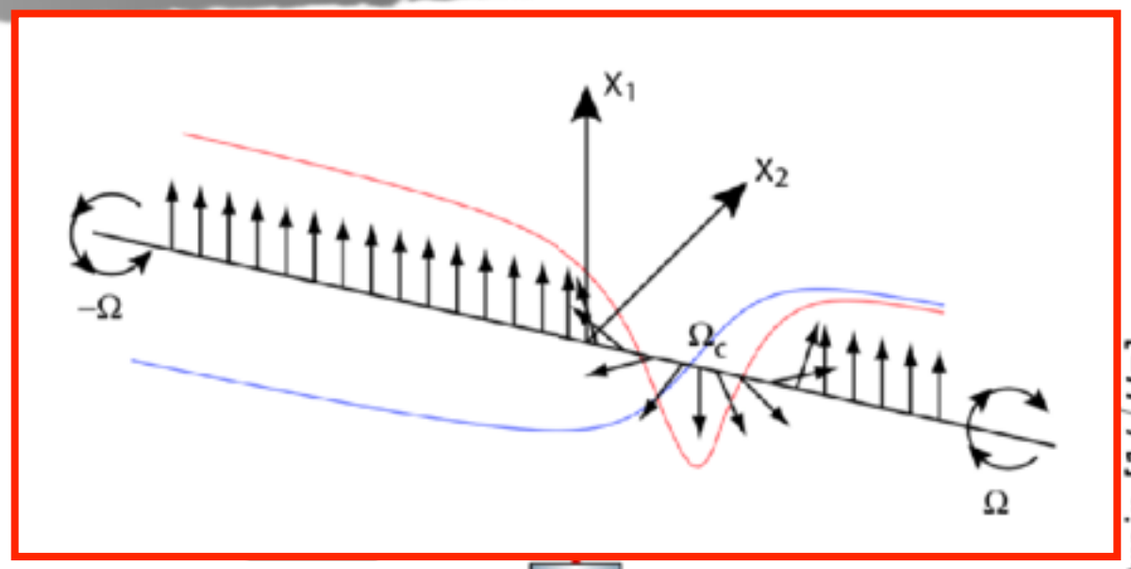
National Tsing Hua University (NTHU), Taiwan
LIGO-Virgo-KAGRA (LVK) Collaboration
Yu-hang Zhao, Matteo Leonardi, (+ Yoichi Aso, Takayuki Tomaru)
Shinji Miyoki

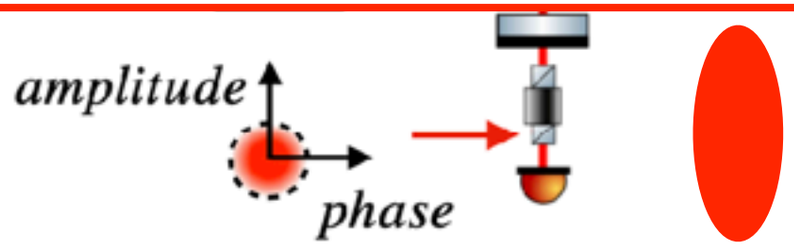


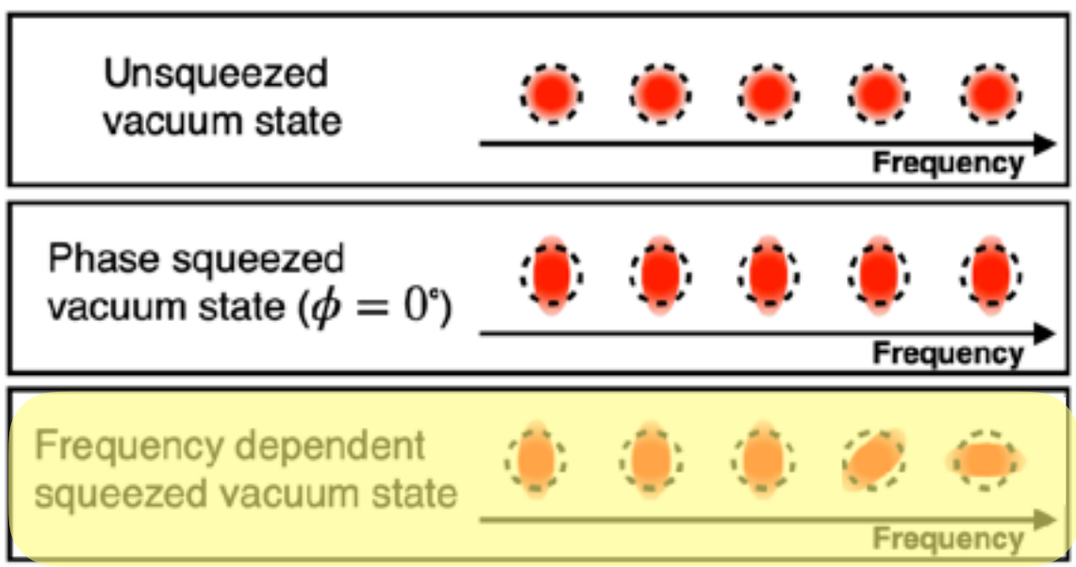
Feb. 21st, 2023

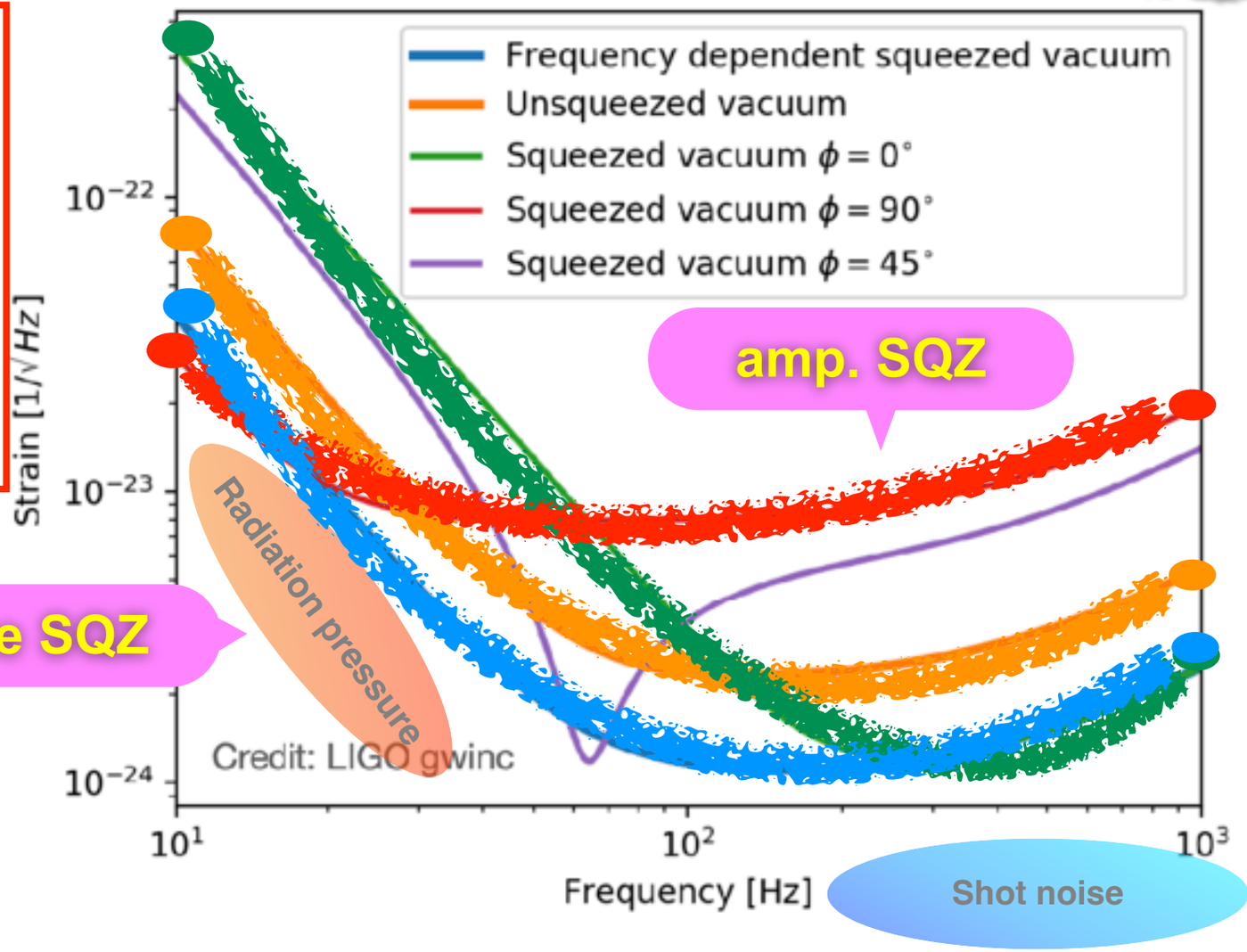

vacuum state
(a)
(b)
Vacuum is NOT empty !
wave-nature
0
π
2π
3π
4π
5π
6π
$\omega_0 t$
−7
0
7
0.2
0
-0.2
-0.4
2
0
-2
p
x
wave 波動性
Fluctuation of photons reflecting from a suspended mirror causes mirror motion
• Quantum Fluctuation
wave-nature
particle 粒子性
Quantum Noise Squeezing
量子噪音壓縮
Ellipse
LIGO-G140147-v1

Freq. Dependent SQZ: FIS -> FDS



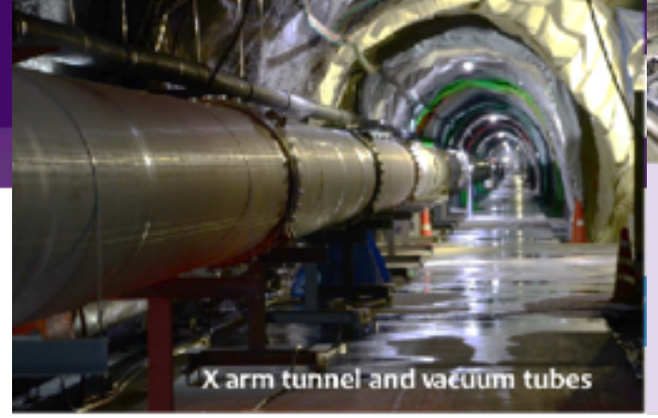


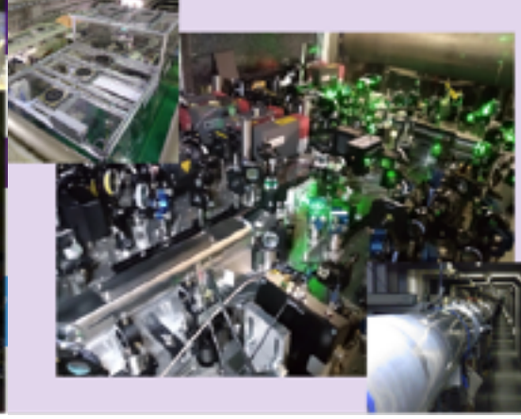




Frequency dependent squeezed vacuum needs proper angle at specific frequencies, which is realized by filter cavity in this plot

credit: Yuhang Zhao



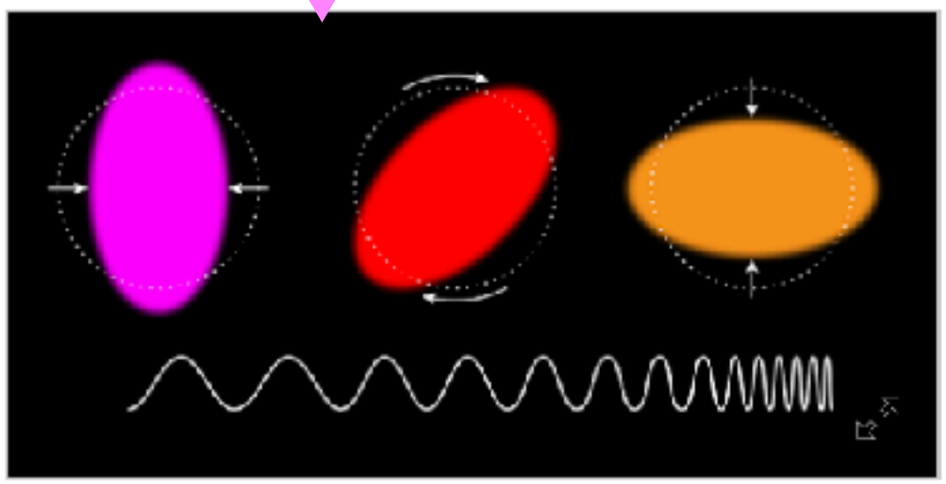


Synopsis: Feeling the Squeeze at All Frequencies

April 28, 2020 • *Physics* 13, s55

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

FDS



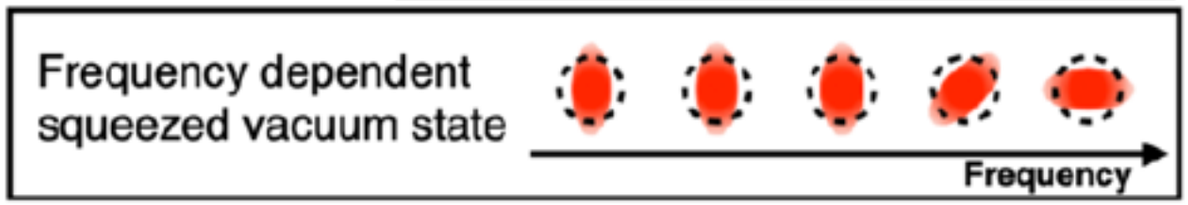
APS/Alan Stonebraker

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

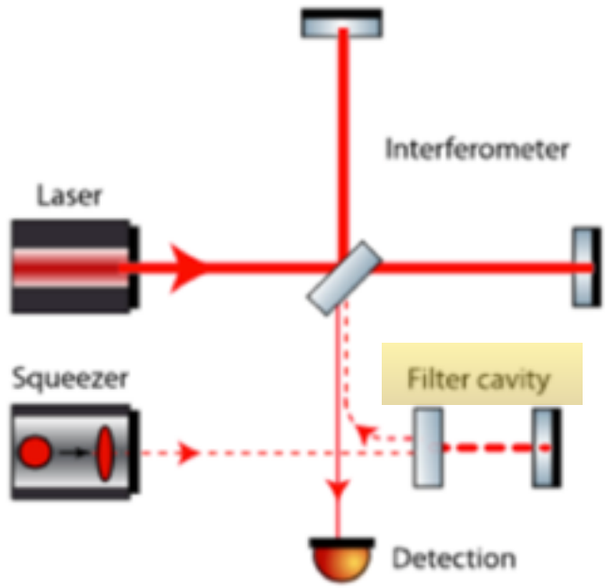
Phys. Rev. Lett. 124, 171101 (2020)

Published April 28, 2020



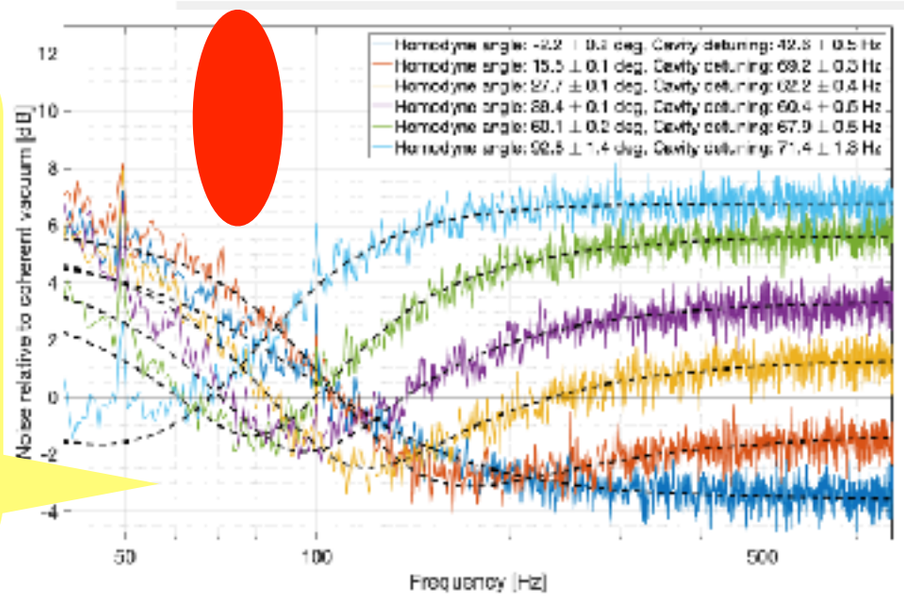
KAGRA Filter Cavity (KFC) Team

KFC sogood™



First Exp. on FDS,

Freq.-Dep. Squeezing, at 100 Hz



Toolbox to diagnose Squeezers

ICRR Inter-University Research Program is added in the acknowledgement:

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

- **Machine-learning enhanced Quantum State Tomography:**

✓ **Quantum State Tomography with Machine-Learning** PRL 128, 073604 (2022). Fiscal Year 2021

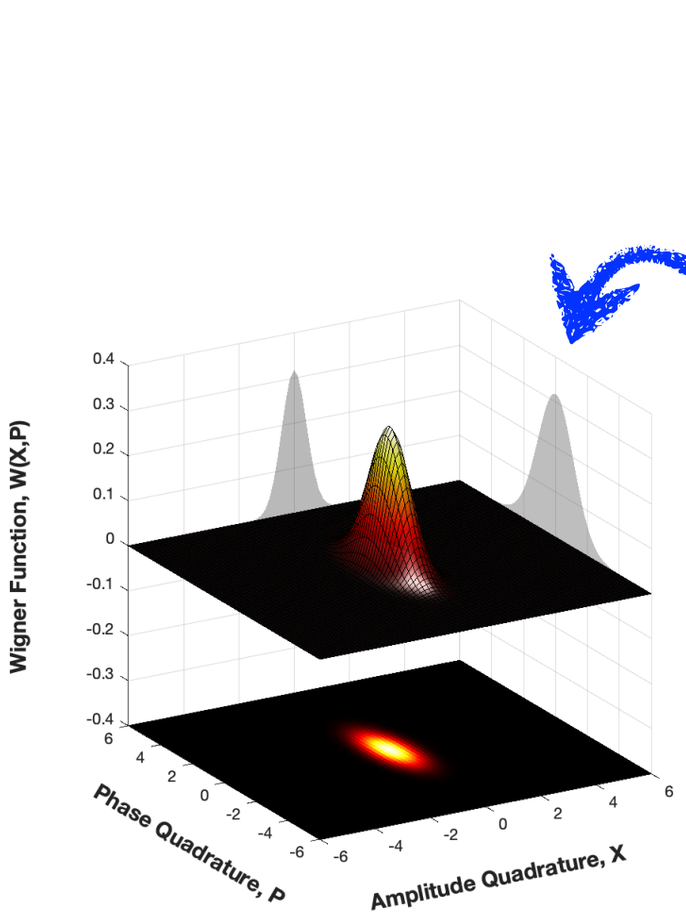
✓ **Quantum Machine Learning:** Advances in Phys. X (Review Article) 8, 2165452 (2023). Fiscal Year 2022

- **Toward Real-Time Quantum State Tomography:**

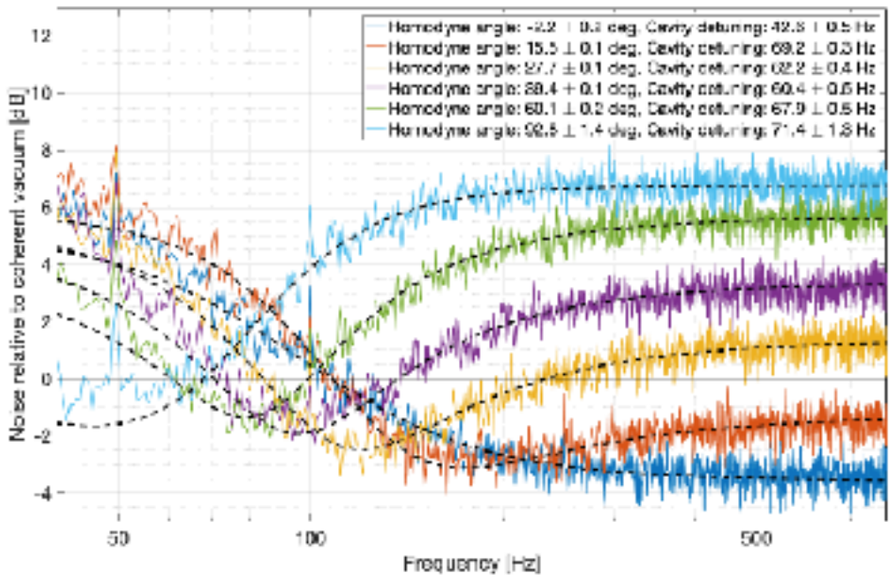
✓ **Wigner current for Squeezed States** arXiv: 2111.08285 (2021). Fiscal Year 2022

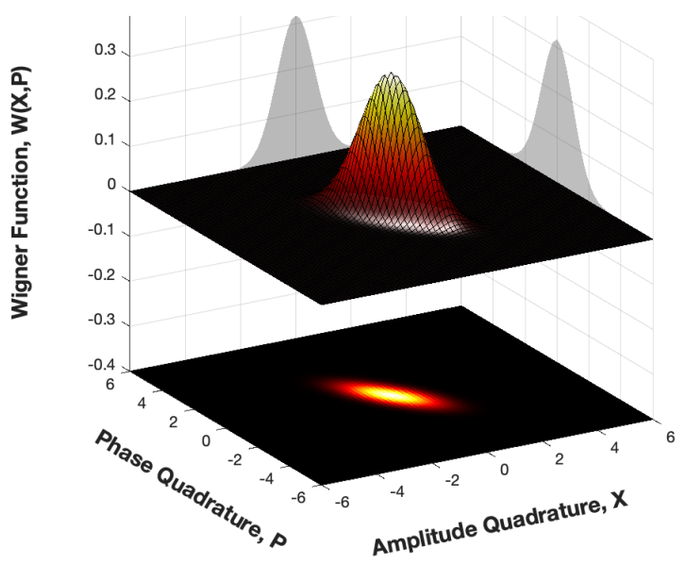
Quantum State Tomography:

Can we Monitor the purity of the quantum state?

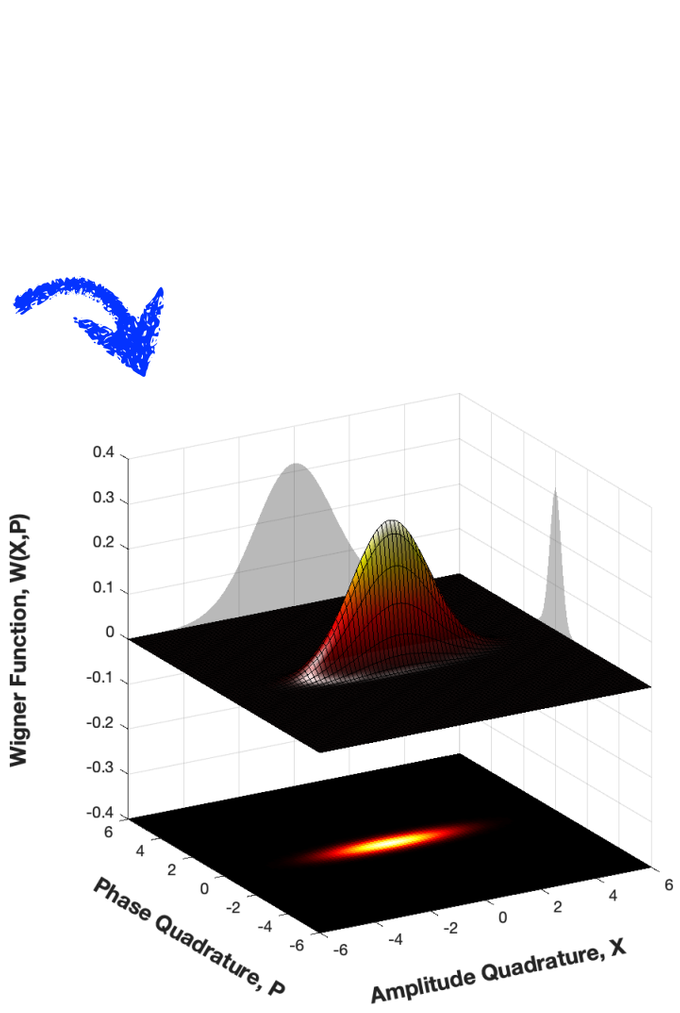


Low frequency region



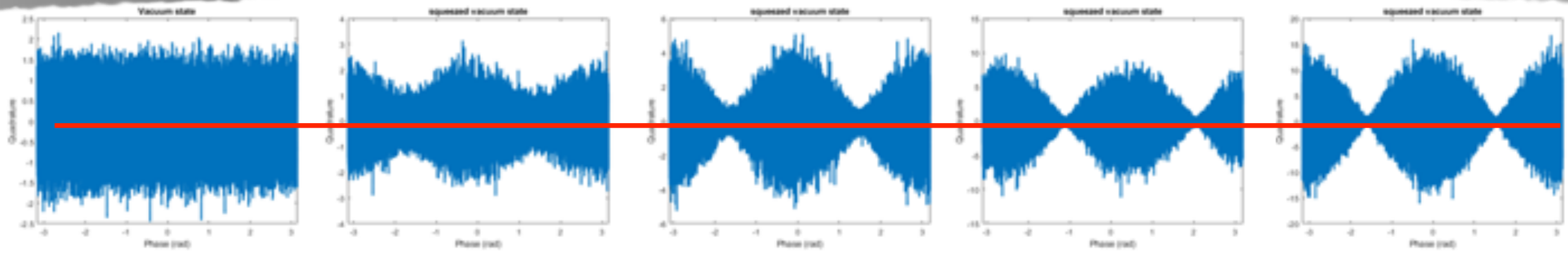


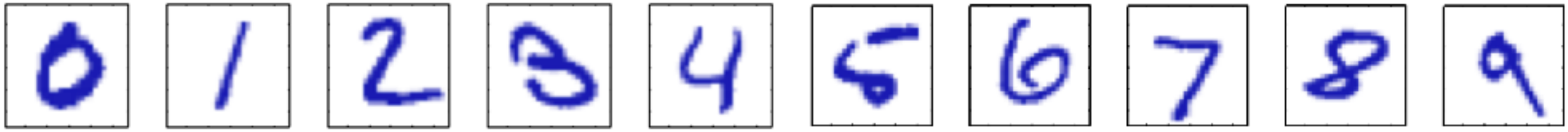
Middle frequency region



High frequency region

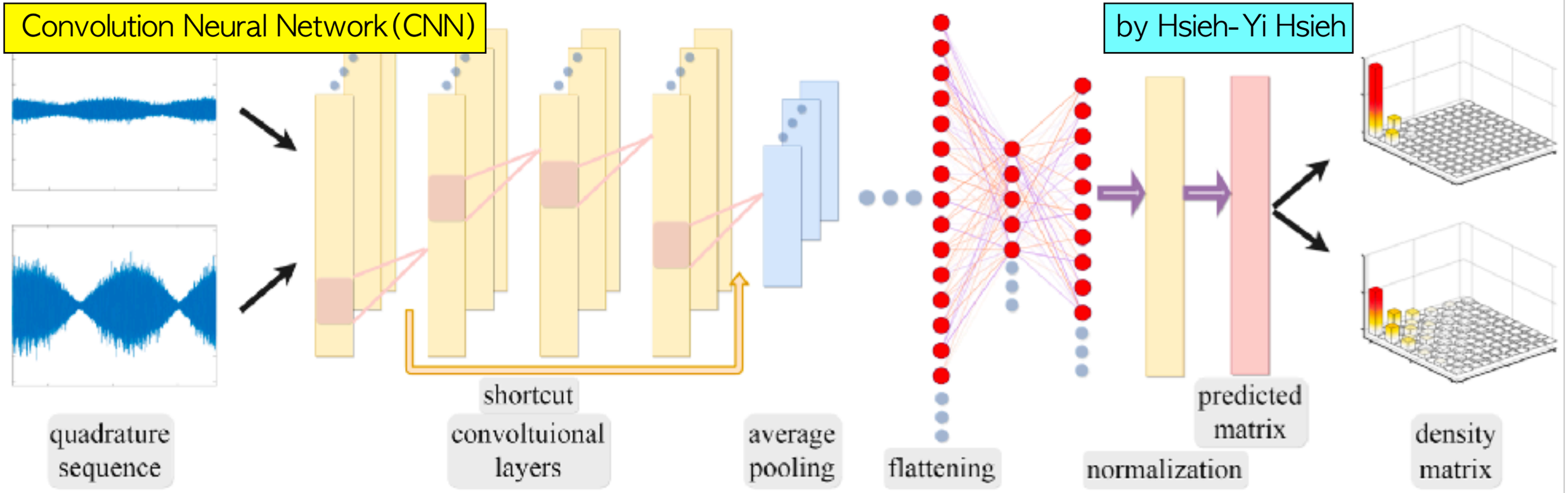
Pattern Recognition & Machine Learning



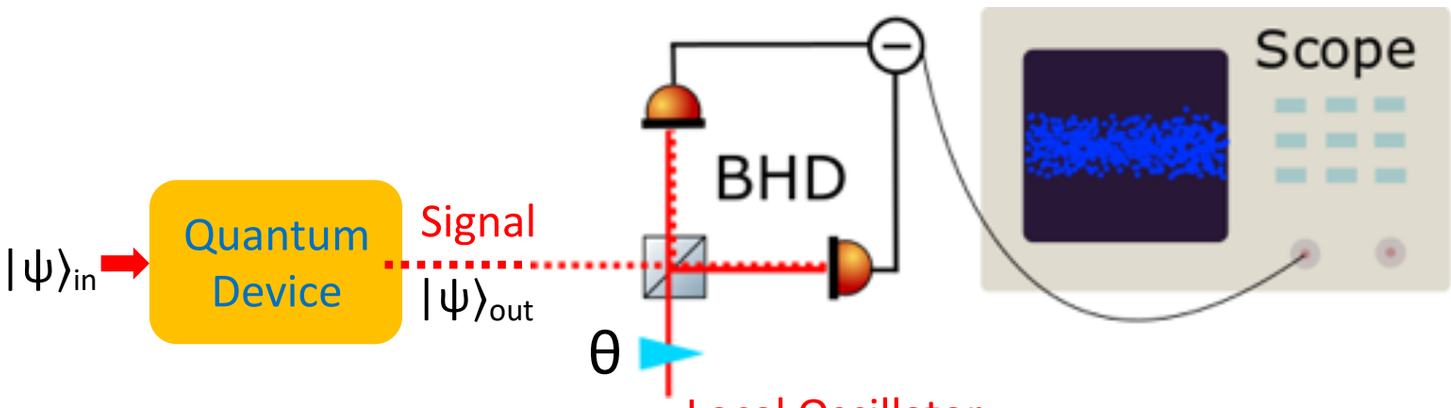


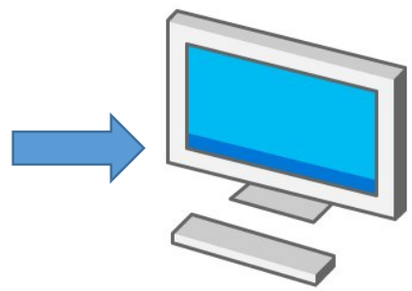
Convolution Neural Network (CNN)

by Hsieh-Yi Hsieh

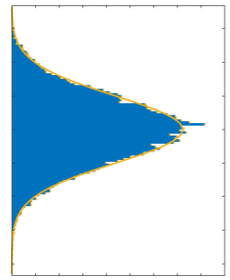


Machine Learning (SQ Learner) vs MLE

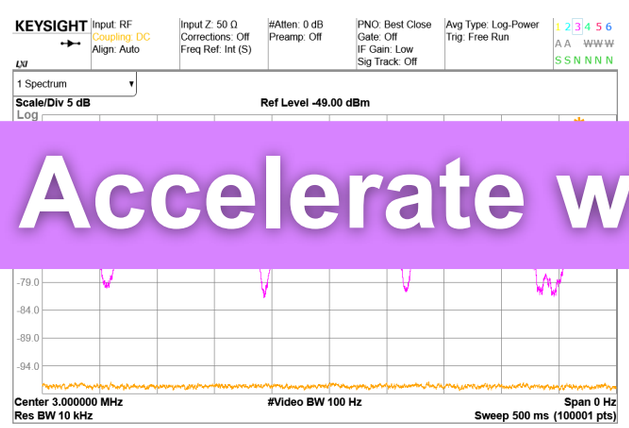




Probability distribution
Pr(q, θ)

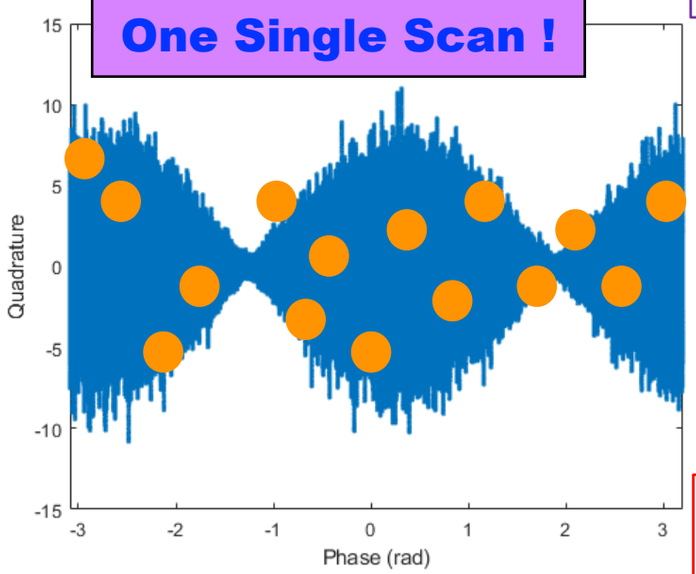


Reconstruction Algorithms



Accelerate with ML, but also Re-use training data

One Single Scan !

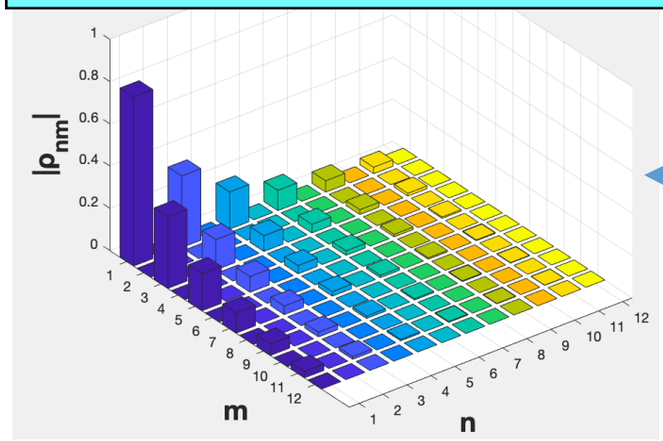


few minutes to reconstruct

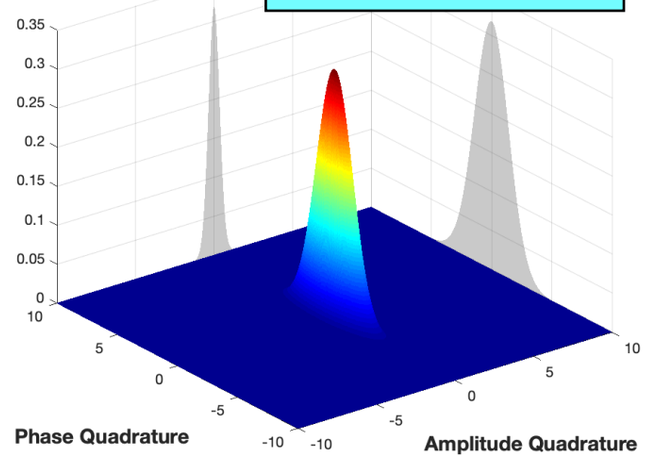
< 1s to reconstruct

Max. Likelihood Estimation, MLE

Density matrix in number basis



Wigner function



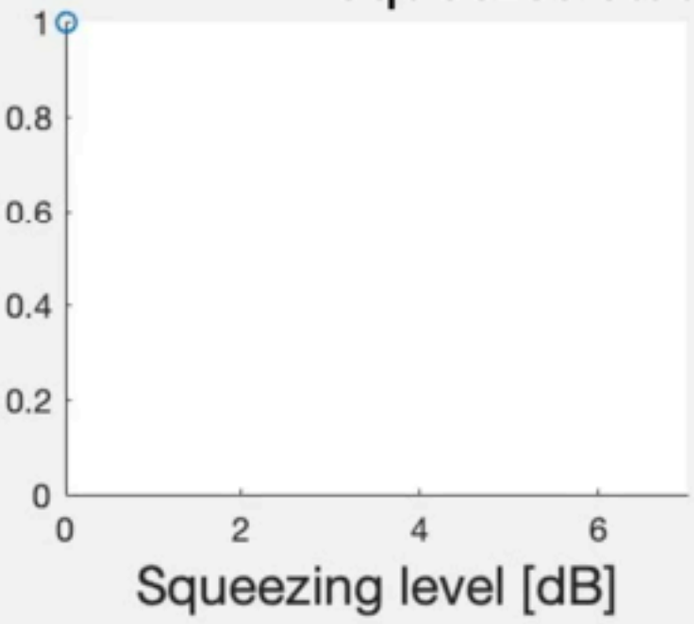
Machine Learning (SQ Learner), CNN

Applications of real-time tomography in squeezed state:

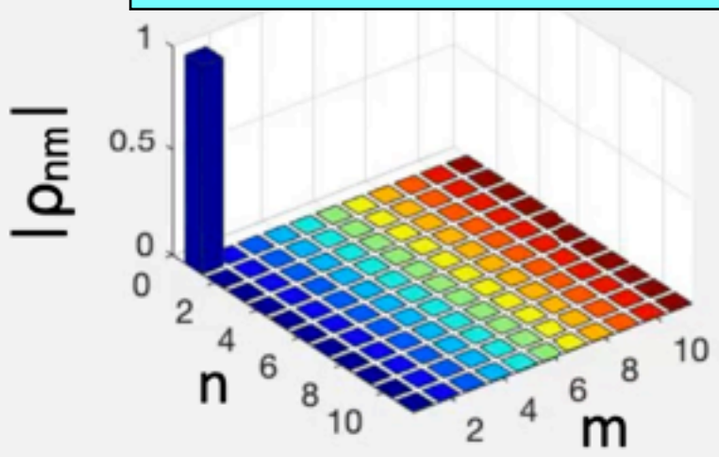
- Monitor the purity of a quantum state in real-time, and reveal the dynamics.
- The purity of a normalized quantum state is a scalar defined as:

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

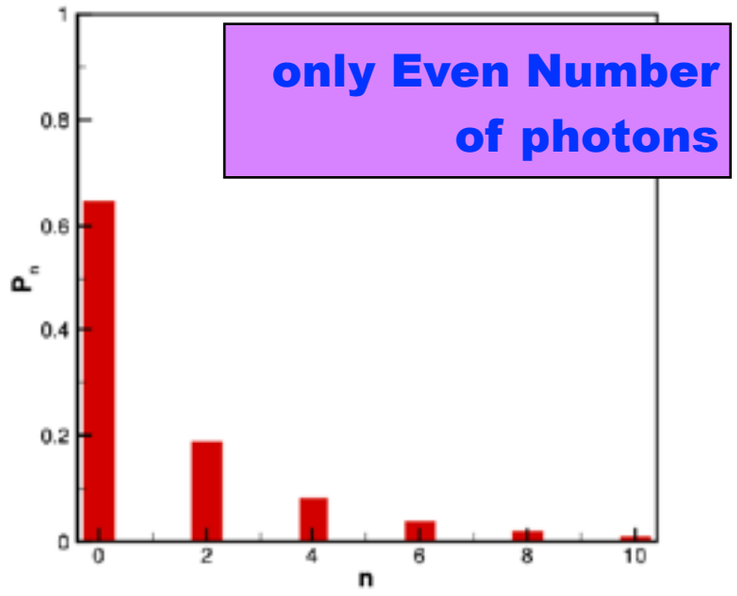
Squeezed state with loss



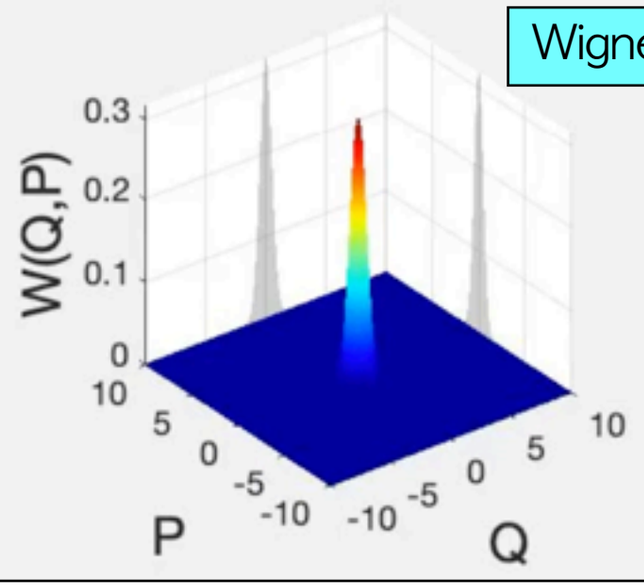
Density matrix in number basis

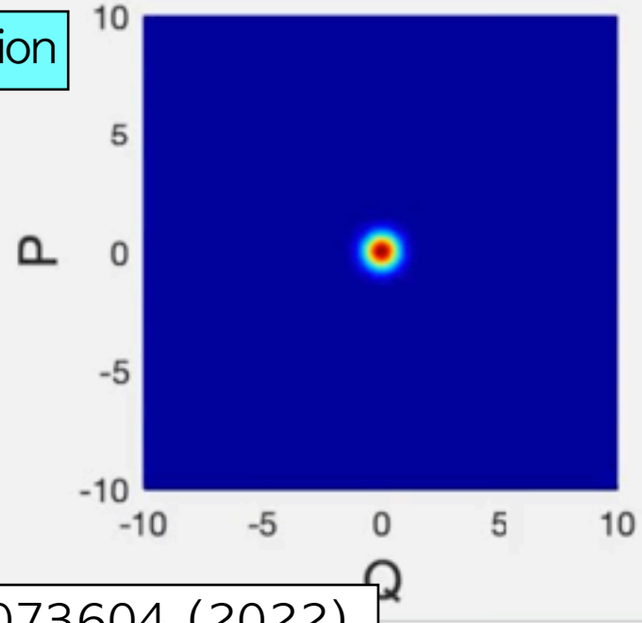


γ =1 for pure squeezed state

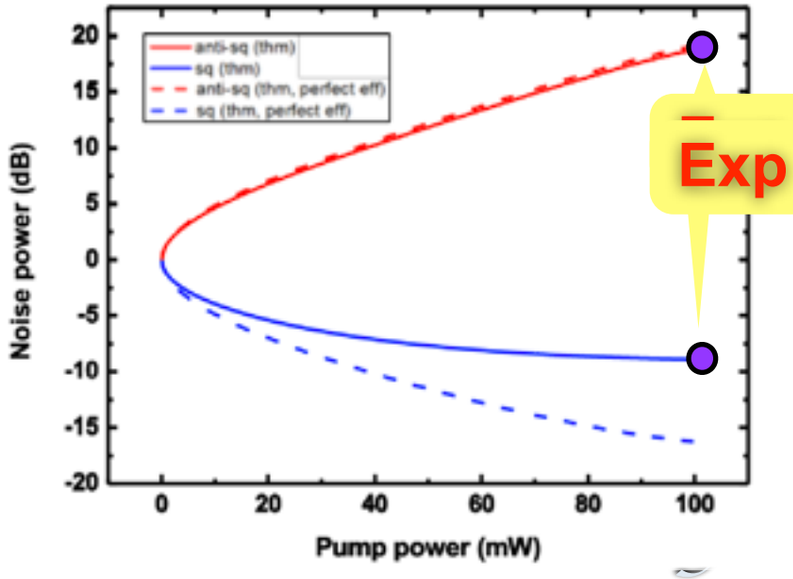


Wigner function





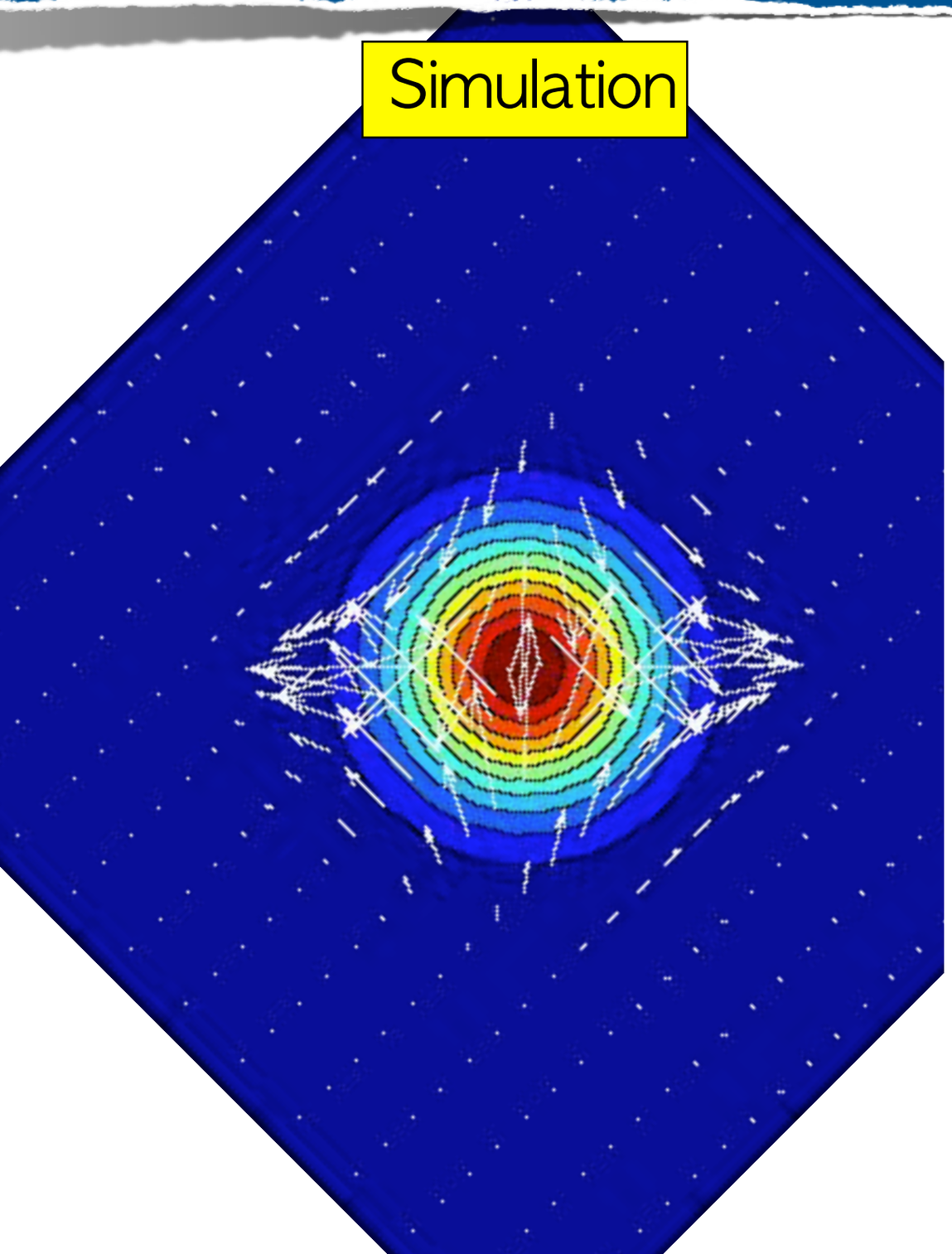
degrees of squeezing/anti-squeezing



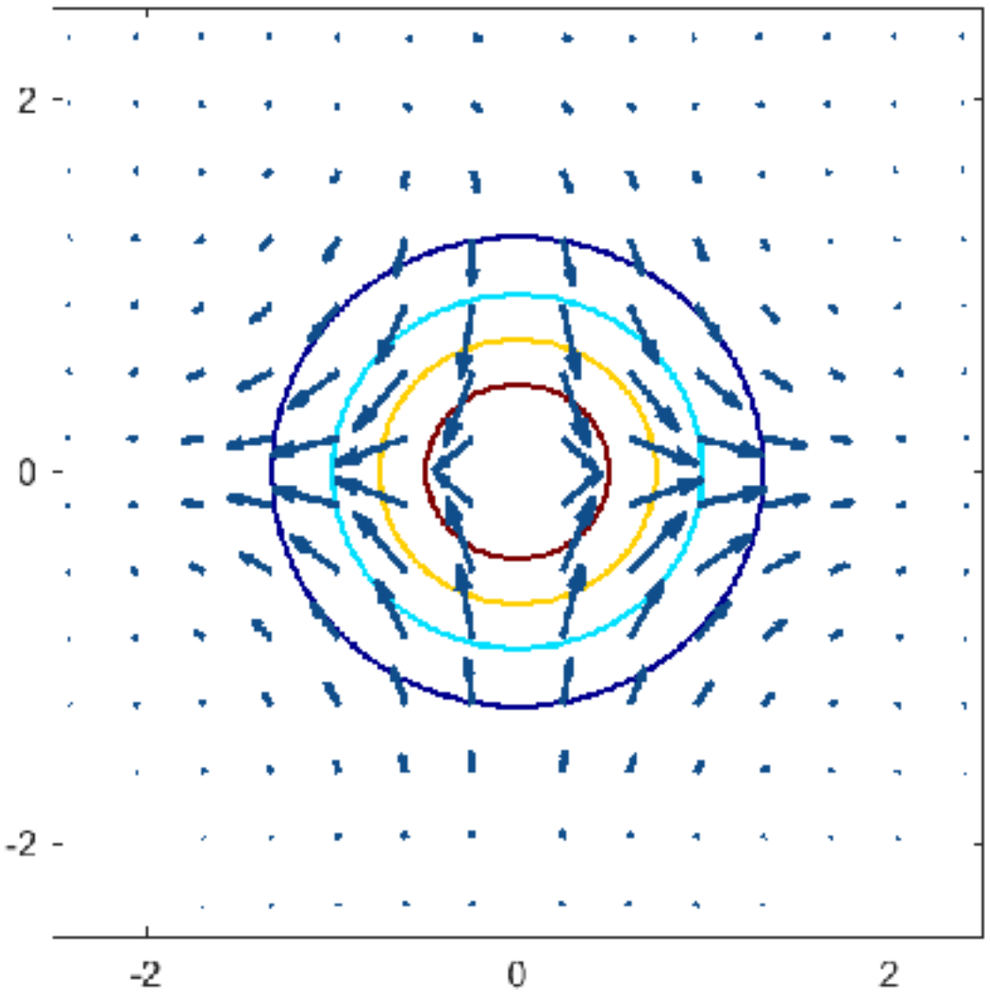
Hsieh-Yi Hsieh et al., Phys. Rev. Lett. 128, 073604 (2022).

Dynamics of Squeezers

Simulation

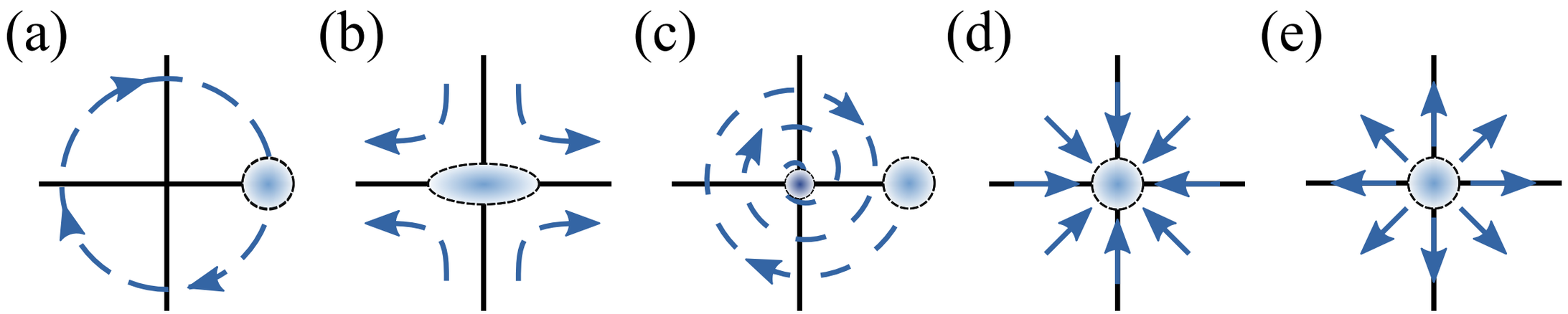


Exp. Reconstruction

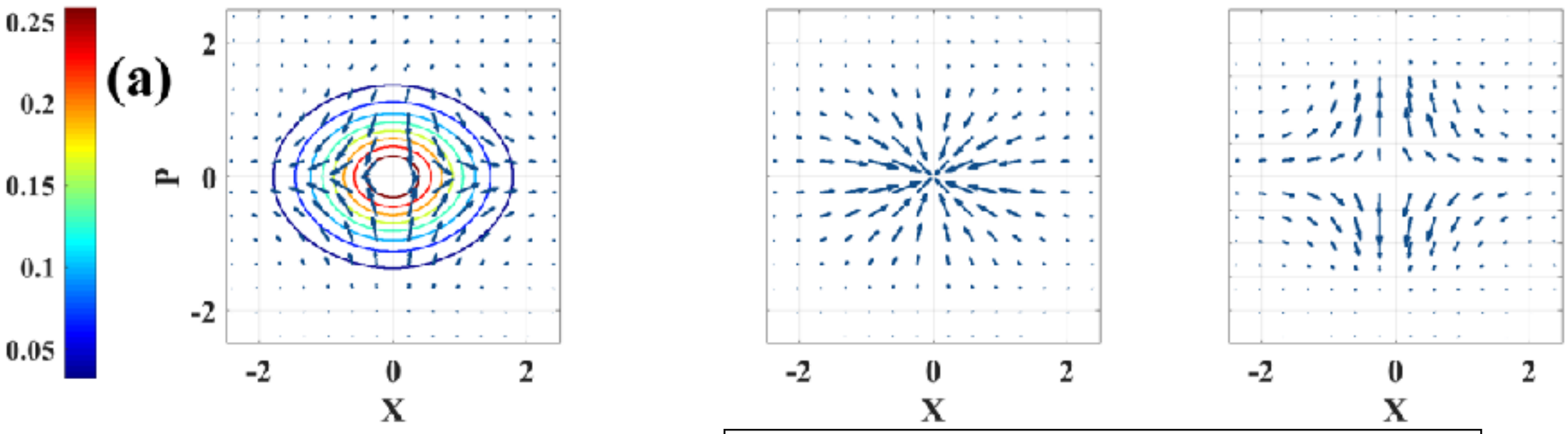


Yi-Ru Chen et al., arXiv: 2111.08285 (2021).

Topological Charges:



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

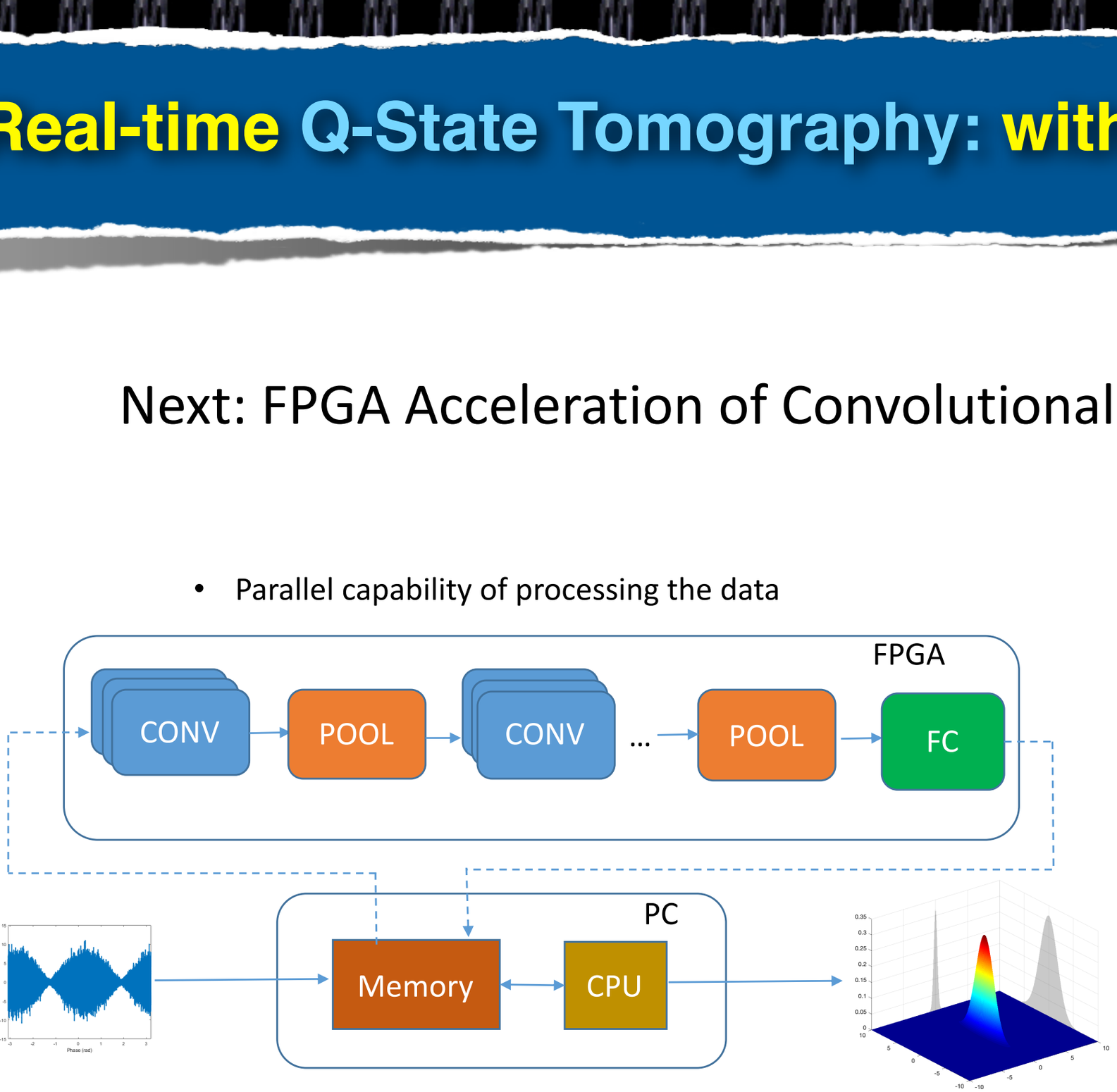


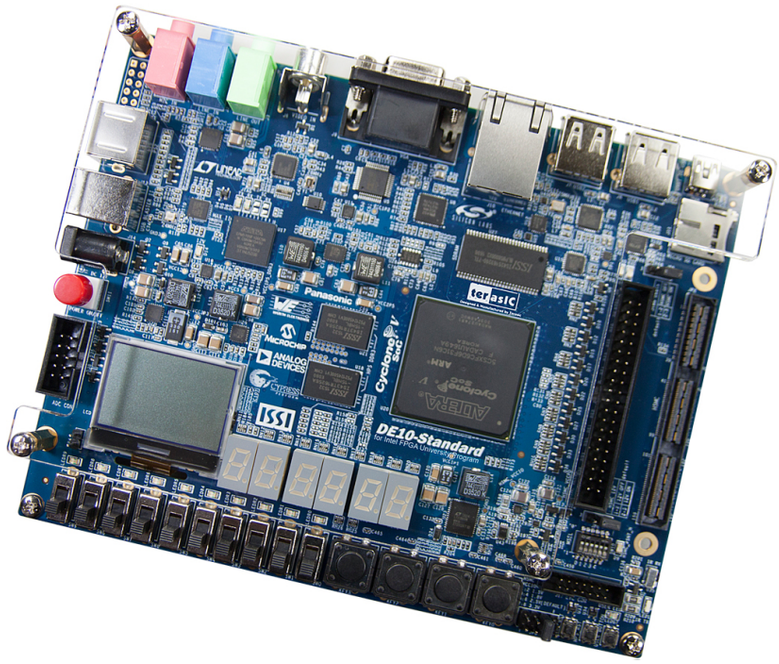
Yi-Ru Chen et al., arXiv: 2111.08285 (2021).

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

ありがとうございました

Thanks for your attentions ^.^