KAGRA KAGRA Observatory

国立天文台 NAOJ

國立清華大學 NATIONAL TSING HUA UNIVERSITY

Toward real-time quantum state tomography for the squeezed state with machine learning

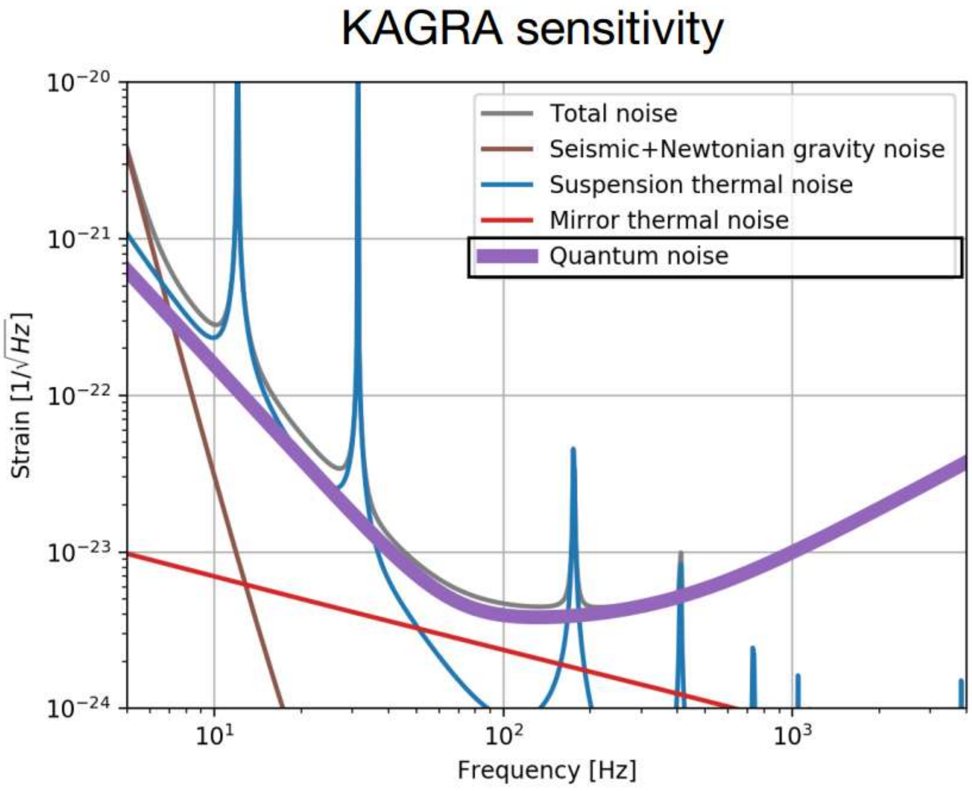
Hsien-Yi Hsieh, Yi-Ru Chen, Hsun-Chun Wu, Yao-Chin Huang,
Chien-Ming Wu and Prof. Ray-Kuang Lee

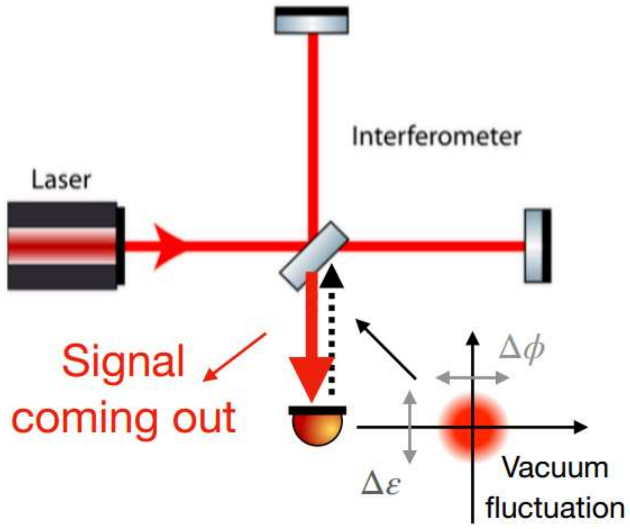
National Tsing Hua University, Taiwan

We participate in the development of frequency dependent squeezing (FDSQZ) which is led by Dr. Matteo Leonardi in National Astronomical Observatory of Japan

Sensitivity of KAGRA is limited by Quantum noise

- KAGRA is designed to operate at cryogenic temperatures to reduce thermal noise.

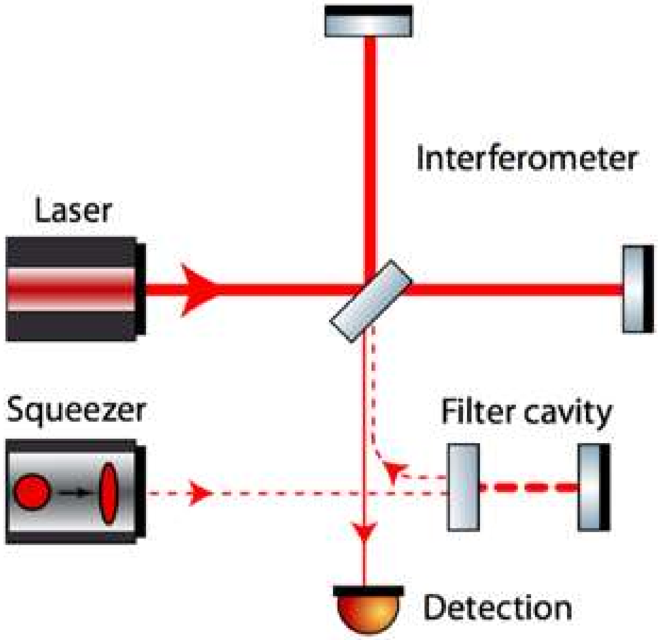




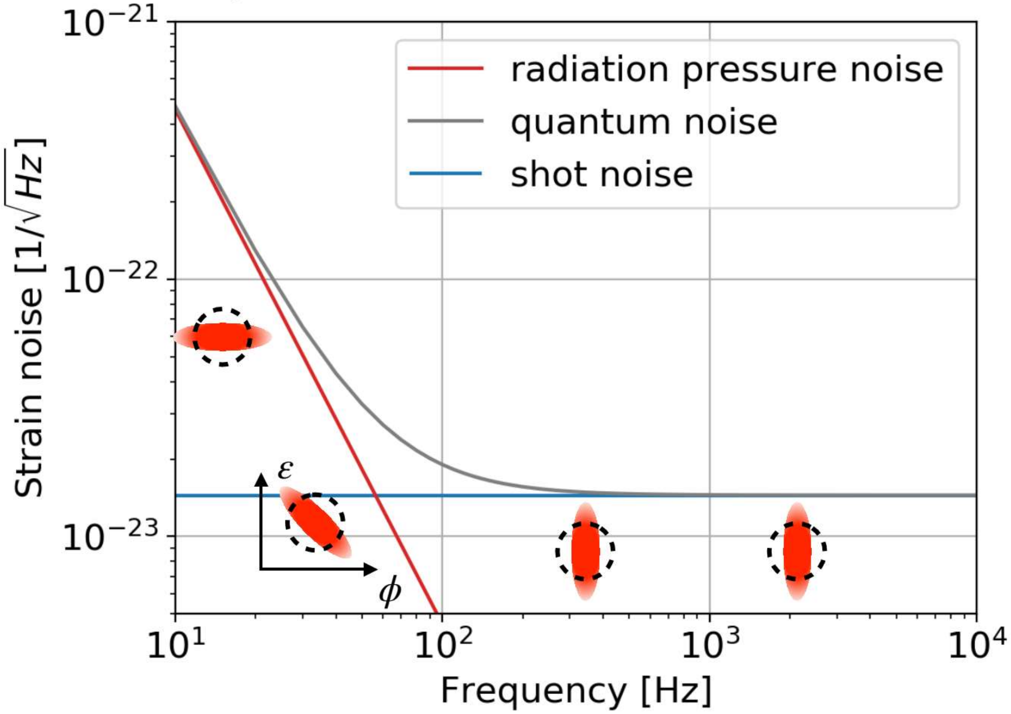
- To reduce this vacuum noise, using the squeezed light is a promising approach.

Kentaro Somiya, ''Quantum noise reduction techniques in KAGRA''
The European Physical Journal D volume 74, Article number: 10 (2020)

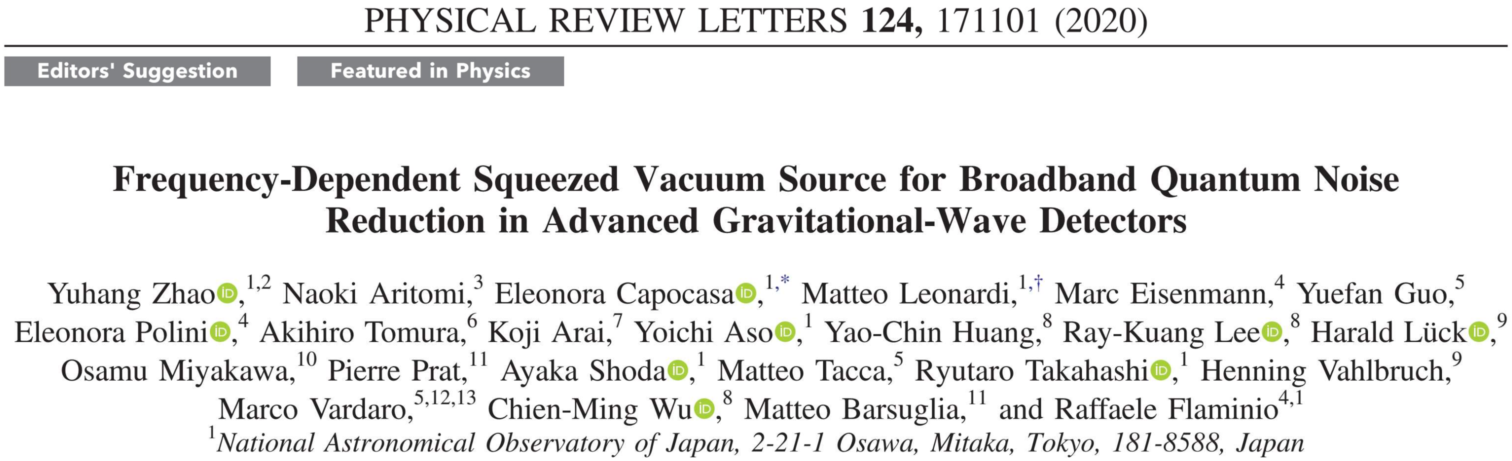
Broadband Quantum noise reduction by frequency dependent squeezed light



M. Evans et. al. Physical Review D, 2013, 88(2):57-61.



This frequency dependent squeezing could be realized by inject the frequency independent state generated by OPO cavity into a long filter cavity.

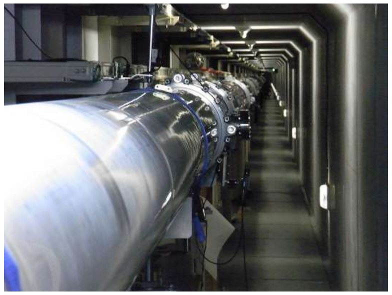


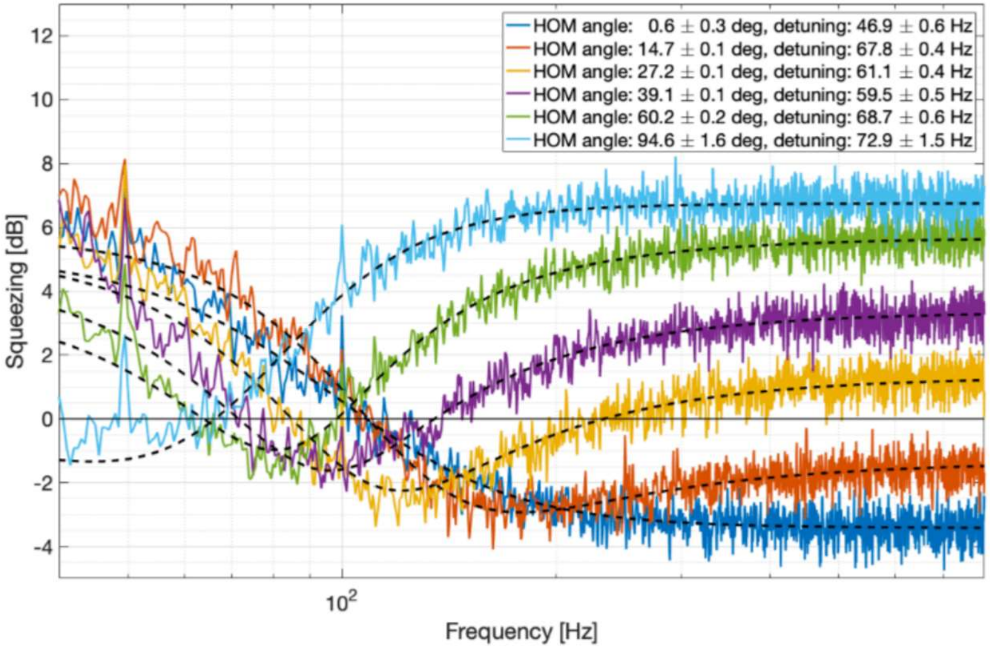
PHYSICAL REVIEW LETTERS **124,** 171101 (2020)

Editors' Suggestion **Featured in Physics**

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

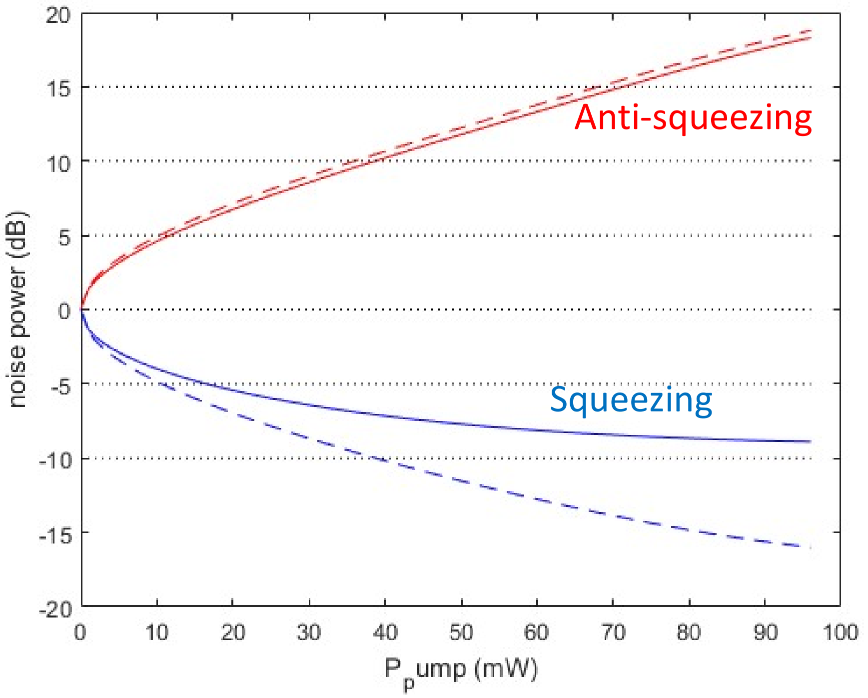
Yuhang Zhao,[1,2] Naoki Aritomi,[3] Eleonora Capocasa,[1,*] Matteo Leonardi,[1,†] Marc Eisenmann,[4] Yuefan Guo,[5]
Eleonora Polini,[4] Akihiro Tomura,[6] Koji Arai,[7] Yoichi Aso,[1] Yao-Chin Huang,[8] Ray-Kuang Lee,[8] Harald Lück,[9]
Osamu Miyakawa,[10] Pierre Prat,[11] Ayaka Shoda,[1] Matteo Tacca,[5] Ryutaro Takahashi,[1] Henning Vahlbruch,[9]
Marco Vardaro,[5,12,13] Chien-Ming Wu,[8] Matteo Barsuglia,[11] and Raffaele Flaminio[4,1]
[1]*National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo, 181-8588, Japan*



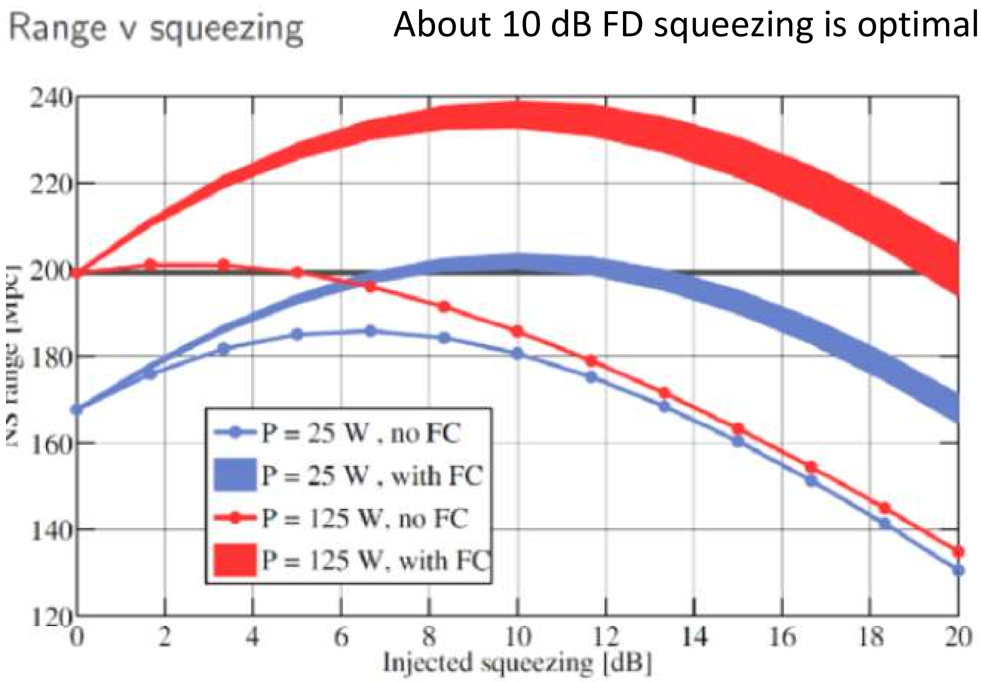


- First demonstration of frequency dependent squeezing by using 300m filter cavity to rotate squeezing ellipse below 100 Hz .
- More than 3dB squeezing at high frequency, about 1dB squeezing at low frequency
- Target 9 dB squeezing

More degree of squeezing is not always a good thing



Dashed line: squeezing with less loss
Solid line: squeezing with more loss and imperfect detection

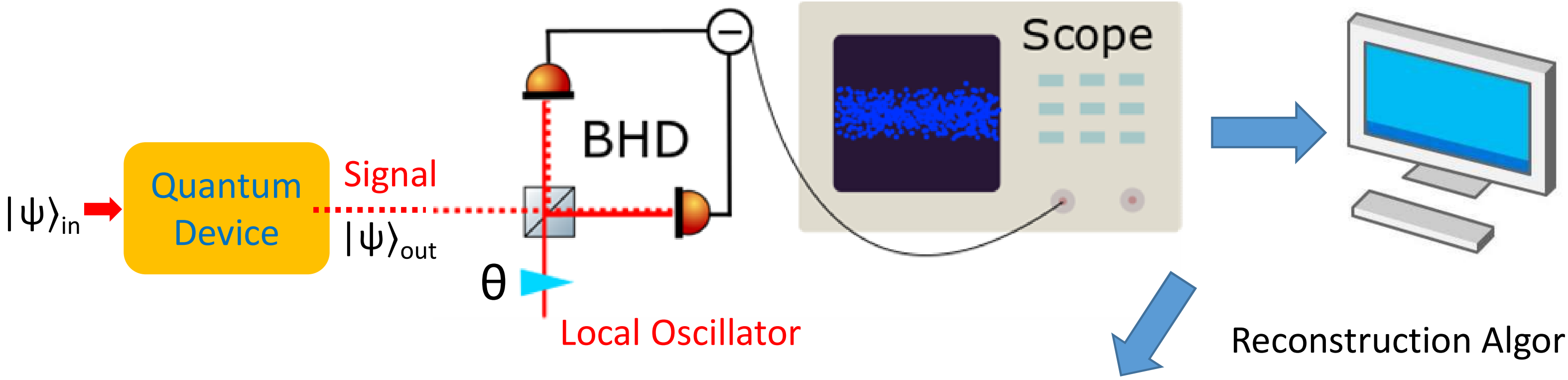


About 10 dB FD squeezing is optimal

Figure Credit: John Miller

- Not only the squeezing, but also the anti-squeezing will be injected into the interferometer and detector.
- 10 dB impure squeezing reduces shot noise ,but contributed 20 dB to the radiation pressure noise.

Quantum state tomography: Optical Homodyne Tomography



$|\psi\rangle_{in}$

Quantum Device

Signal

$|\psi\rangle_{out}$

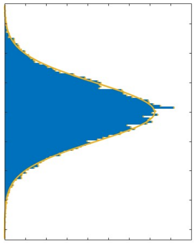
BHD

θ

Local Oscillator

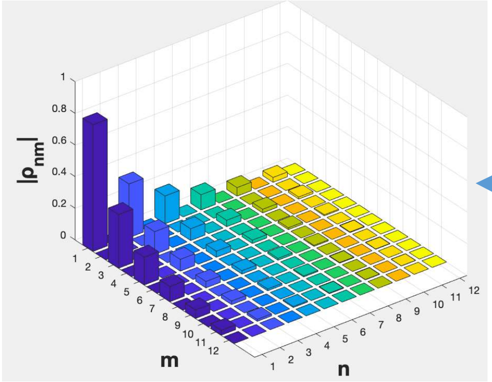
Scope

Probability distribution
Pr(q, θ)

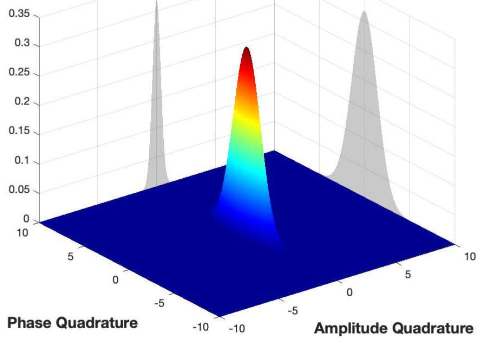


Reconstruction Algorithms

- To characterize a quantum state
- Measure the phase-resolved field quadratures by homodyne detection
- Do measurements along different rotated directions by varying LO phase θ
- Get the probability distribution Pr(q,θ)
- Collect all Pr. distribution over the 2 π interval
- Use reconstruction algorithms to convert the experimental data into the state's density matrix and/or Wigner function.



Wigner function W(Q,P)



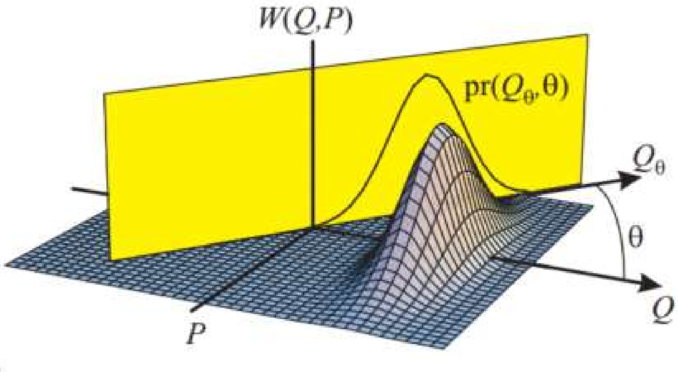
REVIEWS OF MODERN PHYSICS, VOLUME 81, JANUARY–MARCH 2009 DOI: 10.1103/RevModPhys.81.299

Continuous-variable optical quantum-state tomography

A. I. Lvovsky*
Department of Physics and Astronomy, University of Calgary, Calgary, Alberta, Canada T2N 1N4

M. G. Raymer†
Department of Physics and Oregon Center for Optics, University of Oregon, Eugene, Oregon 97403, USA

(Published 16 March 2009)



Reconstruction Algorithms:

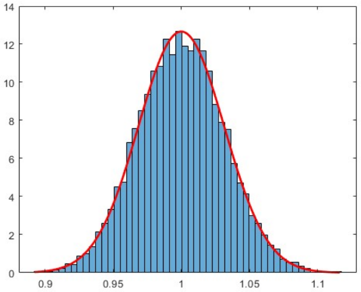
- **Inverse Radon transformation**

$$W_{\mathrm{Det}}(Q,P) = \frac{1}{2\pi^2}\int_0^{\pi}\int_{-\infty}^{+\infty} \mathrm{pr}(Q_\theta,\theta) \times K(Q\cos\theta + P\sin\theta - Q_\theta)\, dQ_\theta\, d\theta$$

O The oldest and simplest tomographic estimator.
O The probability distribution pr(Q_θ, θ) is the integral projection of the Wigner function.
O Works well only when the statistical and systematic errors are negligible.
X May deliver an unphysical density matrix e.g., negative eigenvalues or probabilities greater than 1 .

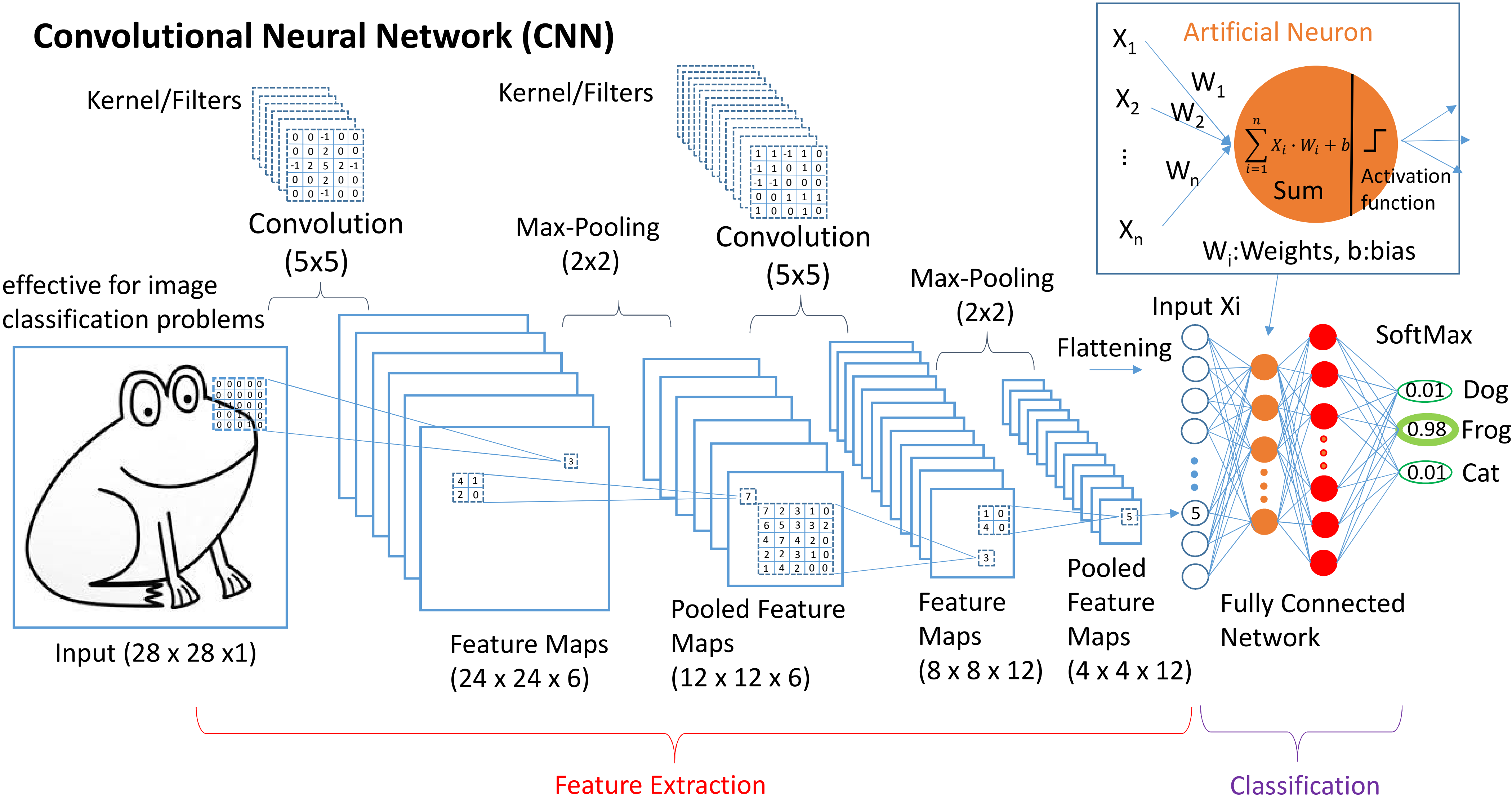
- **Maximum Likelihood estimation** (MLE)

O The most popular technique for dealing with the problems of inversion linear transformation.
O Restricting the domain of density matrices to the proper space.
O Searching for the probability distribution which maximizes the likelihood of the inputs data
O Guarantee the state to be theoretically valid
X It can't identify the quantum state uniquely. Inadmissible for fidelity, mean squared error.
"Maximum likelihood quantum state tomography is inadmissible" https://arxiv.org/abs/1808.01072 (2018).



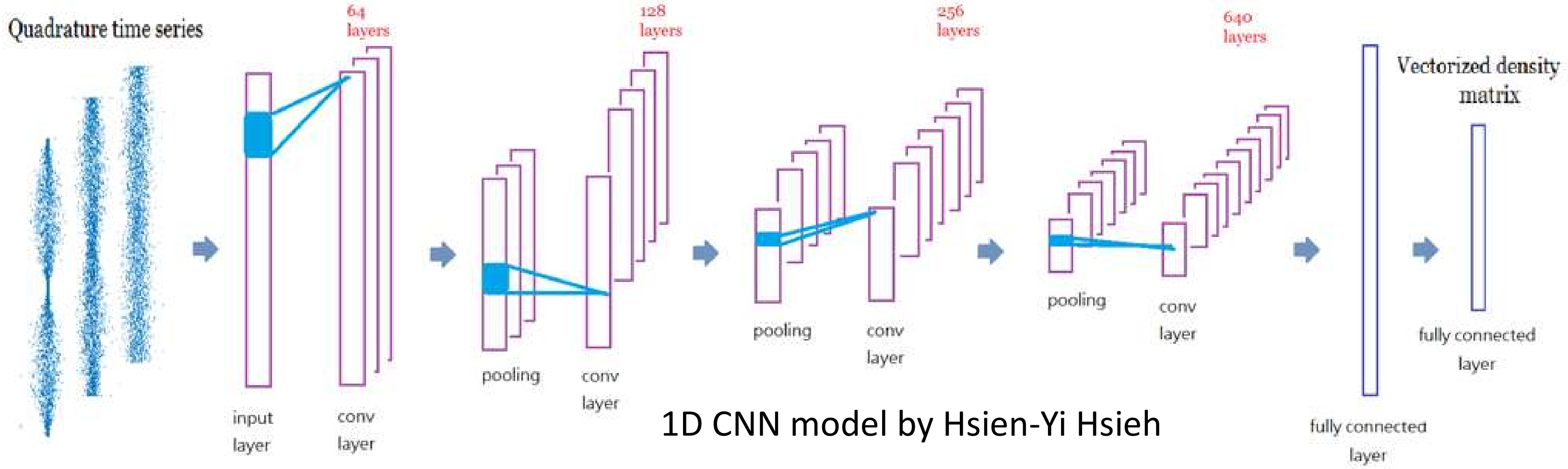
- **Bayesian mean estimation** (BME) " Optimal, reliable estimation of quantum states " New Journal of Physics. 12 (4): 043034

Convolutional Neural Network (CNN)

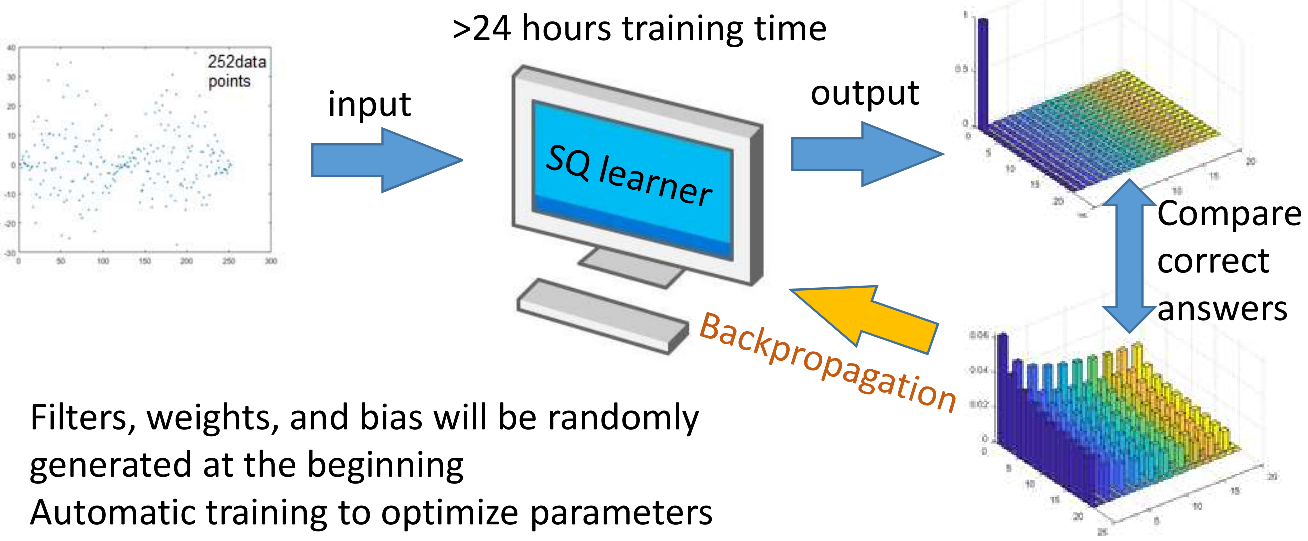


- To reduce the dimensionality of the input and send the meaningful features to the neuron network

Machine learning for squeezed state tomography: SQ Learner



1D CNN model by Hsien-Yi Hsieh



>24 hours training time

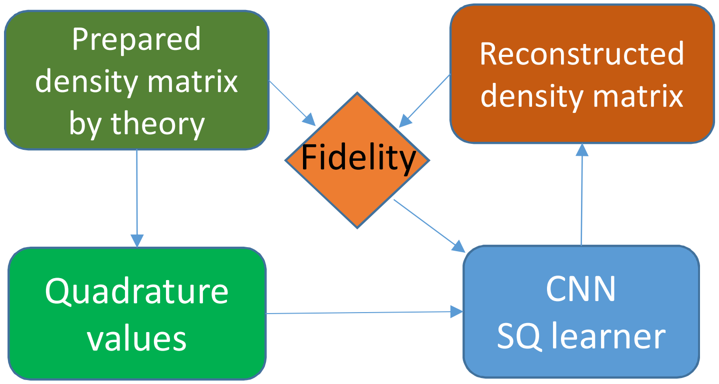
input

output

Compare correct answers

Backpropagation

Do Fidelity Analysis to check the performance



Prepared density matrix by theory

Reconstructed density matrix

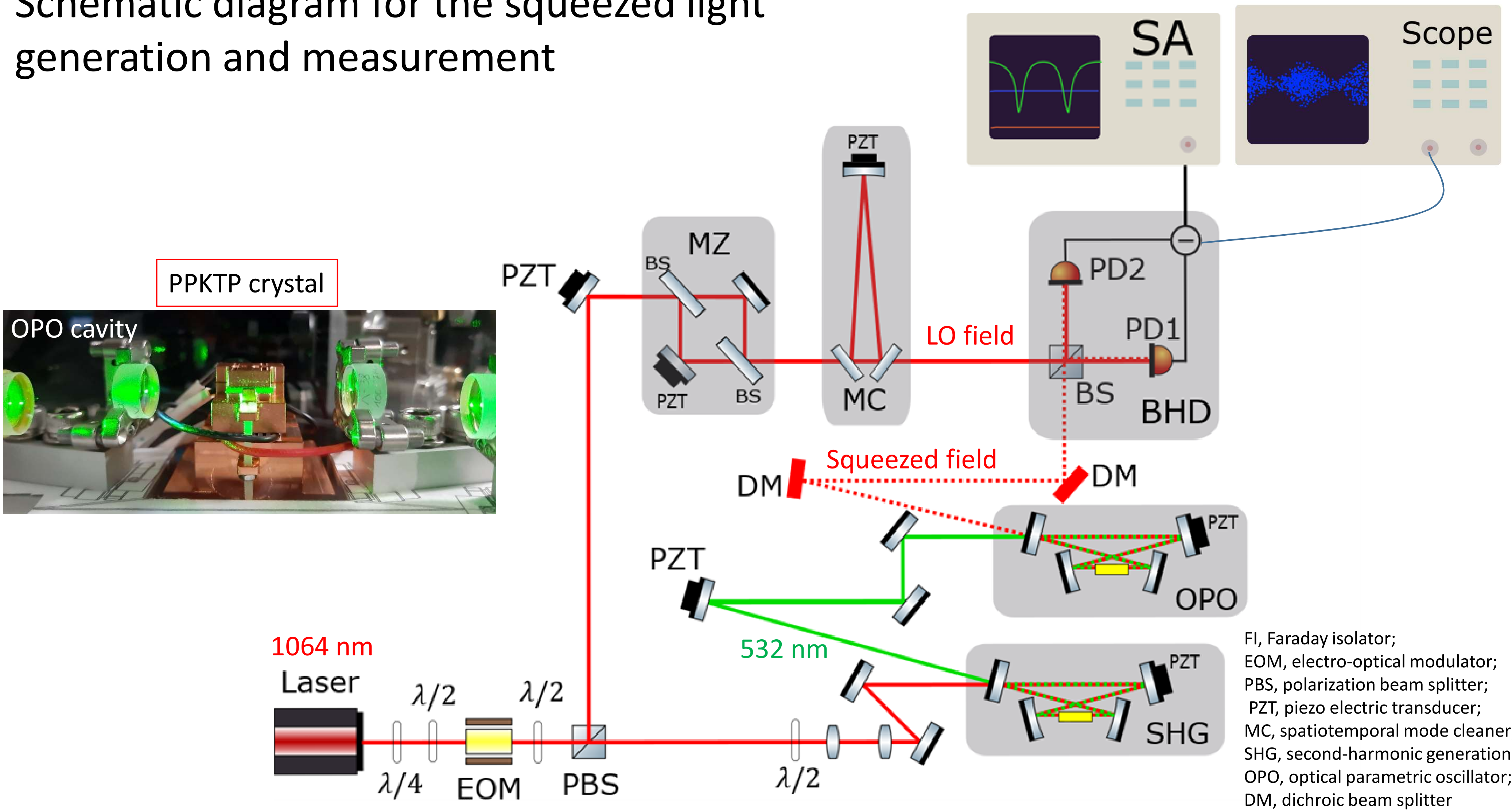
Fidelity

Quadrature values

CNN SQ learner

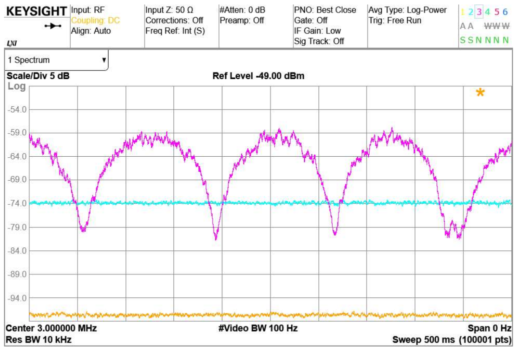
- Filters, weights, and bias will be randomly generated at the beginning
- Automatic training to optimize parameters

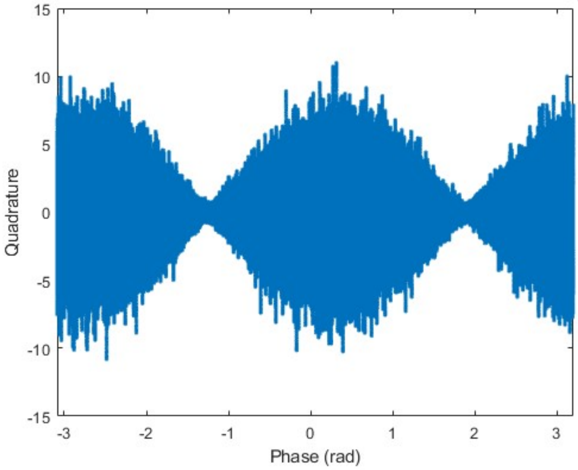
Schematic diagram for the squeezed light generation and measurement



FI, Faraday isolator;
EOM, electro-optical modulator;
PBS, polarization beam splitter;
PZT, piezo electric transducer;
MC, spatiotemporal mode cleaner;
SHG, second-harmonic generation;
OPO, optical parametric oscillator;
DM, dichroic beam splitter

Ppower = 65.1 mW, 8dB squeezing

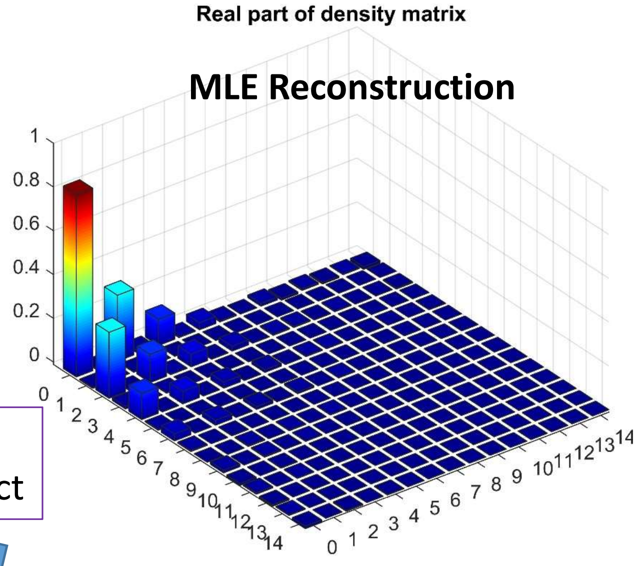

KEYSIGHT
Input: RF
Coupling: DC
Align: Auto
Input Z: 50 Ω
Corrections: Off
Freq Ref: Int (S)
#Atten: 0 dB
Preamp: Off
PNO: Best Close
Gate: Off
IF Gain: Low
Sig Track: Off
Avg Type: Log-Power
Trig: Free Run
1 Spectrum
Scale/Div 5 dB
Ref Level -49.00 dBm
Center 3.000000 MHz
Res BW 10 kHz
#Video BW 100 Hz
Span 0 Hz
Sweep 500 ms (100001 pts)

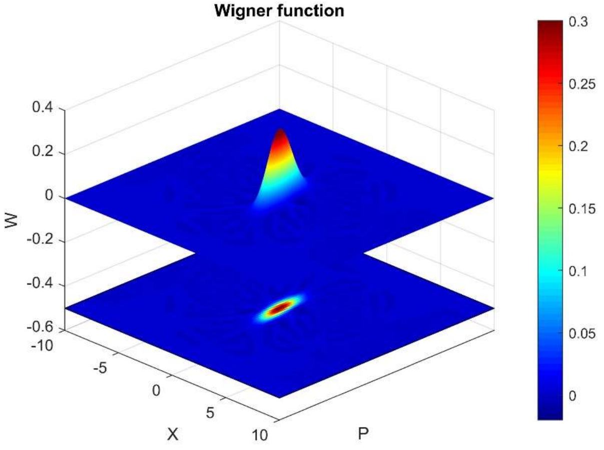


few minutes
to reconstruct

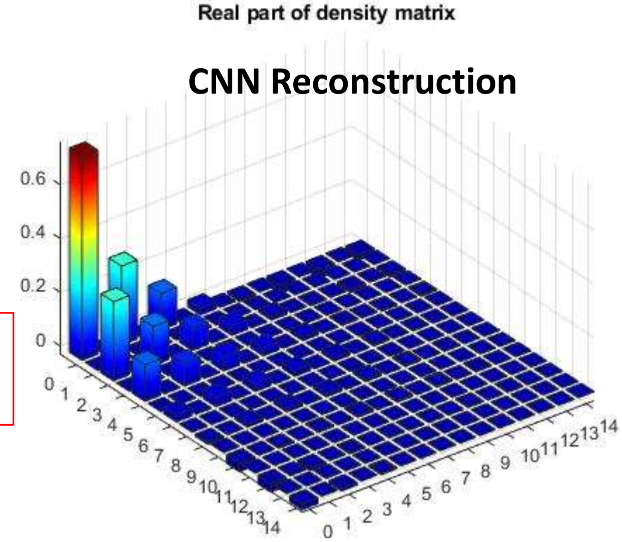
< 1s to
reconstruct

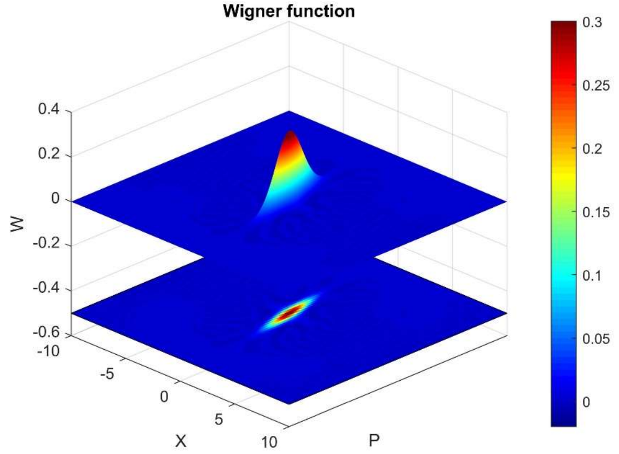
MLE Reconstruction





CNN Reconstruction





Machine SQ Learner vs Max. Likelihood Estimation (MLE)

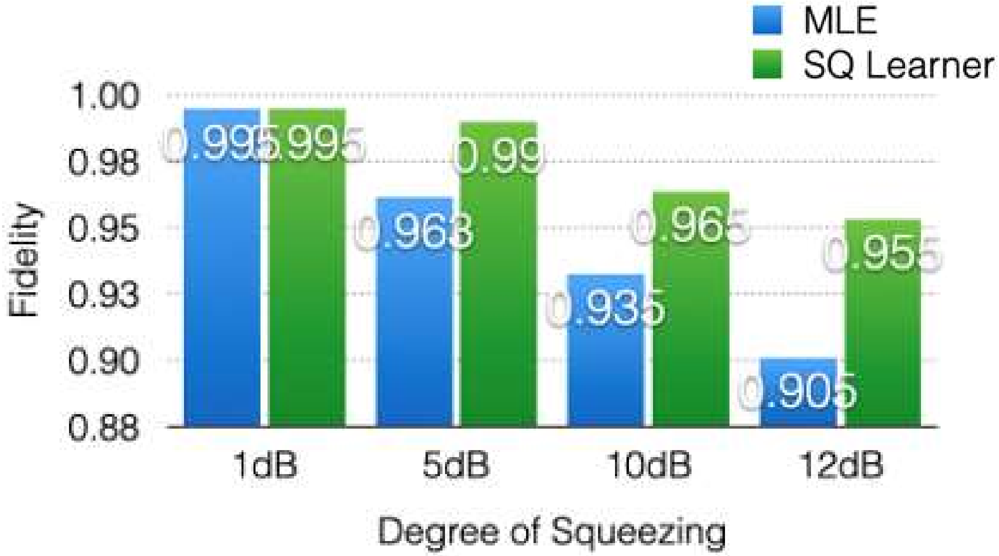
< 1s to reconstruct

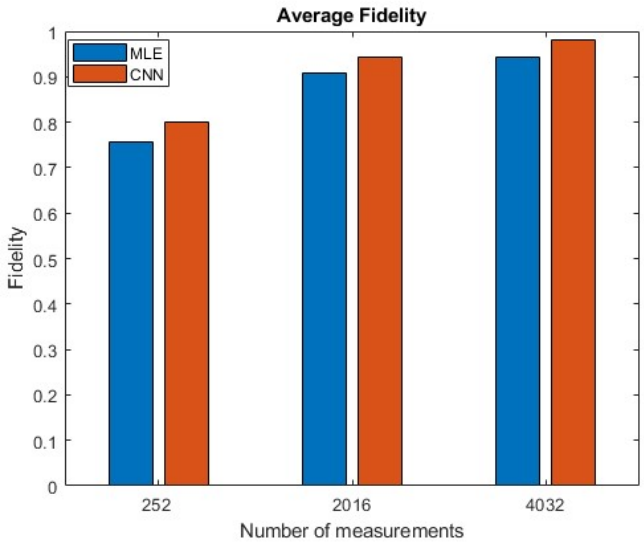
few minutes to reconstruct

The fidelity F for two states (density matrix) is given by

$$\mathcal{F}\left(|\psi_1\rangle,\hat{\rho}_2\right)\equiv\langle\psi_1|\hat{\rho}_2|\psi_1\rangle=\mathrm{tr}\left[|\psi_1\rangle\langle\psi_1|\hat{\rho}_2\right]$$
$$=2\pi\iint W_1(x,p)W_2(x,p)\,dxdp$$

The reconstruction is precise if Fidelity is equal to 1

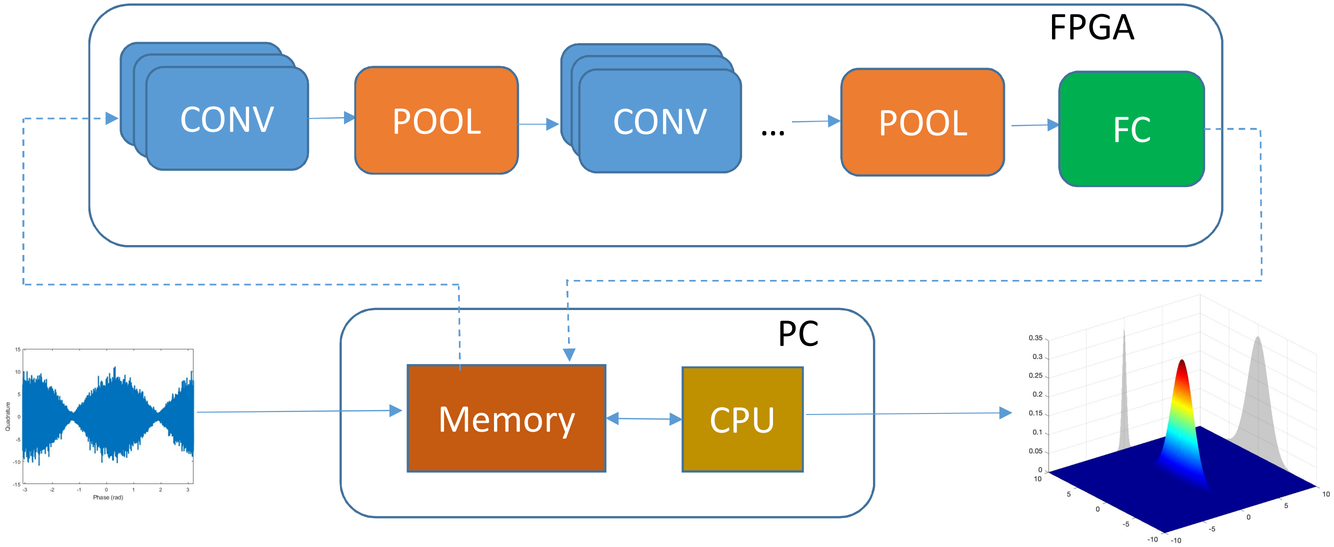




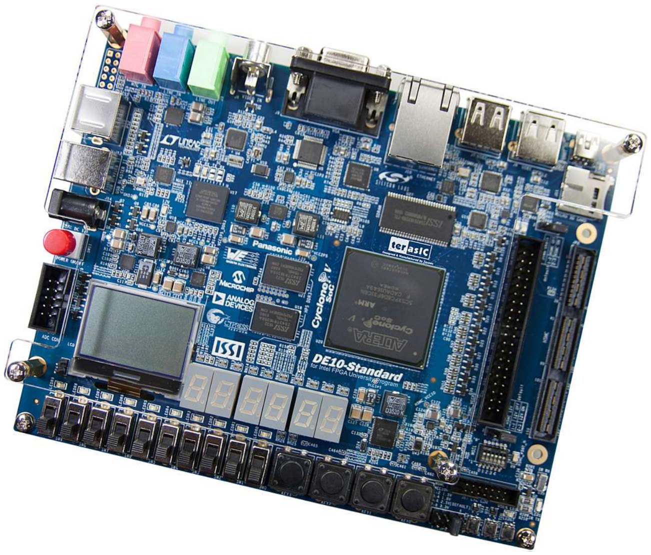
Reconstruction fidelity as a function of degree of squeezing and number of quadrature measurements.

Next: FPGA Acceleration of Convolutional Neural Networks

- Parallel capability of processing the data



- Reducing the loading of CPU



DE10-Standard

Applications of real-time tomography in squeezed state:

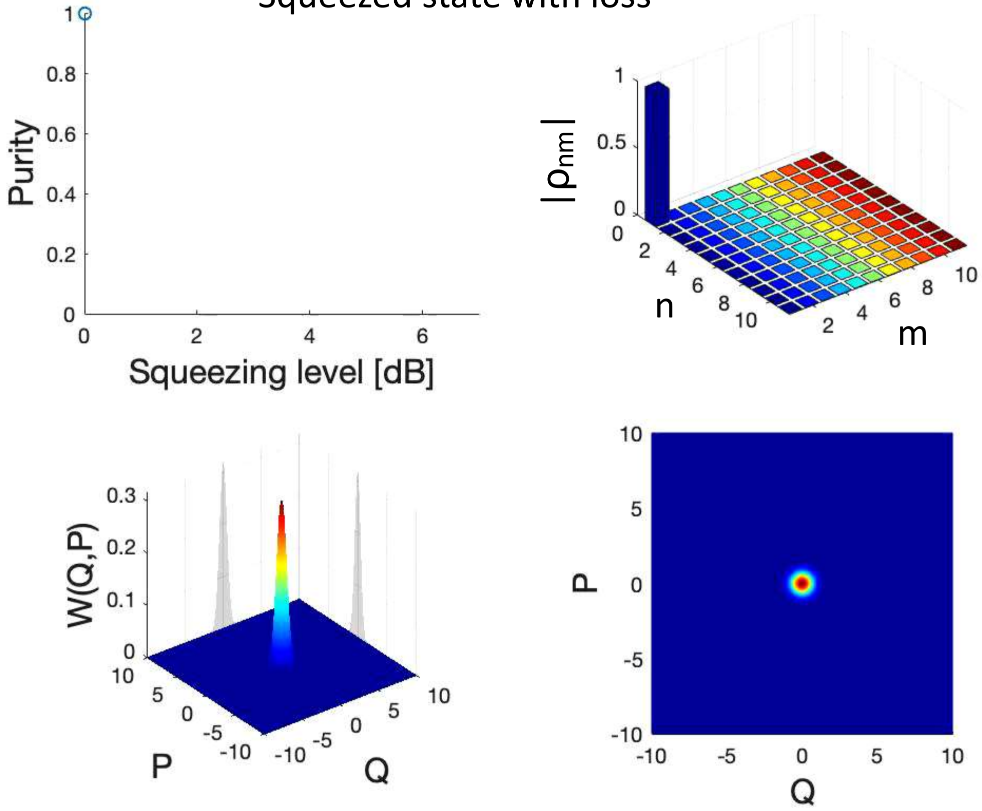
- Monitor the purity of the quantum state.
- The purity of a normalized quantum state is a scalar defined as

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

$\gamma = 1$ for pure squeezed state:
degrees of squeezing = anti-squeezing

- Monitor the properties of quantum states in real-time, and study the corresponding dynamic behaviors.

Squeezed state with loss



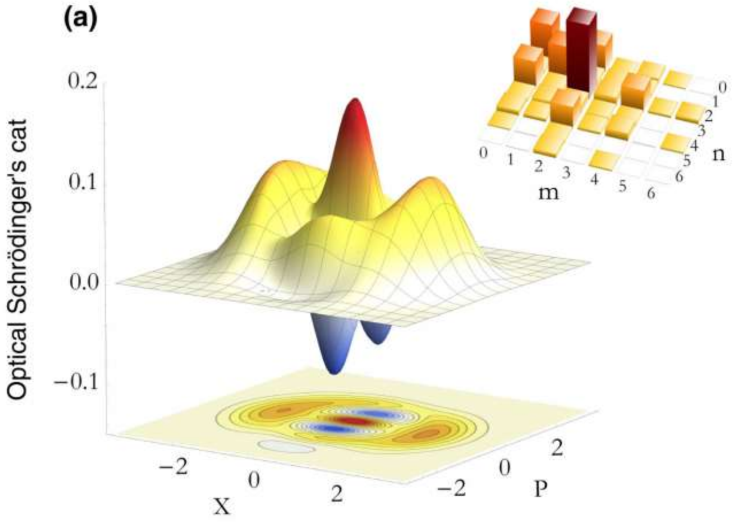
Vol. 7, No. 5 / May 2020 / *Optica*

Experimental quantum homodyne tomography via machine learning

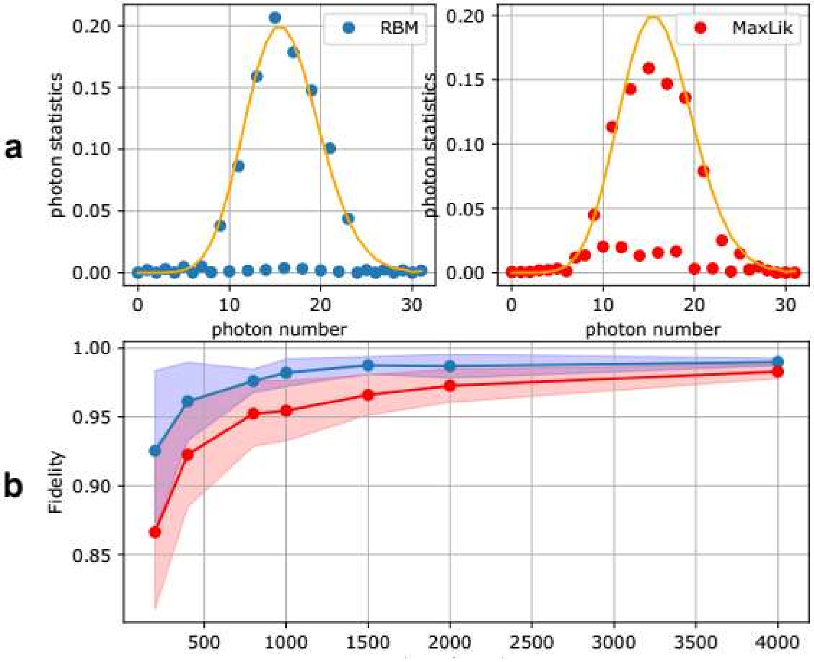
E. S. TIUNOV,[1,2,†] V. V. TIUNOVA (VYBOROVA),[1,†] A. E. ULANOV,[1] A. I. LVOVSKY,[1,3,*] AND A. K. FEDOROV[1,2,4]

[1] *Russian Quantum Center, Skolkovo, Moscow 143025, Russia*
[2] *Moscow Institute of Physics and Technology, Dolgoprudny, Moscow Region 141700, Russia*
[3] *Department of Physics, University of Oxford, Oxford OX1 3PG, UK*

Based on an artificial neural network known as the
Restricted Boltzmann machine (RBM)

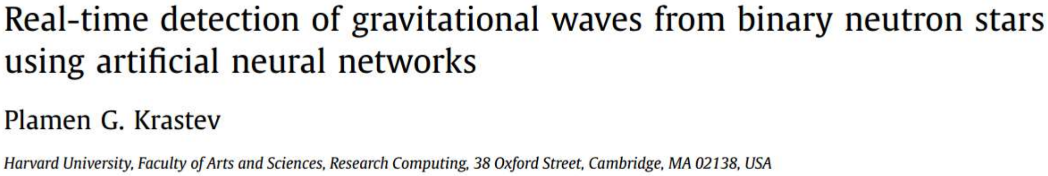


Reconstruction of Schrodinger cat states



Machine learning are popular for gravitational-wave data analysis

Physics Letters B 803 (2020) 135330

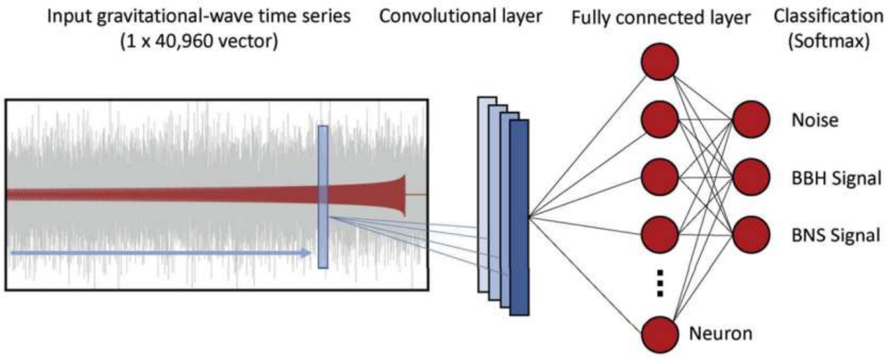


Real-time detection of gravitational waves from binary neutron stars using artificial neural networks

Plamen G. Krastev

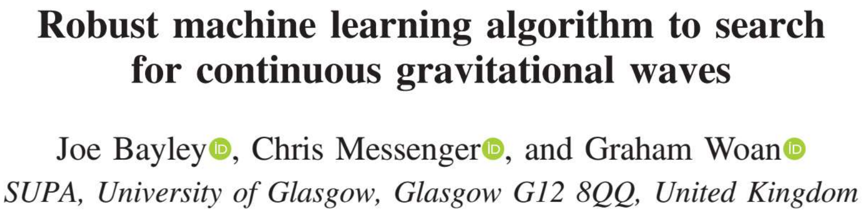
Harvard University, Faculty of Arts and Sciences, Research Computing, 38 Oxford Street, Cambridge, MA 02138, USA

Algorithm: Convolutional Neural Network (CNN)



- Using an artificial neural network to identify gravitational-wave signals

PHYSICAL REVIEW D 102, 083024 (2020)

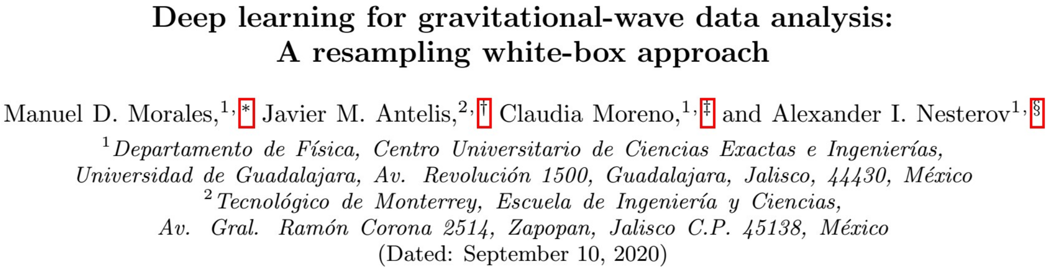


Robust machine learning algorithm to search for continuous gravitational waves

Joe Bayley, Chris Messenger, and Graham Woan

SUPA, University of Glasgow, Glasgow G12 8QQ, United Kingdom

https://arxiv.org/abs/2009.04088

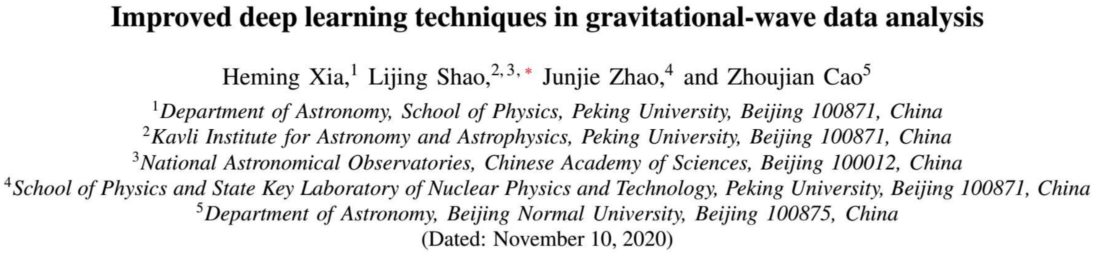


Deep learning for gravitational-wave data analysis: A resampling white-box approach

Manuel D. Morales,[1,*] Javier M. Antelis,[2,†] Claudia Moreno,[1,‡] and Alexander I. Nesterov[1,§]

[1] *Departamento de Física, Centro Universitario de Ciencias Exactas e Ingenierías,*
Universidad de Guadalajara, Av. Revolución 1500, Guadalajara, Jalisco, 44430, México
[2] *Tecnológico de Monterrey, Escuela de Ingeniería y Ciencias,*
Av. Gral. Ramón Corona 2514, Zapopan, Jalisco C.P. 45138, México
(Dated: September 10, 2020)

https://arxiv.org/abs/2011.04418

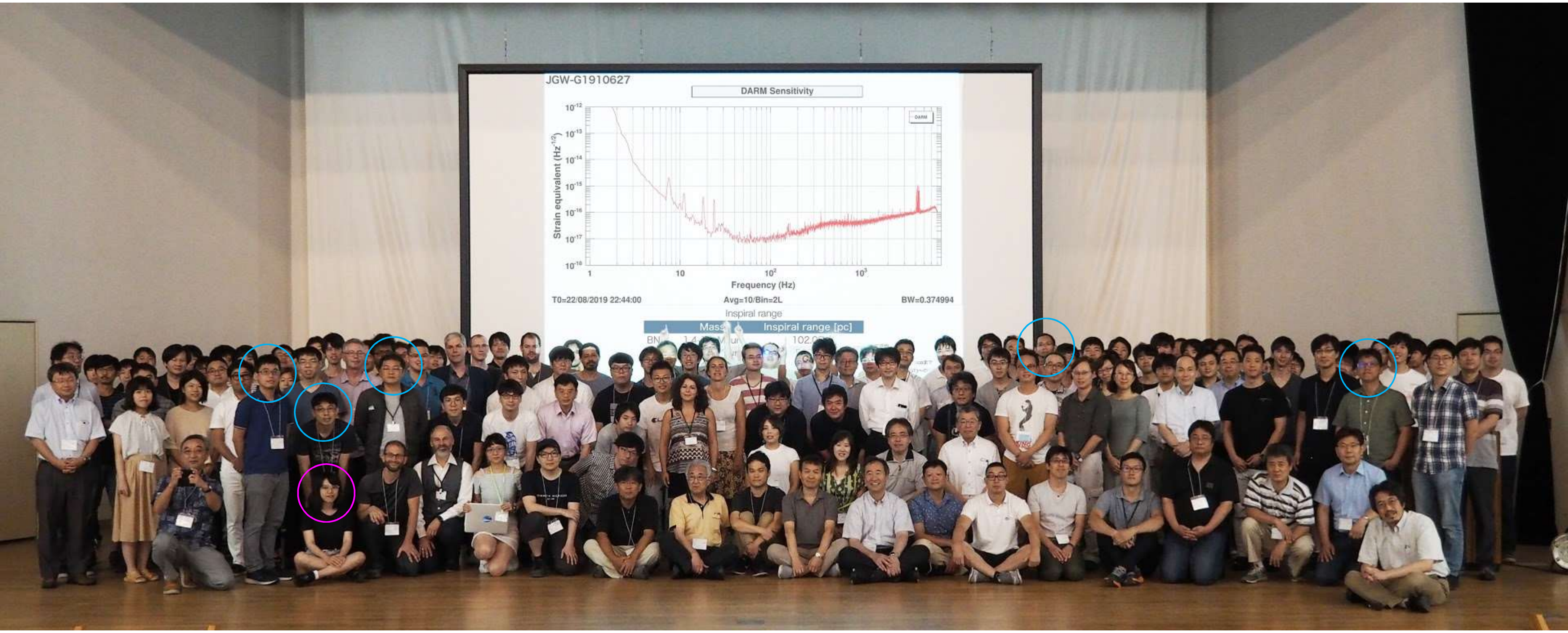


Improved deep learning techniques in gravitational-wave data analysis

Heming Xia,[1] Lijing Shao,[2,3,*] Junjie Zhao,[4] and Zhoujian Cao[5]

[1] *Department of Astronomy, School of Physics, Peking University, Beijing 100871, China*
[2] *Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, China*
[3] *National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China*
[4] *School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*
[5] *Department of Astronomy, Beijing Normal University, Beijing 100875, China*
(Dated: November 10, 2020)

Thank you for your attention



Dr. Y.C. Huang
Mr. S.C. Wu
Dr. D.S. Tsai
Ms. Y.R. Chen

C.M. Wu
chwufo@gmail.com

Prof. R.K. Lee

2019/08/22 23rd Face to Face Meeting @ University of Toyama