Quantum Optics:
Introduction

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LIGO-Virgo-KAGRA (LVK) Collaboration

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

NTHU, Feb. 23rd, 2021

NCTS 2021

Annual Theory Meeting:
Quantum Physics, Quantum Information, and Quantum Technologies

February 17th-19th, 2021

Venue: Lecture Room A of NCTS,
4F, 3rd General Building, NTHU

http://phys.cts.nthu.edu.tw/actnews/intro.php?Sn=510&OSn=1415

Invited Speakers(tentative)

Joonwoo Bae - KAIST, Korea
Francesco Buscemi - NU, Japan
Chi-Fang Chen - Caltech, USA
Yeeong-Cherng Liang - NCKU, Taiwan
Nai-Hui Chia - UMD, USA
Sile NIC CHORMAIC - OIST, Japan
Vandna Gokhroo - WSU, USA
Ratnesh Kumar Gupta - OIST, Japan
Hsin-Yuan Huang - Caltech, USA
Kao-Yueh Kuo - NCTU, Taiwan
Han-Hsuan Lin - NTHU, Taiwan
Xiongfeng Ma - Tsinghua University, China
Yingkai Ouyang - TUOS, UK
Adriana Pálffy - MPIK, Germany
Georgiy Tkachenko - OIST, Japan
Marco Tomamichel - NUS, Singapore
Yanbao Zhang - NTT, Japan

Syllabus :

- Introduction to Quantum Optics:

- **Quantum Mechanics:**
  - qSHO, Uncertainty-relation, Schrodinger/Heisenberg/Interaction pictures

- **Quantum Properties of Light:**
  - Number states, Vacuum States, Coherent States, Squeezed States
  - Phase Space, Quantum State Tomography

- **Simple Optical Instrument:**
  - Beam Splitter, Mach-Zehnder Interferometer
  - HBT, Homedyne Detections
  - Correlation funcitons

Syllabus :

•Photon-atom interaction:

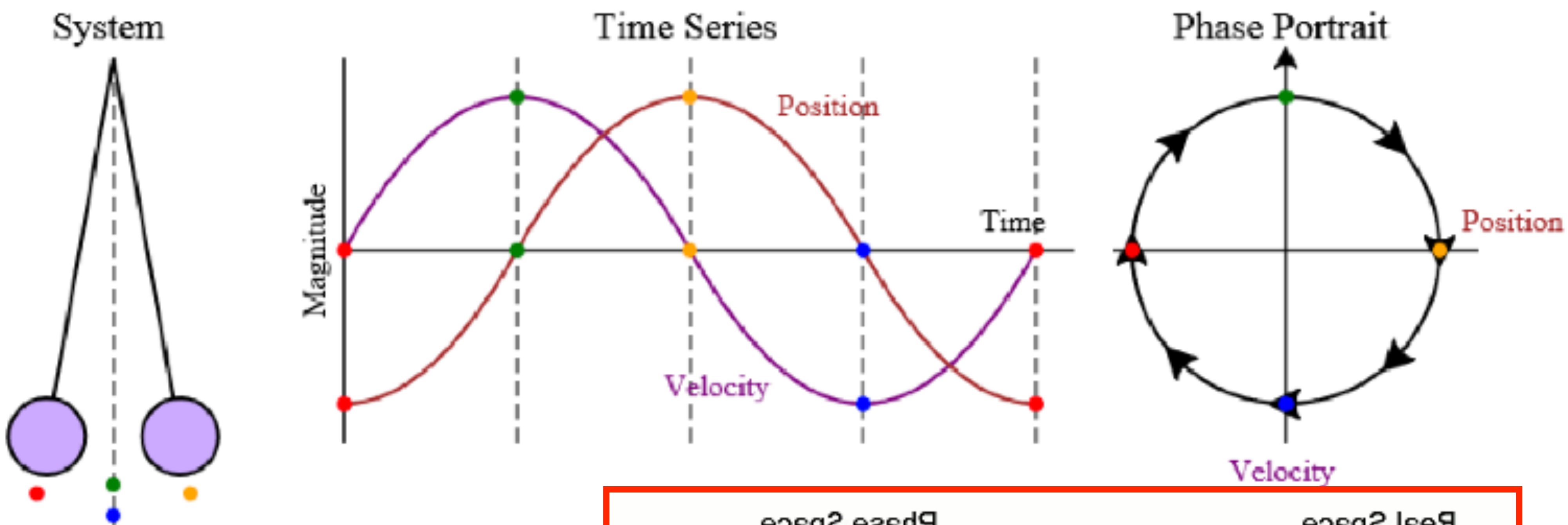
- Rabi oscillation,
- Jaynes-Cummings Hamiltonian,
- Dicke model,
- Cavity-Quantum Electro-Dynamics (c-QED),
- Electromagnetically Induced Transparency (EIT),
- Optical Parametric Oscillator (OPO),
- Dissipative Systems,

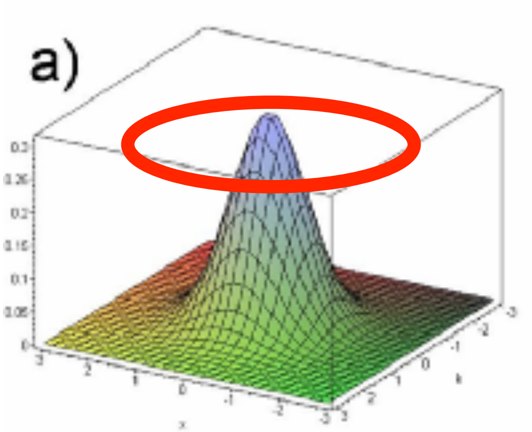
• Selected Applications:

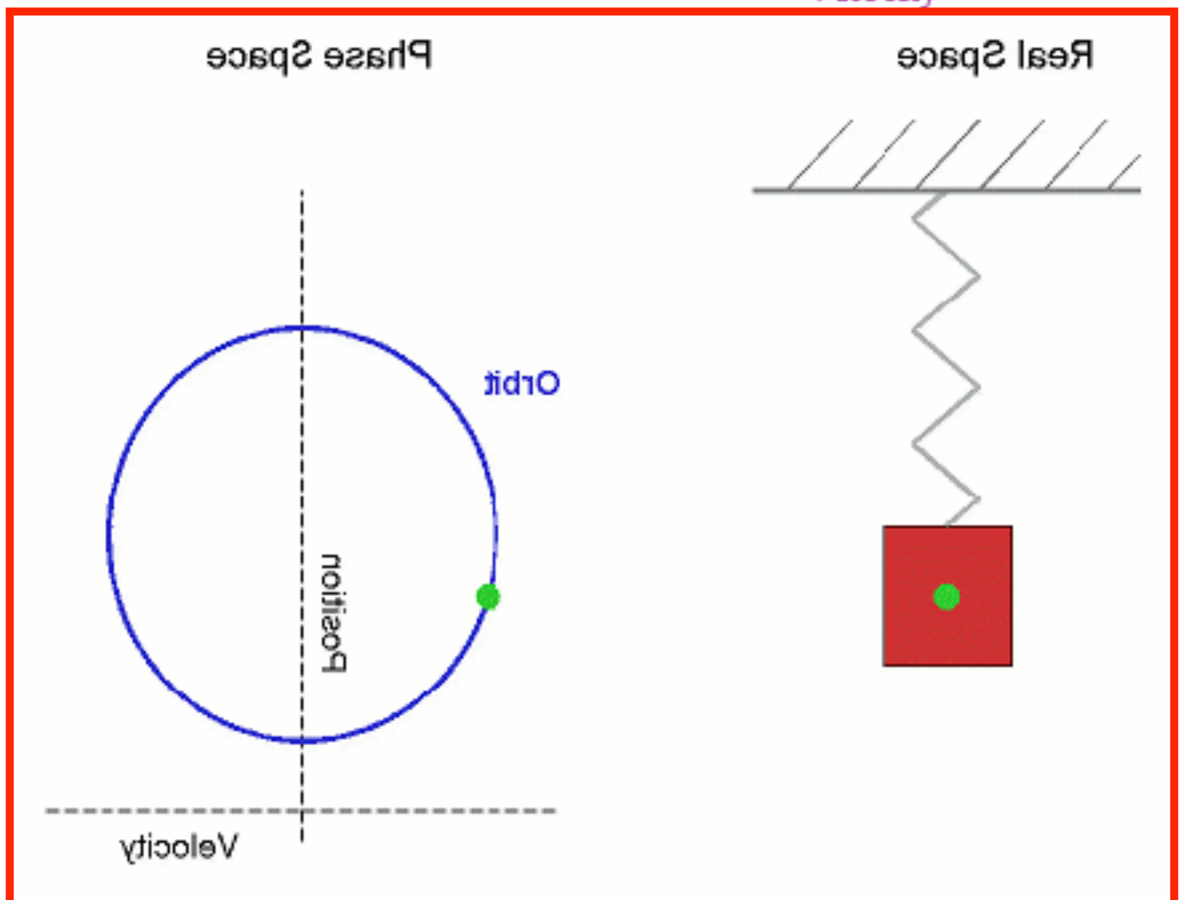
- Quantum Sensor: Gravitational Wave Detectors
- Test of Quantum Mechanics: Quantum Zeno effect
- Quantum Communication: QKD
- Quantum Computing: Quantum Photonic Circuit

Phase space

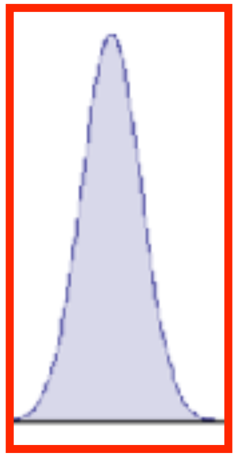
- Classical Mechanics



- 



wave-nature



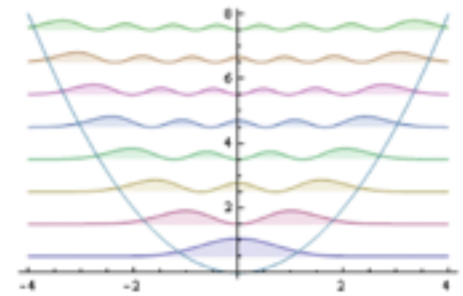
from Wiki

Quantum Simple Harmonic Oscillator (SHO)

coherent states $|\alpha\rangle,\ |\beta\rangle,\ |\gamma\rangle$

number states $|n\rangle,\ |m\rangle$

$$|\alpha\rangle = e^{\frac{-|\alpha|^2}{2}} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$

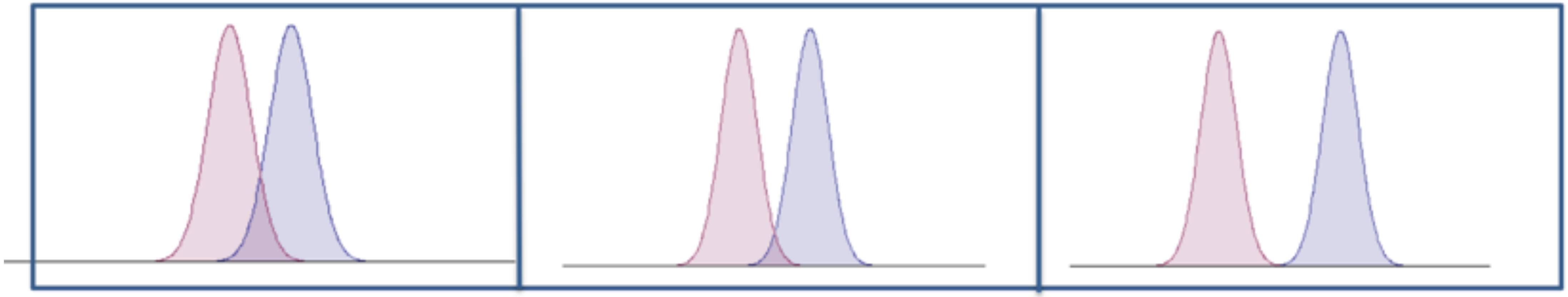


coherent states form a complete set $\mathbf{1} = \int_{\mathbb{R}^2} \frac{d^2\alpha}{2\pi} |\alpha\rangle\langle\alpha|$

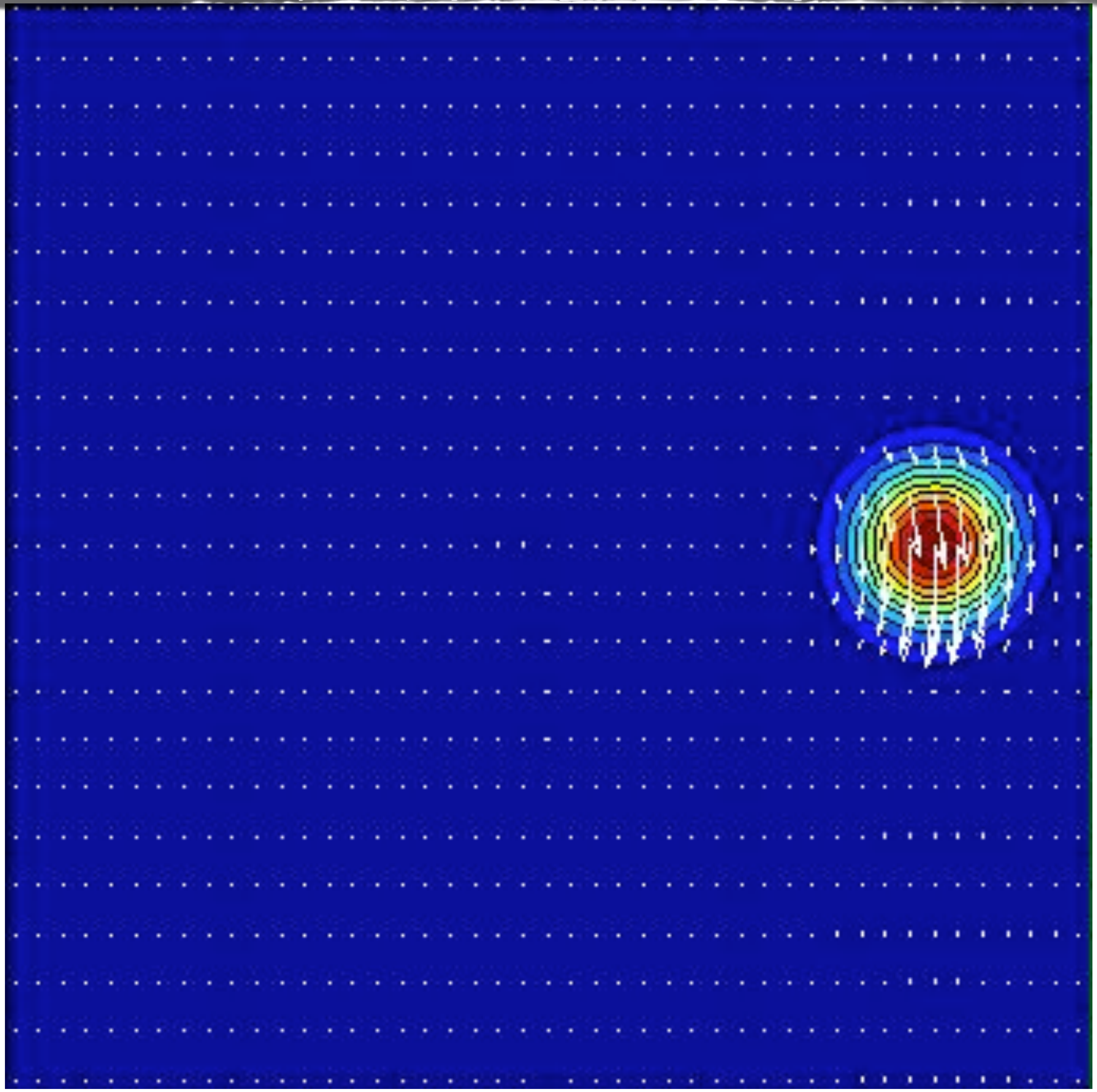
but not an orthonormal basis $\left|\langle\beta|\alpha\rangle\right|^2 = e^{-|\alpha-\beta|^2}$

<u>two coherent states are never orthogonal to each other</u>

there is always a non-vanishing overlap between them

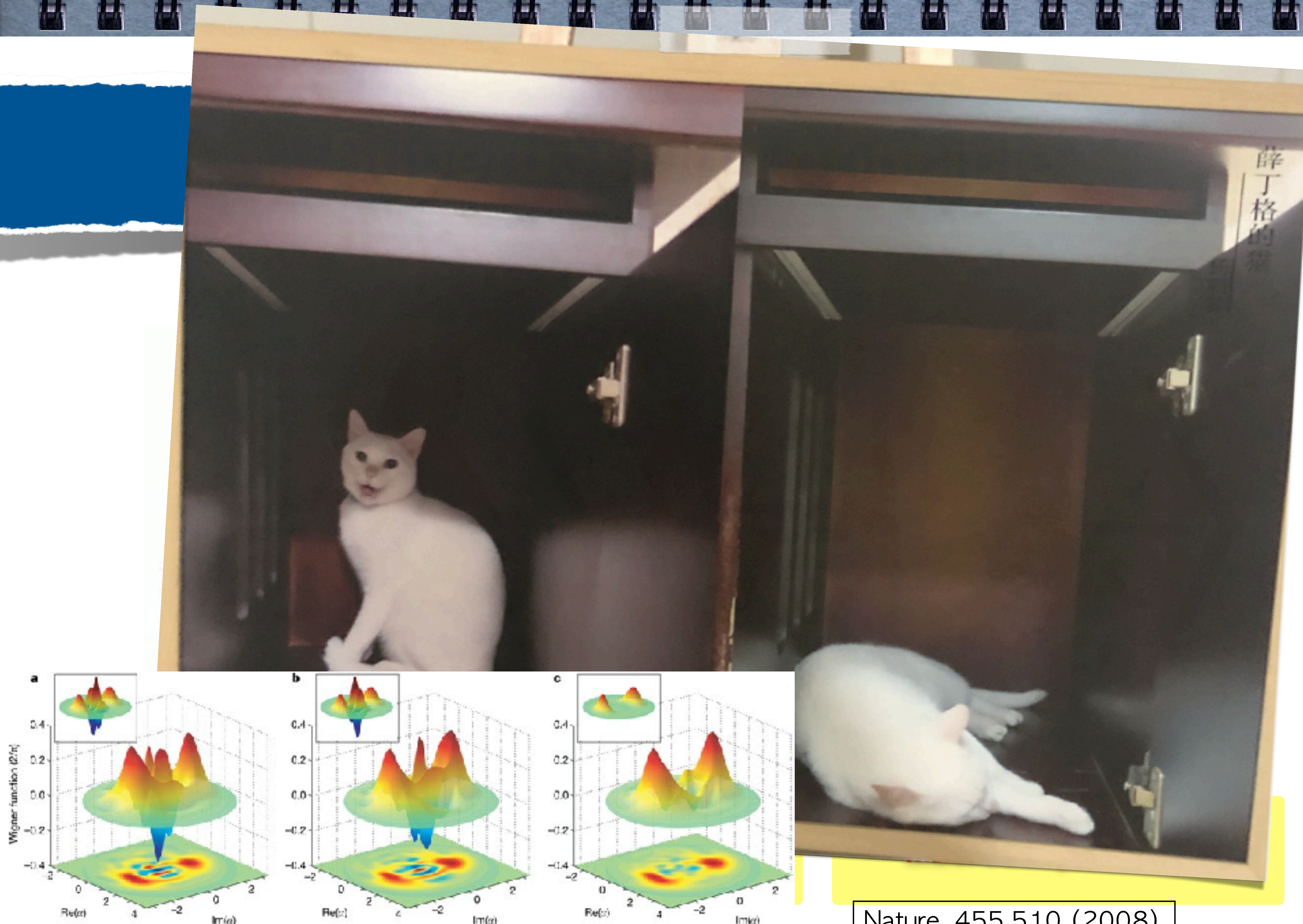


Coherent states



with Popo Yang

Popo Yang, Ivan F. Valtierra, Andrei B. Klimov, Shin-Tza Wu, RKL, Luis L. Sanchez-Soto, and Gerd Leuchs, Physica Scripta for the New Focus issue: Quantum Optics and Beyond - in honour of Wolfgang Schleich.



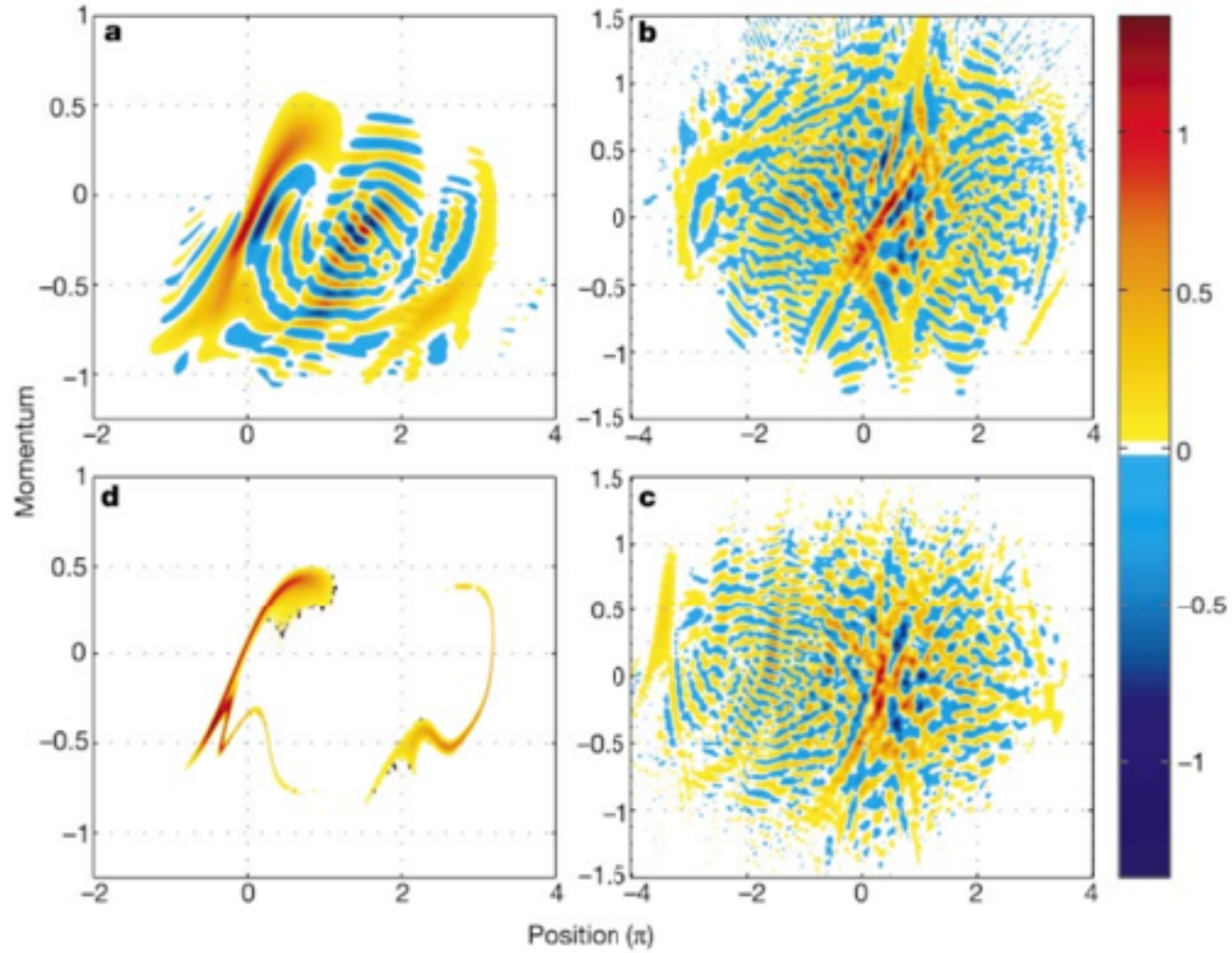
Nature, 455,510 (2008).

Sub-Planck structure in phase space and its relevance for quantum decoherence

Wojciech Hubert Zurek

Theory Division, T-6, MS B288, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

Heisenberg's principle[1] states that the product of uncertainties of position and momentum should be no less than the limit set by Planck's constant, $\hbar/2$. This is usually taken to imply that phase space structures associated with sub-Planck scales ($\ll \hbar$) do not exist, or at least that they do not matter. Here I show that this common assumption is false: non-local quantum superpositions (or 'Schrödinger's cat' states) that are confined to a phase space volume characterized by the classical action A, much larger than $\hbar$, develop spotty structure on the sub-Planck scale, $a = \hbar^2/A$. Structure saturates on this scale particularly quickly in quantum versions of classically chaotic systems—such as gases that are modelled by chaotic scattering of molecules—because their exponential sensitivity to perturbations[2] causes them to be driven into non-local 'cat' states. Most importantly, these sub-Planck scales are physically significant: a determines the sensitivity of a quantum system or environment to perturbations. Therefore, this scale controls the effectiveness of decoherence and the selection of preferred pointer states by the environment[3–8]. It will also be relevant in setting limits on the sensitivity of quantum meters.

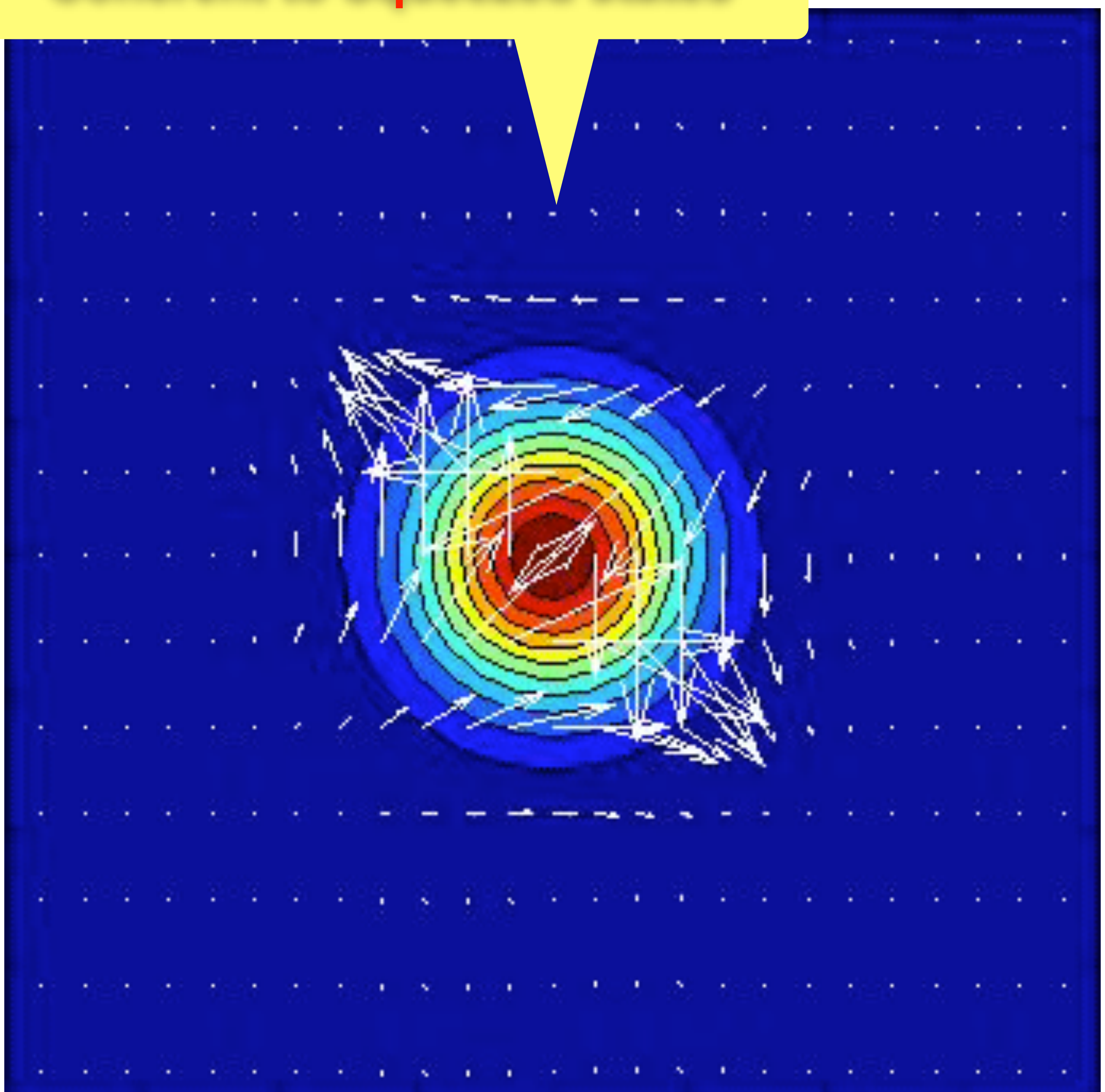


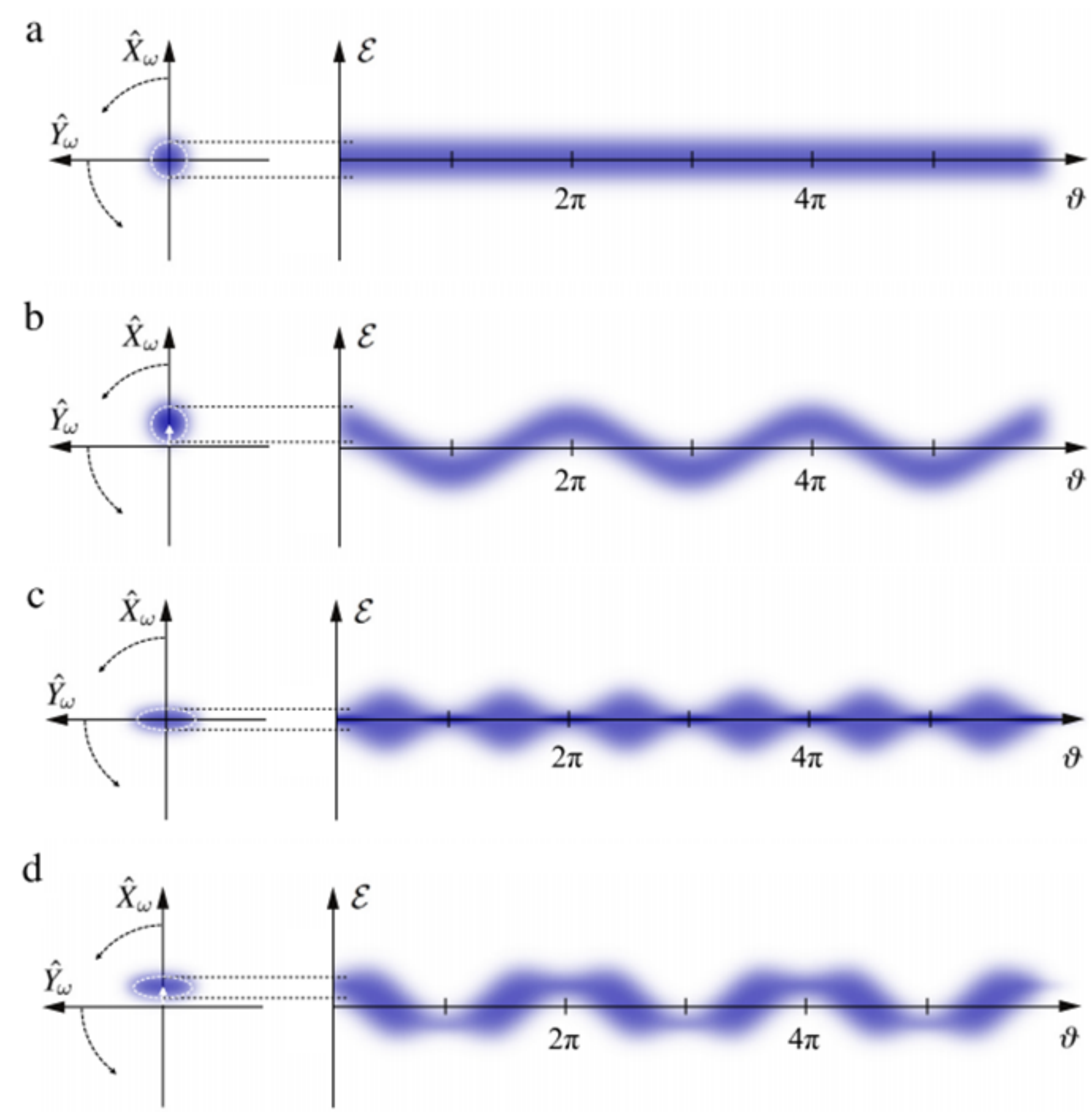
Cat states

W. Zurek, Nature 412, 712 (2001).

Squeezed States

Coherent to Squeezed states

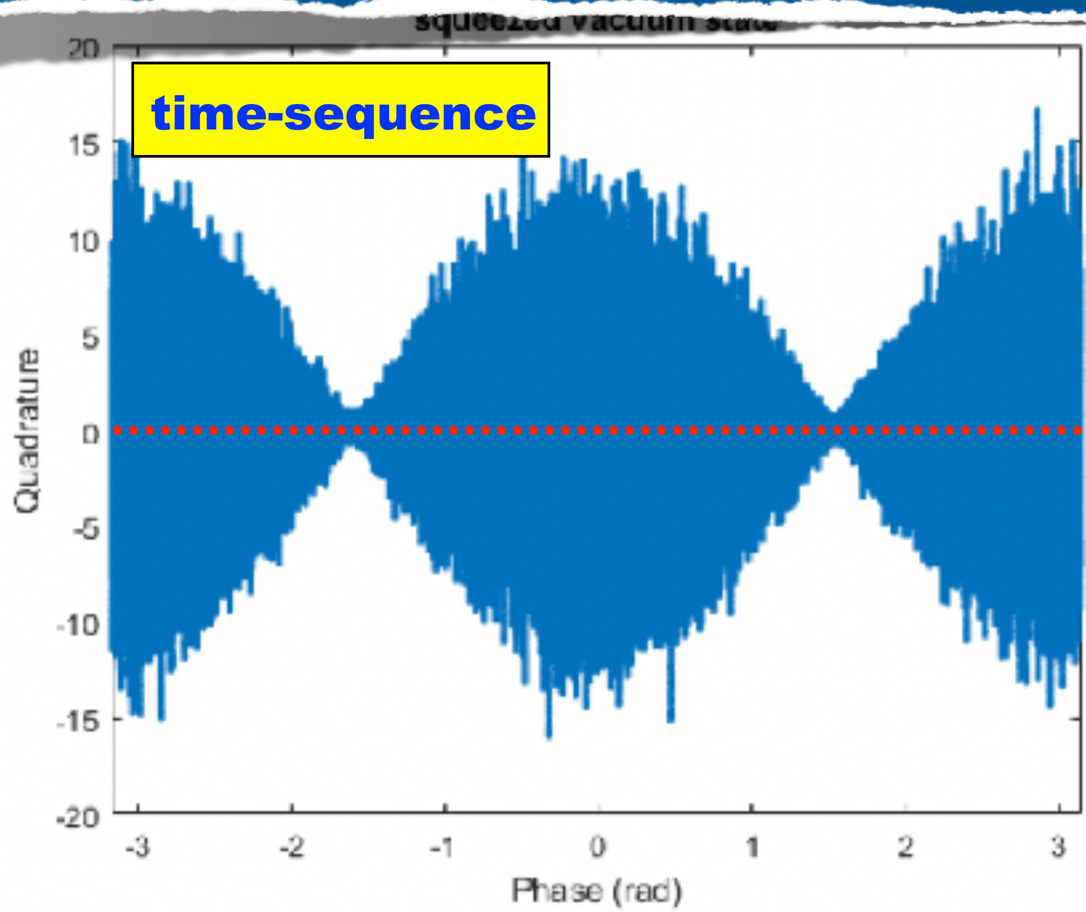


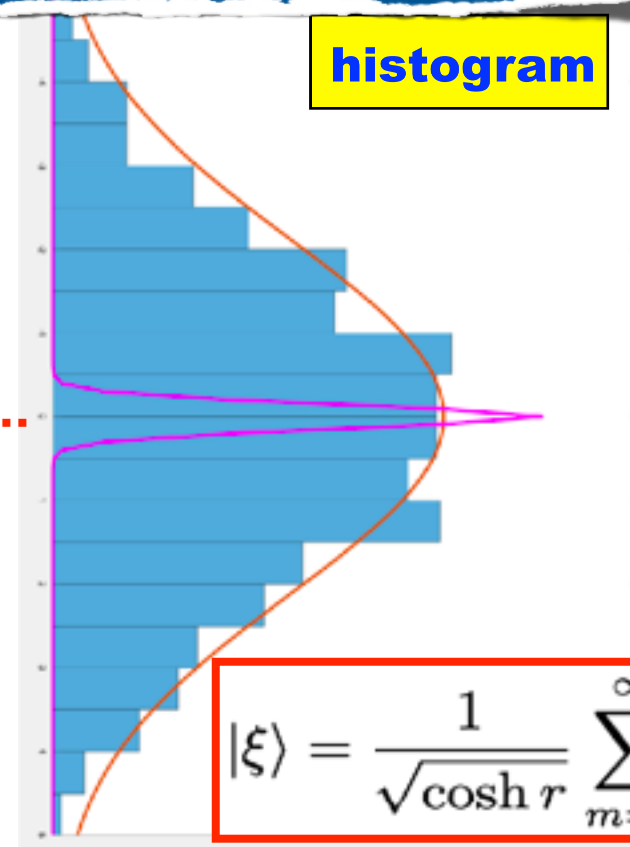


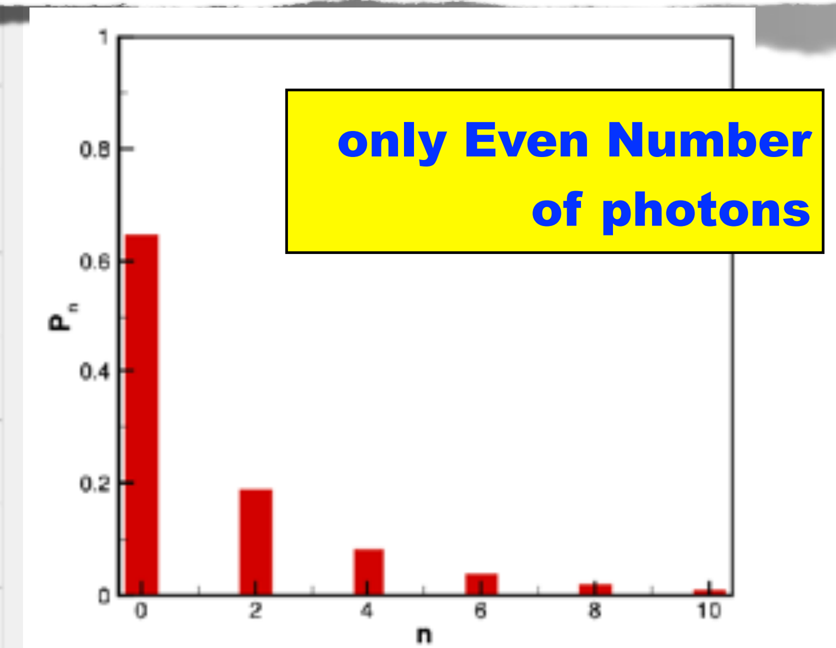
Courtesy:
Roman Schnabel (2017).

by Popo Yang

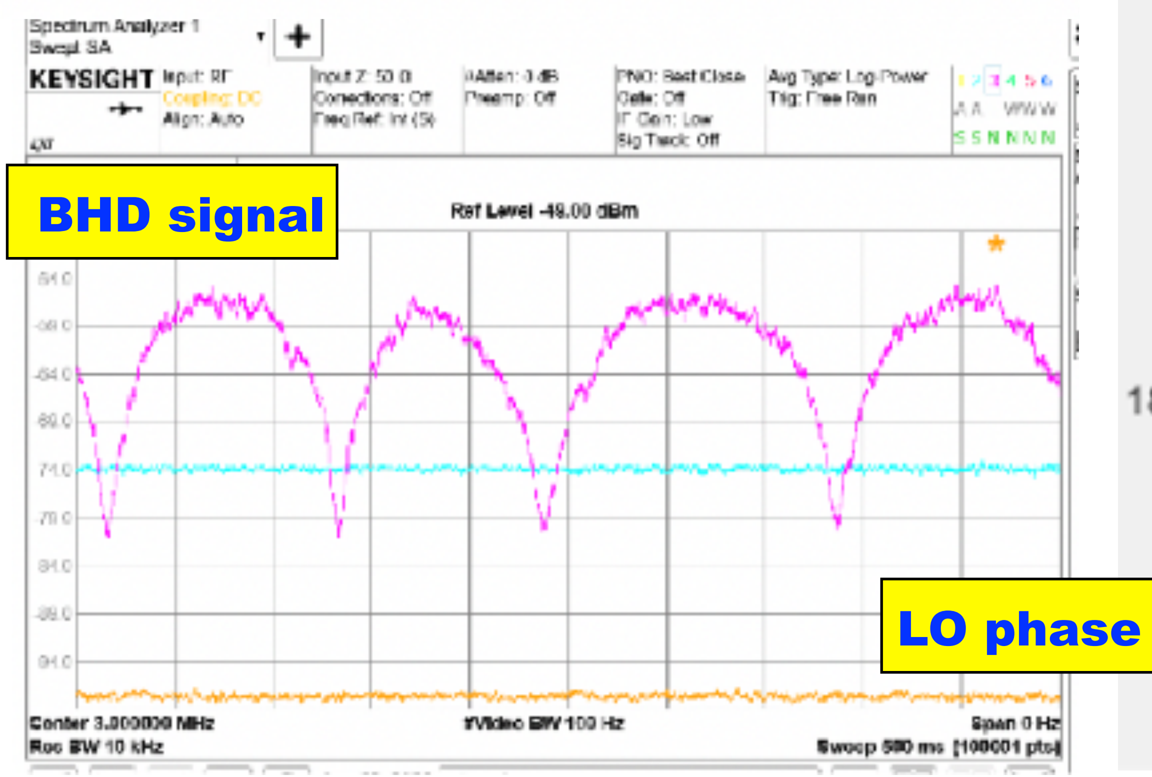
Squeezed States

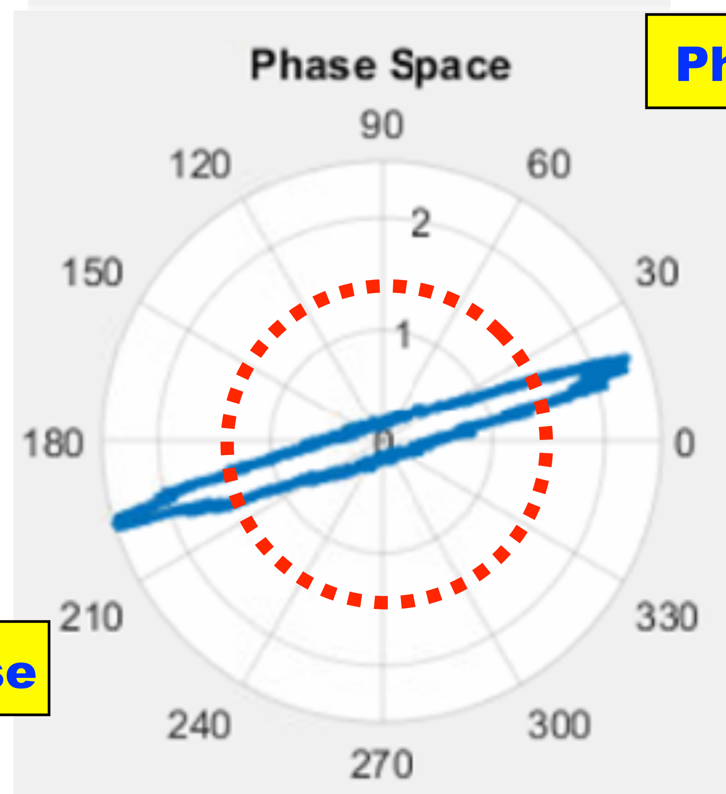


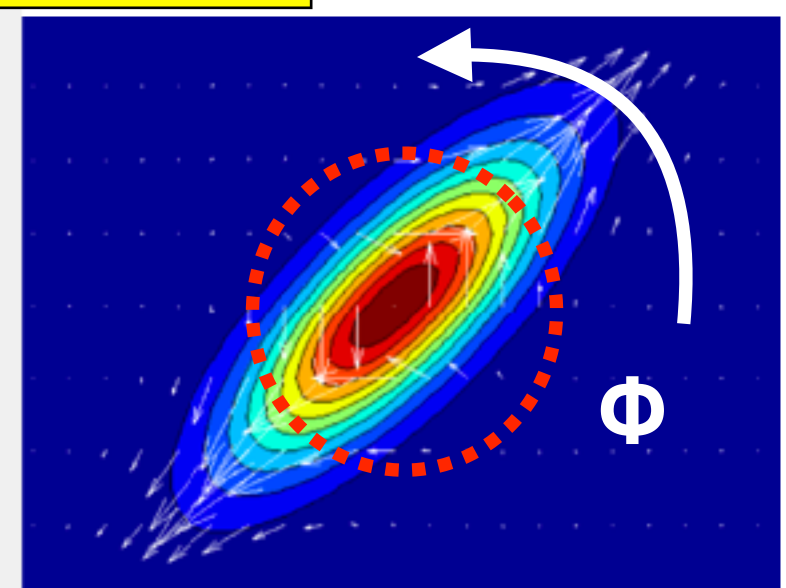




$$|\xi\rangle = \frac{1}{\sqrt{\cosh r}} \sum_{m=0}^{\infty} (-1)^m \frac{\sqrt{(2m)!}}{2^m m!} e^{im\theta} \tanh^m r |2m\rangle$$







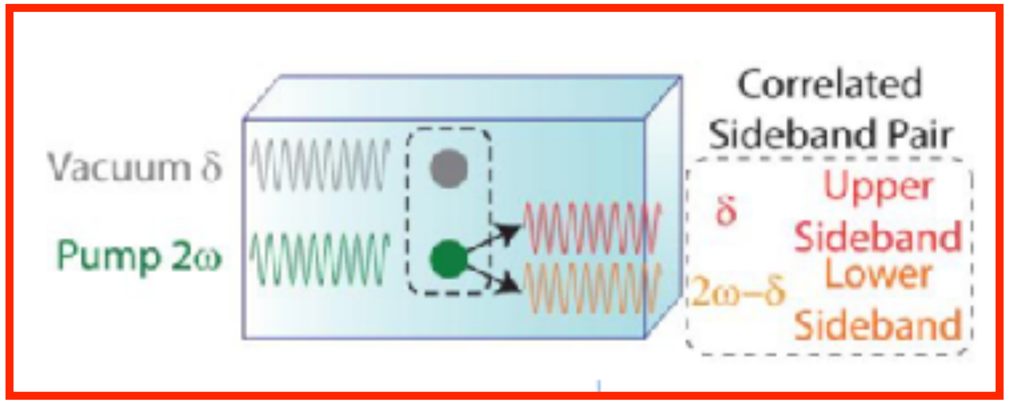
Optical Parametric Oscillator, OPO

For the degenerate parametric process, *i.e.*, two-photon process, its Hamiltonian is

$$\hat{H} = i\hbar(g\hat{a}^{\dagger 2} - g^*\hat{a}^2),$$

where g is a coupling constant. The state of fields generated by this Hamiltonian is

$$|\Psi(t)\rangle = \exp[(g\hat{a}^{\dagger 2} - g^*\hat{a}^2)t]|0\rangle.$$



Then, one can define the unitary squeeze operator

$$\hat{S}(\xi) = \exp[\frac{1}{2}\xi^*\hat{a}^2 - \frac{1}{2}\xi\hat{a}^{\dagger 2}],$$

where $\xi = r\exp(i\theta)$ is an arbitrary complex number.

Squeezed Operator

- If $|\Psi\rangle$ is the vacuum state $|0\rangle$, then $|\Psi_s\rangle$ state is the *squeezed vacuum*,

$$|\xi\rangle = \hat{S}(\xi)|0\rangle.$$

- The variances for squeezed vacuum are

$$\begin{aligned}\Delta\hat{a}_1^2 &= \frac{1}{4}[\cosh^2 r + \sinh^2 r - 2\sinh r\cosh r\cos\theta],\\ \Delta\hat{a}_2^2 &= \frac{1}{4}[\cosh^2 r + \sinh^2 r + 2\sinh r\cosh r\cos\theta],\end{aligned}$$

- For $\theta = 0$, we have

$$\Delta\hat{a}_1^2 = \frac{1}{4}e^{-2r}, \quad \text{and} \quad \Delta\hat{a}_2^2 = \frac{1}{4}e^{+2r},$$

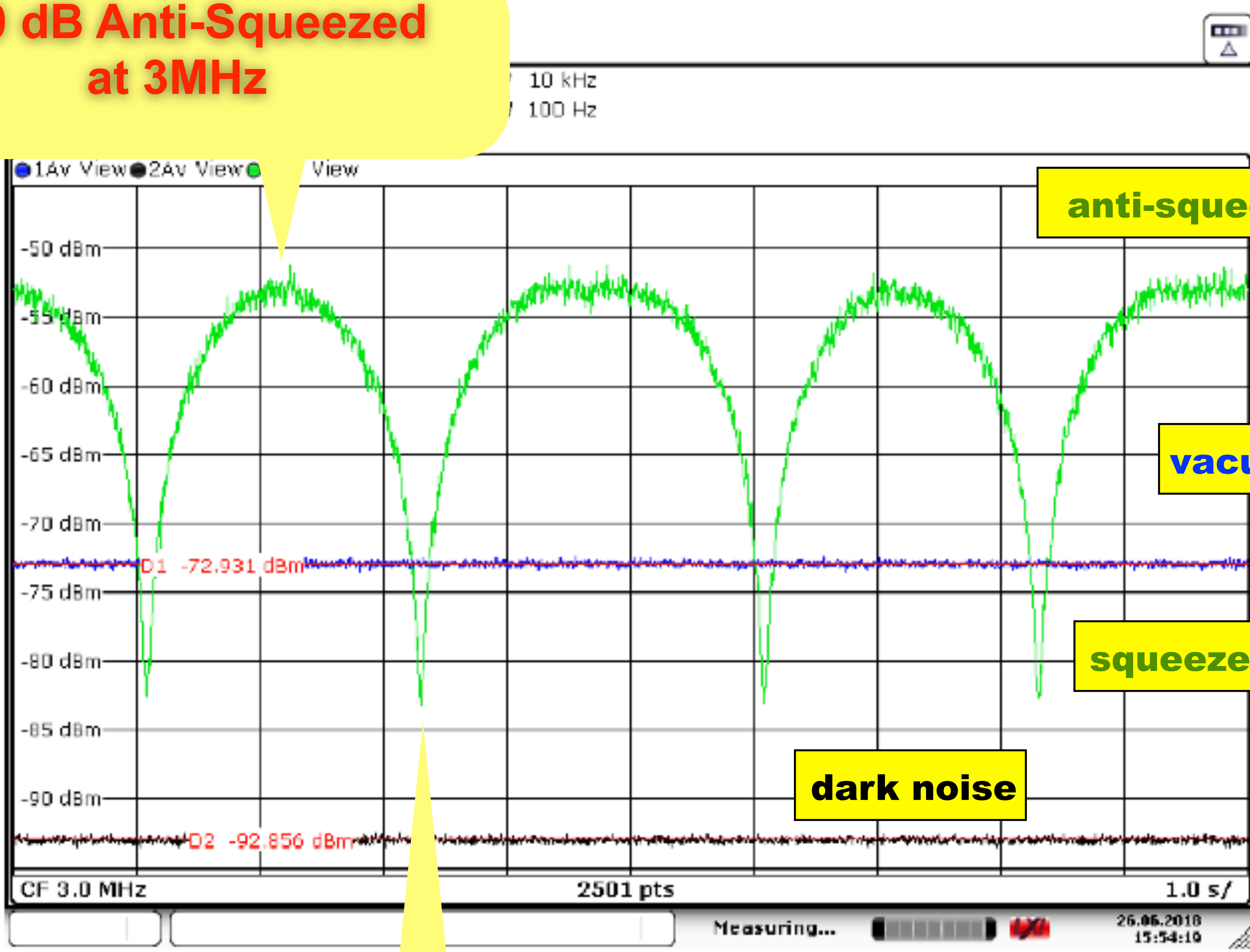
and squeezing exists in the $\hat{a}_1$ quadrature.

- For $\theta = \pi$, the squeezing will appear in the $\hat{a}_2$ quadrature.

OPO 532nm incident power: 96mW
MC output(LO beam)= 14.5mW

specially ordered InGaAs Photodiodes
Laser Components GmbH ϕ=500μm QE≥99%

+20 dB Anti-Squeezed at 3MHz



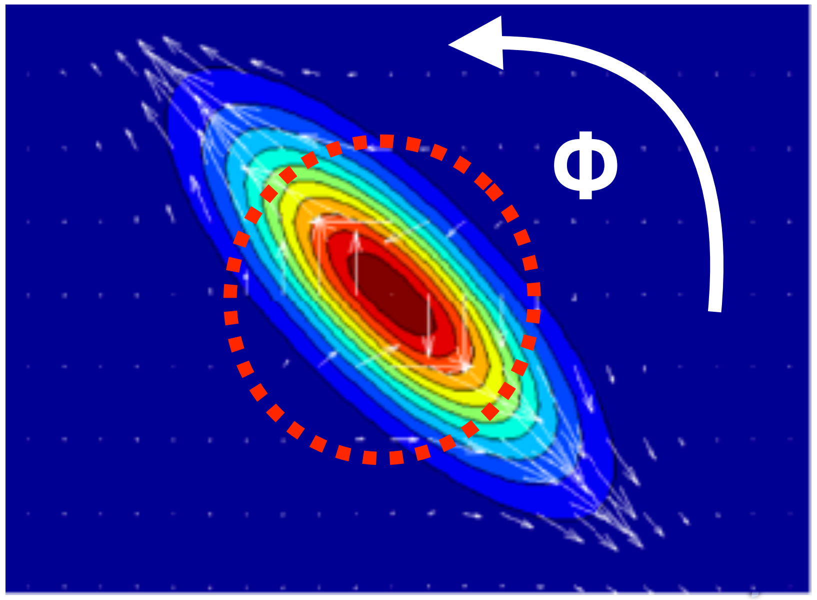
Clearance= 20dB

Zero Span mode at 3MHz
RBW=10kHz
VBW=100Hz

Blue Line: 14.5mW Vacuum noise
Black Line: Dark noise

-10 dB Squeezed vacuum at 3MHz

Squeezing angle, Φ



by Chien-Ming Wu

Date: June 26th, 2018

Axioms of Quantum Mechanics

1. **State:** The properties of a quantum system are completely defined by specification of its state vector $|\Psi\rangle$. The state vector is an element of a complex Hilbert space $\mathcal{H}$ called the space of states.

2. **Observable:** With every physical property $\hat{A}$ (energy, position, momentum, angular momentum, ...) there exists an associated linear, *Hermitian operator* $\hat{A}$ (usually called observable), which acts in the space of states $\mathcal{H}$. The eigenvalues of the operator are the possible values of the physical properties.

3. **Probability:**

   (a) If $|\Psi\rangle$ is the vector representing the state of a system and if $|\Phi\rangle$represents another physical state, there exists a probability $p(|\Psi\rangle, |\Phi\rangle)$ of finding $|\Psi\rangle$ in state $|\Phi\rangle$, which is given by the squared modulus of the scalar product on $\mathcal{H}$: : $p(|\Psi\rangle, |\Phi\rangle) = |\langle\Psi|\Phi\rangle|^2$ (Born Rule).

   (b) If $\mathcal{A}$ is an observable with eigenvalues a_k and eigenvectors $|k\rangle$, $\hat{A}|k\rangle = a_k|k\rangle$, given a system in the state $|\Psi\rangle$, the probability of obtaining a_k as the outcome of the measurement of $\hat{A}$ is $p(a_k) = |\langle k|\Psi\rangle|$. After the measurement the system is left in the state projected on the subspace of the eigenvalue a_k (Wave function collapse).

4. **Time evolution:** The evolution of a closed system is *unitary.* The state vector $|\Psi(t)\rangle$ at time t is derived from the state vector $|\Psi(t_0)\rangle$ at time t_0 by applying a unitary operator $\hat{U}(t, t_0)$, called the evolution operator: $|\Psi(t)\rangle = \hat{U}(t, t_0)|\Psi(t_0)\rangle$.

Quantum State Tomography

Non-Hermitian QM

Quantum Measurement (weak measurement)

Decoherence

Arrow of Time

Entangled-History

PRL 112, 130404 (2014) PHYSICAL REVIEW LETTERS week ending 4 APRIL 2014

Local $\mathcal{PT}$ Symmetry Violates the No-Signaling Principle

Yi-Chan Lee,[1,2,*] Min-Hsiu Hsieh,[2] Steven T. Flammia,[3] and Ray-Kuang Lee[1,4]

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Synopsis: Reflecting on an Alternative Quantum Theory

APS/Alan Stonebraker

Local PT Symmetry Violates the No-Signaling Principle
Yi-Chan Lee, Min-Hsiu Hsieh, Steven T. Flammia, and Ray-Kuang Lee
Phys. Rev. Lett. **112**, 130404 (2014)
Published April 3, 2014

PHYSICAL REVIEW LETTERS **123**, 080404 (2019)

Simulating Broken $\mathcal{PT}$-Symmetric Hamiltonian Systems by Weak Measurement

Minyi Huang,[1,*] Ray-Kuang Lee,[2,3,4,†] Lijian Zhang,[5,‡] Shao-Ming Fei,[6,7,§] and Junde Wu[1,∥]

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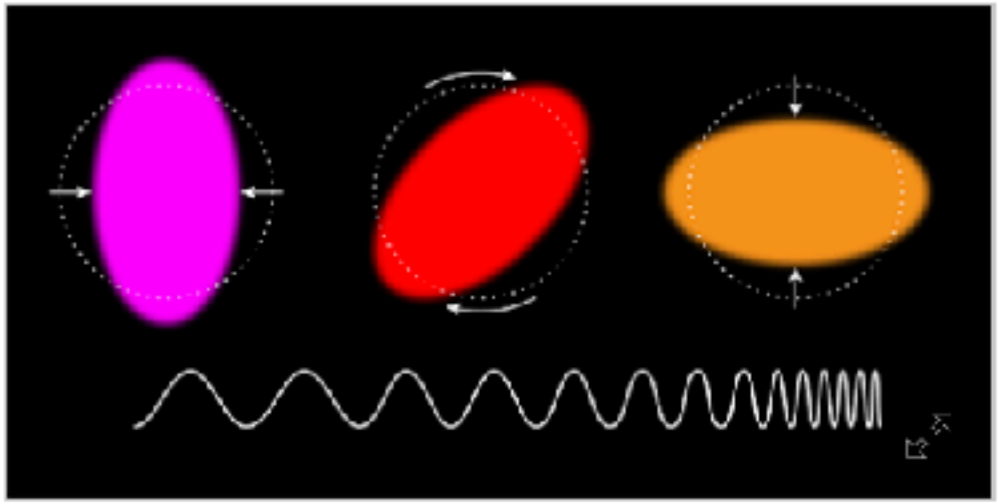
Synopsis: Feeling the Squeeze at All Frequencies

April 28, 2020 • *Physics* 13, s55

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



APS/Alan Stonebraker

First Exp. on FDS,

Freq.-Dep. Squeezing,

at 100 Hz

Gravitational-wave observatories have recently begun "squeezing" the light in their detectors, which reduces noise and improves sensitivity but only in a limited frequency range. Now two groups have demonstrated a method that reduces noise over a wide range of gravitational-wave frequencies. This quantum squeezing technique, when deployed with other planned upgrades, should double the sensitivity of gravitational-wave observatories.

Detecting gravitational waves involves beaming lasers back and forth in long-armed interferometers and looking for changes in the interference. The signal is affected by quantum noise in the light, which has amplitude and phase components. Amplitude noise dominates at low gravitational-wave frequencies, while phase noise is more of a problem at high frequencies.

Print

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 Squeezing for Advanced LIGO

L. McCuller, C. Whittle, D. Ganapathy, K. Komori, M. Tse, A. Fernandez-Galiana, L. Barsotti, P. Fritschel, M. MacInnis, F. Matichard, K. Mason, N. Mavalvala, R. Mittleman, Haocun Yu, M.E. Zucker, and M. Evans

Phys. Rev. Lett. 124, 171102 (2020)

Published April 28, 2020

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The New York Review of Books

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EMAIL PRINT

The Trouble with Quantum Mechanics

Steven Weinberg

The New York Times

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Opinion

Even Physicists Don't Understand Quantum Mechanics

Worse, they don't seem to want to understand it.

By Sean Carroll

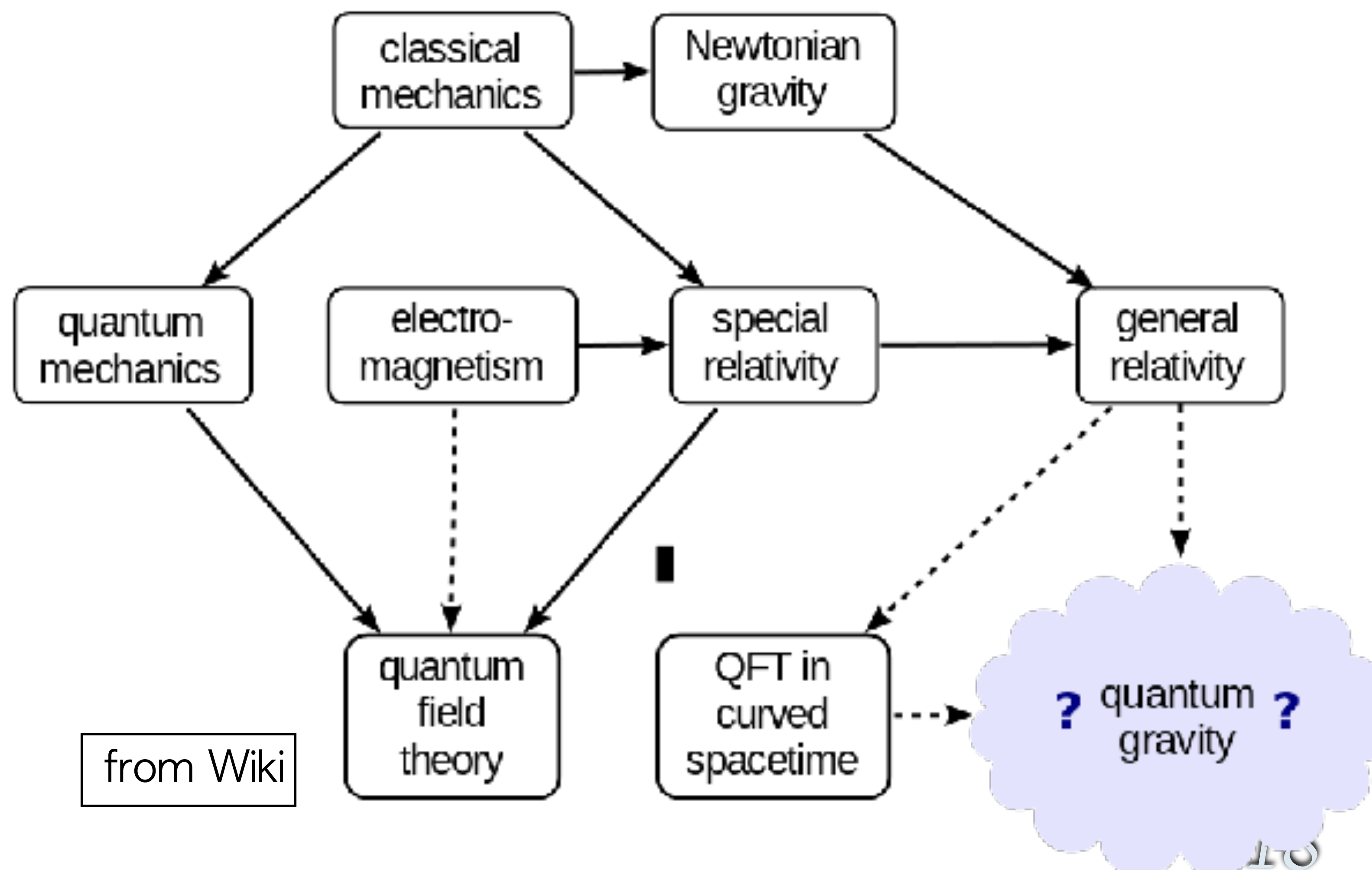
Dr. Carroll is a physicist.

Sept. 7, 2019

The Trouble with Quantum Physics, and Why it Matters

"Quantum physics—the physics of atoms and other ultratiny objects, like molecules and subatomic particles—is the most successful theory in all of science. But there's something troubling here. Quantum physics doesn't seem to apply to humans."

By Adam Becker | Mar 30, 2018



from Wiki

Can we see Quantum (state) ?

PHYSICS TODAY / APRIL 1985 PAG. 38-47

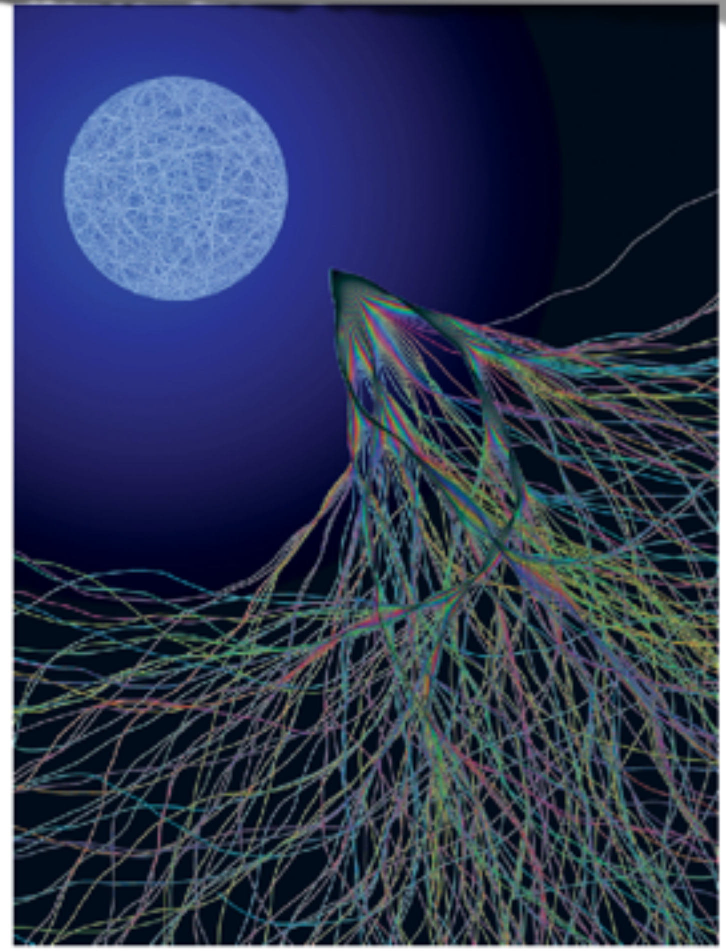
Is the moon there when nobody looks? Reality and the quantum theory

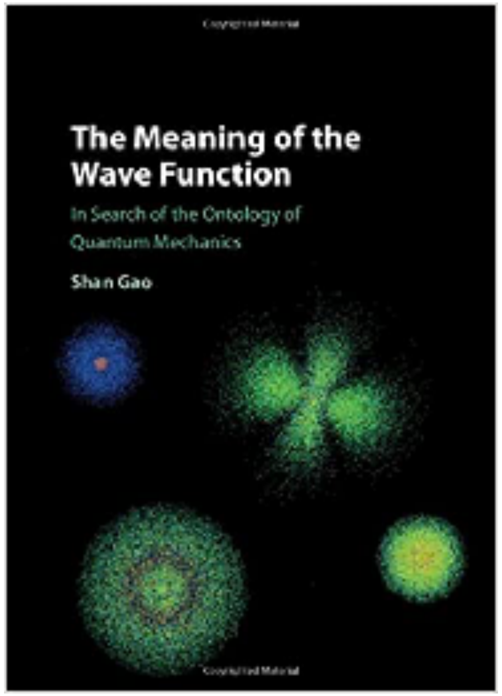
Einstein maintained that quantum metaphysics entails spooky actions at a distance; experiments have now shown that what bothered Einstein is not a debatable point but the observed behaviour of the real world.

N. David Mermin

[David Mermin is director of the Laboratory of Atomic and Solid State Physics at Cornell University. A solid-state theorist, he has recently come up with some quasithoughts about quasicrystals. He is known to PHYSICS TODAY readers as the person who made "boojum" an internationally accepted scientific term. With N.W.Ashcroft, he is about to start updating the world's funniest solid-state physics text. He says he *is* bothered by Bell's theorem, but may have rocks in his head anyway.]

Quantum mechanics is magic[1]





nature physics

ARTICLES

PUBLISHED ONLINE: 6 MAY 2012 | DOI: 10.1038/NPHYS2309

On the reality of the quantum state

Matthew F. Pusey[1]*, Jonathan Barrett[2] and Terry Rudolph[1]

Quantum states are the key mathematical objects in quantum theory. It is therefore surprising that physicists have been unable to agree on what a quantum state truly represents. One possibility is that a pure quantum state corresponds directly to reality. However, there is a long history of suggestions that a quantum state (even a pure state) represents only knowledge or information about some aspect of reality. Here we show that any model in which a quantum state represents mere information about an underlying physical state of the system, and in which systems that are prepared independently have independent physical states, must make predictions that contradict those of quantum theory.

No-go theorem

Textbook and Reference books