安東研輪講

2013年7月3日

分子研報告

道村唯太
東京大学大学院理学系研究科物理学専攻
安東研究室 博士課程2年

概要

- 出張先: 分子科学研究所 (愛知県岡崎市)
- 期間: 2013年6月10日-6月14日
- 目的: ネタ探し、情報交換
  量子測定理論、弱測定、量子もつれ、
  量子光学系、重力波検出器 ……
  http://qm.ims.ac.jp/wiki/doku.php/gravitational_wave_and_weak_measurement
  (要パスワード)

- 費用負担先:
  鹿野さん側
- 宿泊場所: 分子研 三島ロッジ

分子科学研究所

- 自然科学研究機構の機関の一つ

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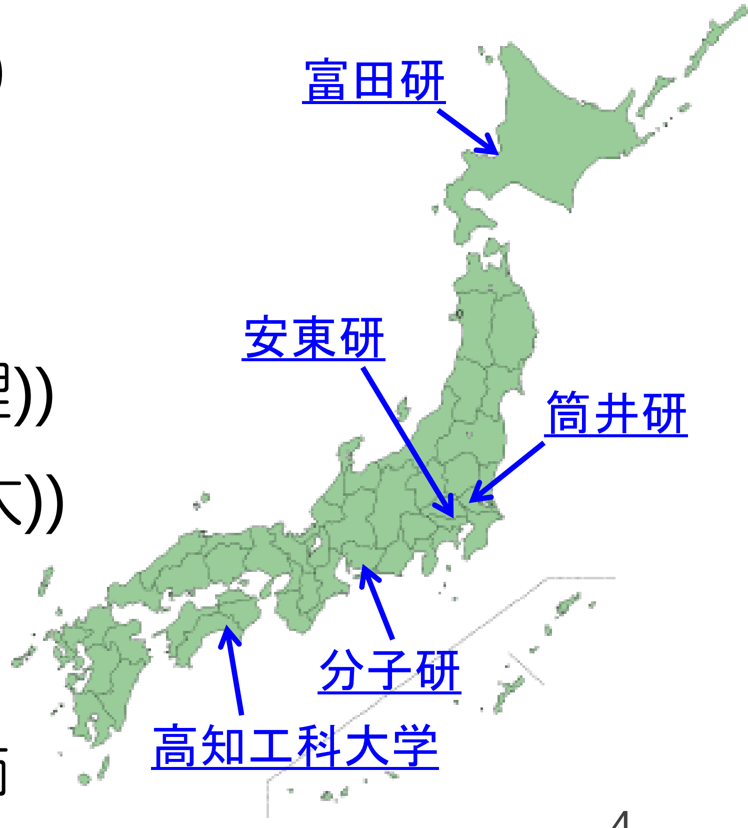
  高知工科大学システム工学群
  光エレクトロニクス専攻　講師



スケジュール1

- 特になし

- 6月10日 (鹿野、松岡、松本、道村)
  顔合わせ
  重力波検出器[道村]
  職探し[鹿野]

- 6月11日 (鹿野、松岡、松本、道村、李、福田、小林)
  弱測定による〇〇の可視化実験[小林]
  重力波検出器[松本/道村]
  光子の過去[道村]

スケジュール2

- 6月12日 (鹿野、松岡、松本、道村、李、福田)
  信号識別への弱値増幅の利用[松岡]
  大島グループ実験室見学[三宅/林/藤原]
  巨視的量子現象[松本]

- 6月13日 (鹿野、松岡、松本、道村、李、福田)
  弱測定の数理[李]
  一般確率論[福田]

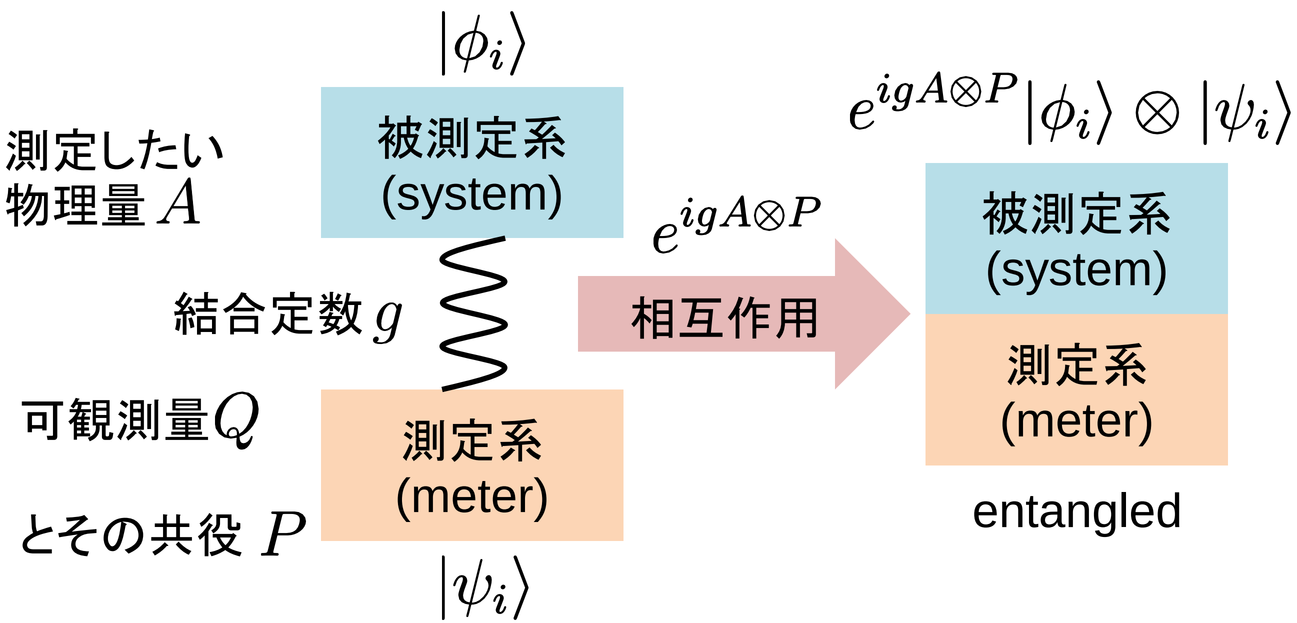
- 6月14日 (鹿野、松岡、松本、道村)
  雑談

弱値とは

- Y. Aharonov+: [PRL 60, 1351 (1988)]
- 観測量Aの弱値
  被測定系の初期状態$|\phi_i\rangle$、終状態$|\phi_f\rangle$
  $$\langle A\rangle_w \equiv \frac{\langle\phi_f|A|\phi_i\rangle}{\langle\phi_f|\phi_i\rangle}$$
- 弱値の特徴
  - $|\phi_f\rangle = |\phi_i\rangle$で通常の期待値
  - 複素数である
    波動関数の直接測定などに使える
  - 通常の期待値よりも大きくできる
    $\langle\phi_f|\phi_i\rangle$を小さくすれば良い(直交させる)
    信号増幅に使える

Conventional Measurement

- von Neumann Model

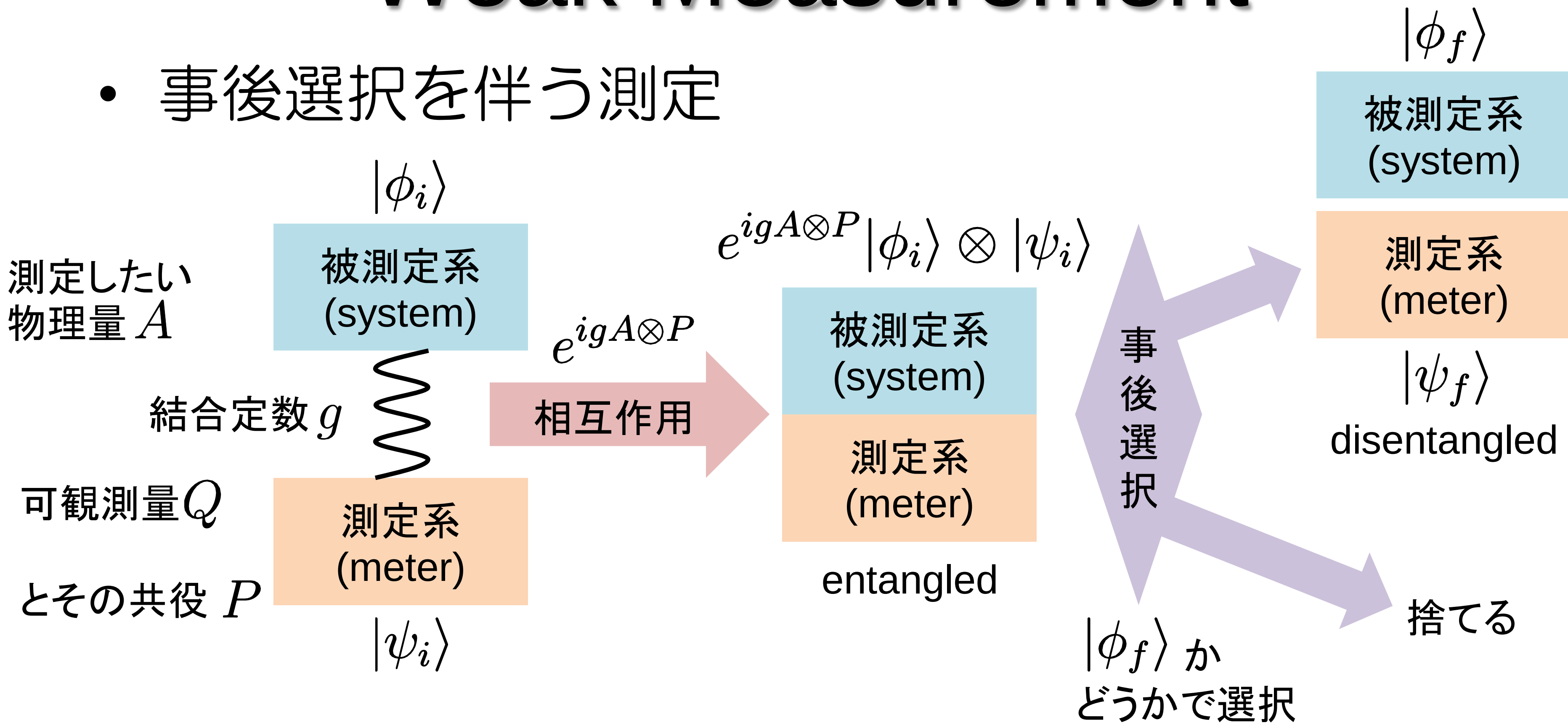


- 結合させたまま測定系の出力を見る
- 期待値は

$$E_A(\phi_i) = \frac{\langle\phi_i|A|\phi_i\rangle}{\langle\phi_i|\phi_i\rangle}$$

Weak Measurement

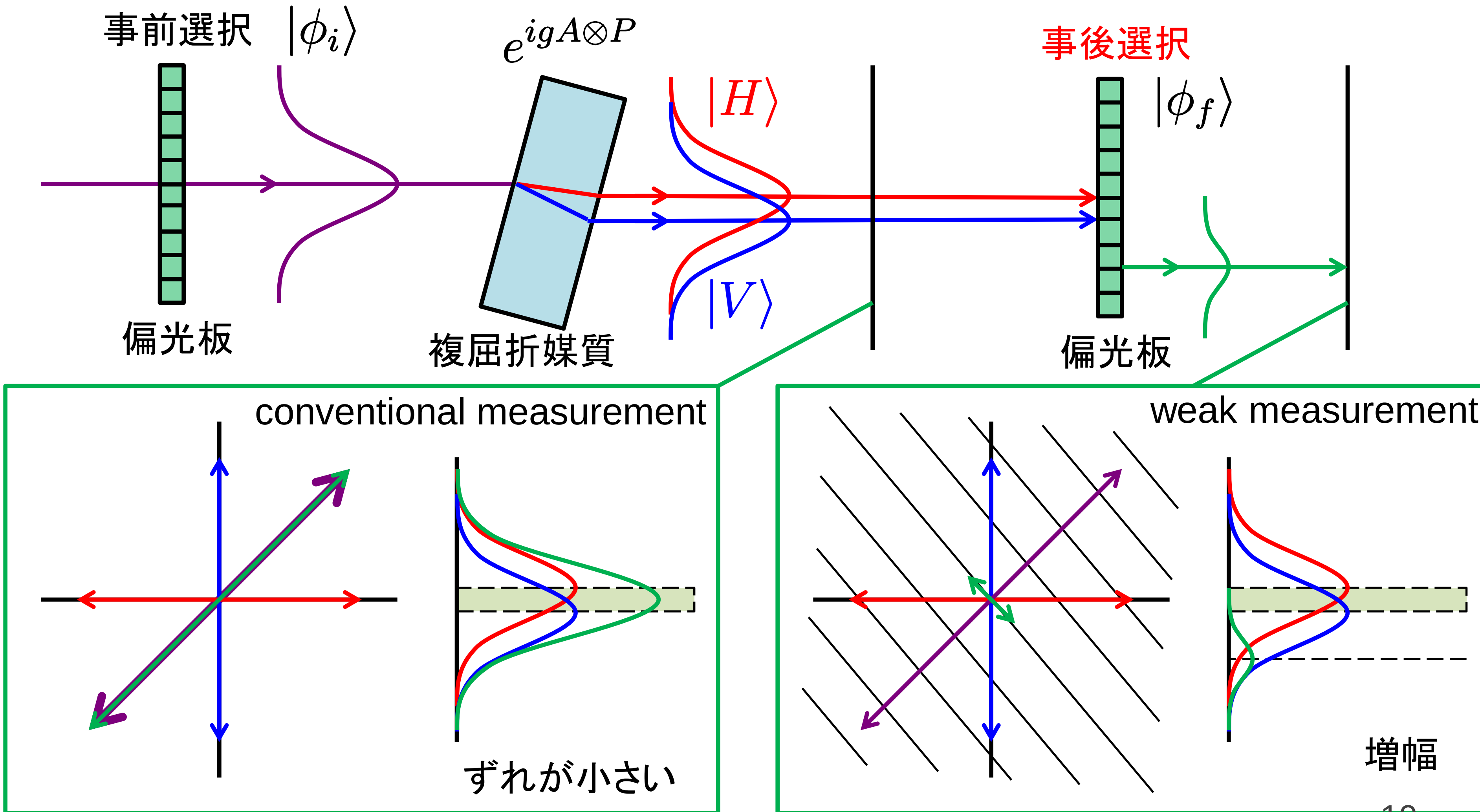
- 事後選択を伴う測定



- 被測定系の状態が $|\phi_f\rangle$ になったときだけ測定する
- 測定値が期待値の範囲外の値になりうる

弱値増幅のわかりやすい例

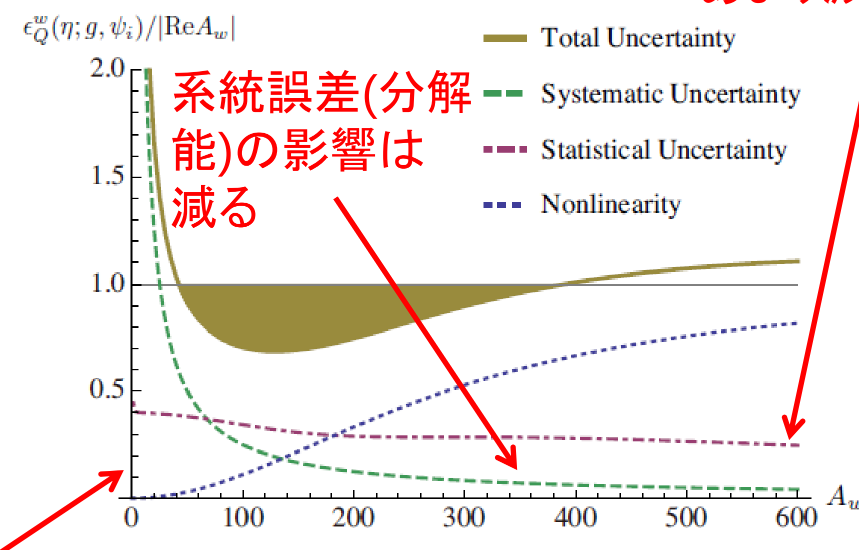
- 偏光による屈折の違いの測定



例からなんとなくわかること

- 波動関数(ビーム径)が重なっていないと意味が無い
- 弱値増幅で分解能を改善させることはできそう
- post selectionで大部分を捨てているので統計は稼げなそう
  - つまり散射雑音はよくならなそう
- 無相互作用測定と似ている(爆発させずに爆弾を判別できるが、成功確率は減る)

統計誤差は
あまり減らない



縦軸はN/S比のようなもの
下に行くほど良い

FIG. 1. Ratio of uncertainty $\epsilon_Q^w(\eta; g, d)$ to the real part of the weak value of the spin $S_z = \sigma_z/2$. By amplifying the weak value out of its numerical range $[-1/2, 1/2]$ to $(S_z)_w \approx 100$, the significance condition (15) is attained with confidence $\eta = 0.95$. (Parameters: $\delta_Q = 1/2$, $N_0 = 10^7$, $g = 1/50$ and $d = 4$.)

J. Lee & I. Tsutsui: arXiv:1305.2721

弱測定の応用例1

- O. Hosten & P. Kwiat: Science 319, 787 (2008)

Observation of the Spin Hall Effect of Light via Weak Measurements

Onur Hosten* and Paul Kwiat

We have detected a spin-dependent displacement perpendicular to the refractive index gradient for photons passing through an air-glass interface. The effect is the photonic version of the spin Hall effect in electronic systems, indicating the universality of the effect for particles of different nature. Treating the effect as a weak measurement of the spin projection of the photons, we used a preselection and postselection technique on the spin state to enhance the original displacement by nearly four orders of magnitude, attaining sensitivity to displacements of ~1 angstrom. The spin Hall effect can be used for manipulating photonic angular momentum states, and the measurement technique holds promise for precision metrology.

Hall effects, in general, are transport phenomena, in which an applied field on the particles results in a motion perpendicular to the field. Unlike the traditional Hall effect and its quantum versions, in which the effect depends on the electrical charge, the spin Hall effect is driven by the spin state of the particles. It was recently suggested (*1*, *2*) and observed (*3*) that, even in the absence of any scattering impurities, when an electric field is applied to a semiconductor, a dissipationless spin-dependent current perpendicular to the field can be generated. A photonic version of the effect—the spin Hall effect of light (SHEL)—was recently proposed (*4*) in which the spin-1 photons play the role of the spin-1/2 charges, and a refractive index gradient plays the role of the electric potential gradient.

We use an air-glass interface to demonstrate the SHEL, in which the transmitted beam of light splits by a fraction of the wavelength, upon refraction at the interface, into its two spin components (Fig. 1A): the component parallel ($s = +1$, right-circularly polarized) and antiparallel ($s = -1$, left-circularly polarized) to the central wave vector. This effect is different from (i) the previously measured (*5*) longitudinal Goos-Hänchen (*6*) and transverse Imbert-Fedorov (*7*, *8*) shifts in total internal reflection, which are described in terms of evanescent wave penetration, and (ii) the recently reported "optical spin Hall effect," which deals with optically generated spin currents of exciton-polaritons in a semiconductor microcavity (*9*). The splitting in the SHEL, implied by angular momentum conservation, takes place as a result of an effective spin-orbit interaction. The same interaction also leads to other effects such as the optical Magnus effect (*10*, *11*), the fine-splitting of the energy levels of an optical resonator (*12*) [in which the interaction resembles the spin-orbit (Russell-Saunders) coupling of electrons in atoms], and the deviation of photons from the simple geodesic paths of general relativity (*13*).

The exact amount of the transverse displacements due to the SHEL at an air-glass interface has been the subject of a recent debate (*4*, *14*–*16*). Our theory and experimental results support the predictions of Bliokh and Bliokh (*15*, *16*); although the calculations of other researchers (*4*, *11*, *14*) are not incorrect, they contain rather unfavorable initial conditions [see supporting online material (SOM)]. One can obtain close estimates of the magnitude of the displacements using solely the conservation of the z component of the total (spin plus orbital) angular mo-

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弱測定によるSpin Hall効果の観測

- 屈折時、右円偏光と左円偏光で横ずれ(~10nm)
- 4桁増幅して観測

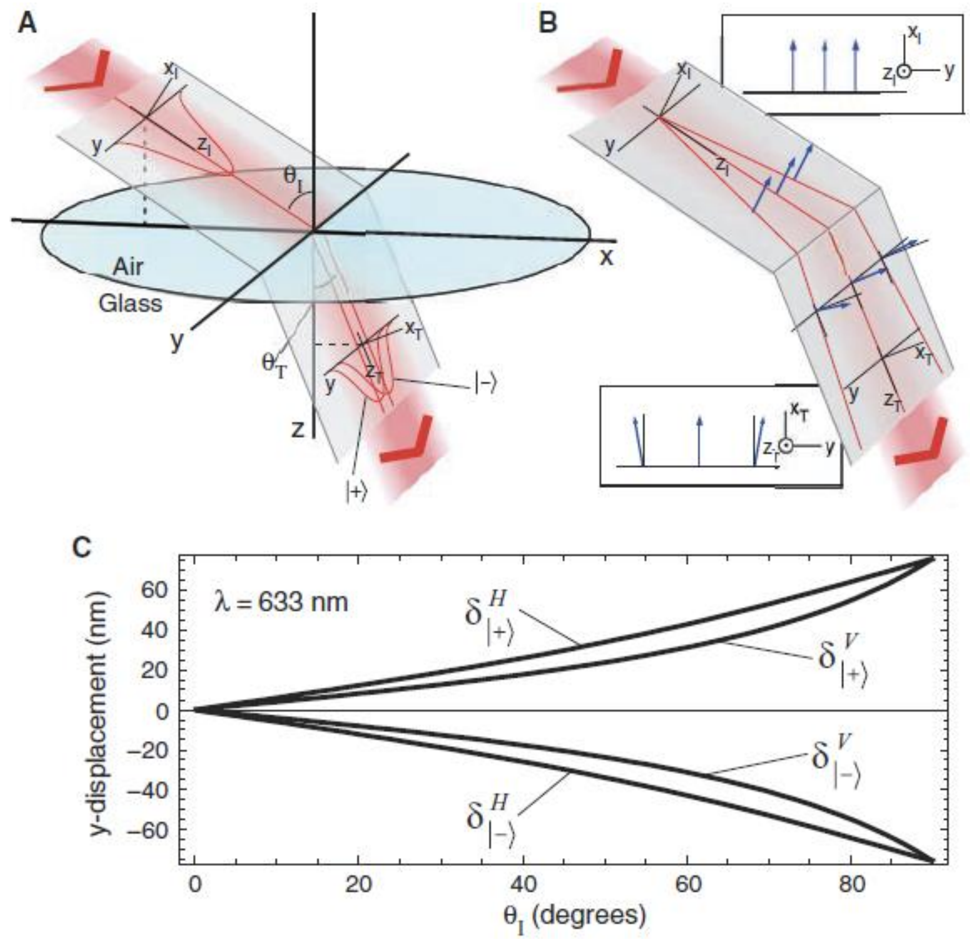

Fig. 1. The SHEL at an air-glass interface. (**A**) $|+\rangle$ and $|-\rangle$ spin components of a wave packet incident at angle θ_I experience opposite transverse displacements (not deflections) upon refraction at an angle θ_T. (**B**) Different plane-wave components acquire different polarization rotations upon refraction to satisfy transversality. The input polarization is in the x_I direction (equivalent to horizontal according to Fig. 3) for all constituent plane waves. Arrows indicate the polarization vectors associated with each plane wave before and after refraction. The insets clarify the orientation of the vectors. (**C**) Theoretical displacements of the spin components (Eq. 1) for horizontally and vertically polarized incident photons with wavelength λ = 633 nm.

弱測定の応用例2

- P. B. Dixon+: PRL 102, 173601 (2009)

Selected for a Viewpoint in *Physics*
PRL **102,** 173601 (2009) PHYSICAL REVIEW LETTERS week ending 1 MAY 2009

Ultrasensitive Beam Deflection Measurement via Interferometric Weak Value Amplification

P. Ben Dixon, David J. Starling, Andrew N. Jordan, and John C. Howell
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627, USA
(Received 12 January 2009; published 27 April 2009)

We report on the use of an interferometric weak value technique to amplify very small transverse deflections of an optical beam. By entangling the beam's transverse degrees of freedom with the which-path states of a Sagnac interferometer, it is possible to realize an optical amplifier for polarization independent deflections. The theory for the interferometric weak value amplification method is presented along with the experimental results, which are in good agreement. Of particular interest, we measured the angular deflection of a mirror down to 400 ± 200 frad and the linear travel of a piezo actuator down to 14 ± 7 fm.

DOI: 10.1103/PhysRevLett.102.173601 PACS numbers: 42.50.Xa, 03.65.Ta, 06.30.Bp, 07.60.Ly

弱測定による角度の測定

- Sagnac干渉計のdark portで見ているのが事後選択をしていることに相当(SBCで調整)
- 10^{-12} rad以下の角度変化を測定

Soleil-Babinet Compensator
右回りと左回りの間に位相差を与える

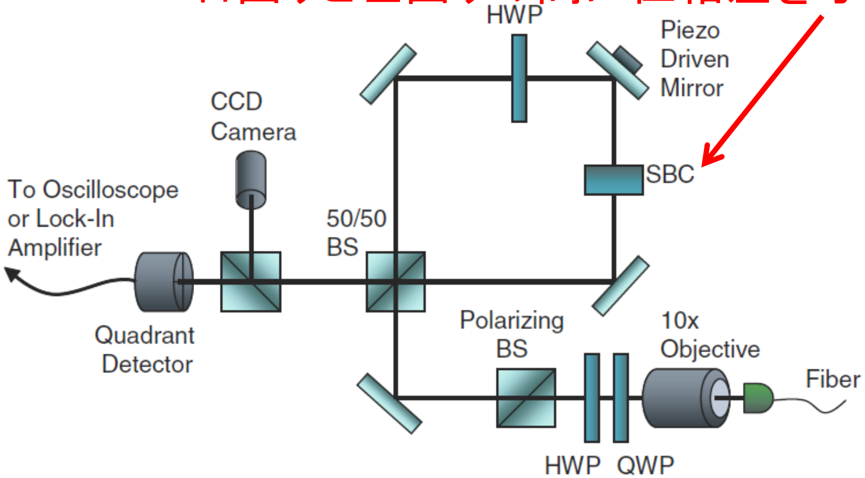

FIG. 1 (color online). Experimental Setup. The objective lens collimates a 780 nm beam. After passing through polarization optics, the beam enters a Sagnac interferometer consisting of three mirrors and a 50/50 beam splitter arranged in a square. The output port is monitored by both a quadrant detector and a CCD camera. The SBC and half-wave plate in the interferometer allow the output intensity of the interferometer to be tuned. The piezo mirror gives a small beam deflection.

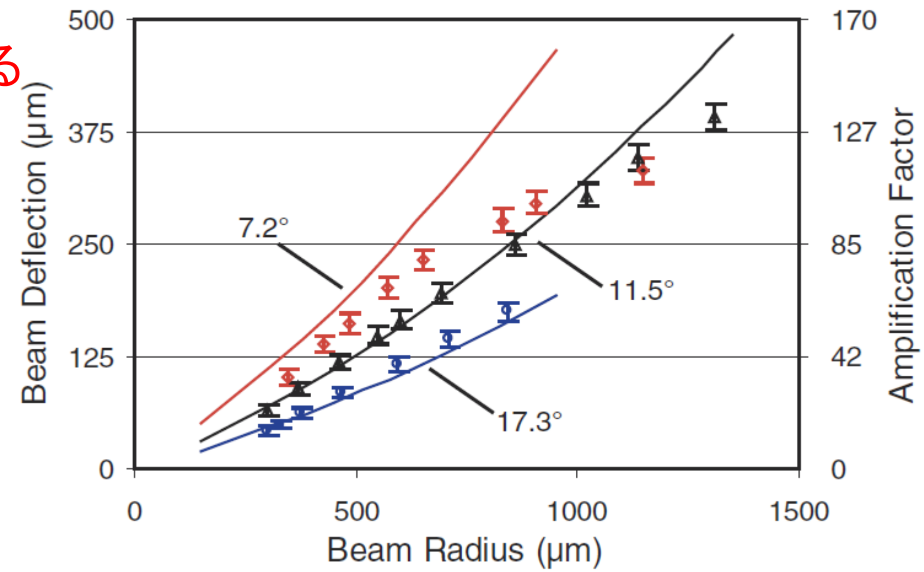

FIG. 2 (color online). Measured beam deflection is plotted as a function of beam radius σ. SBC angle ϕ for each data set is labeled. The scale on the left is the measured beam deflection $\langle x \rangle$. The scale on the right is the amplification factor $\mathcal{A}$. The unamplified deflection is $\delta = 2.95$ μm. The solid lines are theoretical predictions based on Eq. (6).

もう一つの特徴: 弱値は複素数

- 弱測定で波動関数の直接観測などができる
- J. S. Lundeen+: [Nature 474, 188 (2011)]

LETTER

doi:10.1038/nature10120

Direct measurement of the quantum wavefunction

Jeff S. Lundeen[1], Brandon Sutherland[1], Aabid Patel[1], Corey Stewart[1] & Charles Bamber[1]

The wavefunction is the complex distribution used to completely describe a quantum system, and is central to quantum theory. But despite its fundamental role, it is typically introduced as an abstract element of the theory with no explicit definition[1,2]. Rather, physicists come to a working understanding of the wavefunction through its use to calculate measurement outcome probabilities by way of the Born rule[3]. At present, the wavefunction is determined through tomographic methods[4–8], which estimate the wavefunction most consistent with a diverse collection of measurements. The indirectness of these methods compounds the problem of defining the wavefunction. Here we show that the wavefunction can be measured directly by the sequential measurement of two complementary variables of the system. The crux of our method is that the first measurement is performed in a gentle way through weak measurement[9–18], so as not to invalidate the second. The result is that the real and imaginary components of the wavefunction appear directly on our measurement apparatus. We give an experimental example by directly measuring the transverse spatial wavefunction of a single photon, a task not previously realized by any method. We show that the concept is universal, being applicable to other degrees of freedom of the photon, such as polarization or frequency, and to other quantum systems—for example, electron spins, SQUIDs (superconducting quantum interference devices) and trapped ions. Consequently, this method gives the wavefunction a straightforward and general definition in terms of a specific set of experimental operations[19]. We expect it to expand the range of quantum systems that can be characterized and to initiate new avenues in fundamental quantum theory.

At the centre of the direct measurem
disturbance induced by the first measu
ment of an arbitrary variable A. In gene
the coupling between an apparatus and
the translation of a pointer. The pointe
a measurement. In a technique know
coupling strength is reduced and thi
disturbance created by the measurem
promises measurement precision, but
aging. The average of the weak measur
value $\langle\Psi|A|\Psi\rangle$, indicated by an avera
proportional to this amount.

A distinguishing feature of weak m
disturb a subsequent normal (or 'str
observable C in the limit where the cou
lar ensemble subset that gave outcome
age of the weak measurement of A. I
strength, this is called the 'weak value'

$$\langle A\rangle_W = \frac{\langle c|A}{\langle c}$$

Selecting a particular subset of an en
measurement outcome is known as 'p
tool in quantum information processi

Returning to our example of a single particle, consider the weak measurement of position ($A=\pi_x\equiv|x\rangle\langle x|$) followed by a strong measurement of momentum giving $P=p$. In this case, the weak value is:

$$\langle\pi_x\rangle_W = \frac{\langle p|x\rangle\langle x|\Psi\rangle}{\langle p|\Psi\rangle} \quad (2)$$

$$= \frac{e^{ipx/\hbar}\Psi(x)}{\Phi(p)} \quad (3)$$

In the case $p=0$, this simplifies to

$$\langle\pi_x\rangle_W = k\Psi(x) \quad (4)$$

where $k=1/\Phi(0)$ is a constant (which can be eliminated later by normalizing the wavefunction). The average result of the weak measurement of π_x is proportional to the wavefunction of the particle at x. Scanning the weak measurement through x gives the complete wavefunction. At each x, the observed position and momentum shifts of the measurement pointer are proportional to $\mathrm{Re}\Psi(x)$ and $\mathrm{Im}\Psi(x)$, respectively. In short, by reducing the disturbance induced by measuring X and then measuring P normally, we measure the wavefunction of the single particle.

[1]Institute for National Measurement Standards, National Research Council, 1200 Montreal Road, Ottawa, Canada, K1A 0R6.

波動関数の直接測定

- 単光子の空間分布を測定
- 普通は実部と虚部を同時には測れないはず

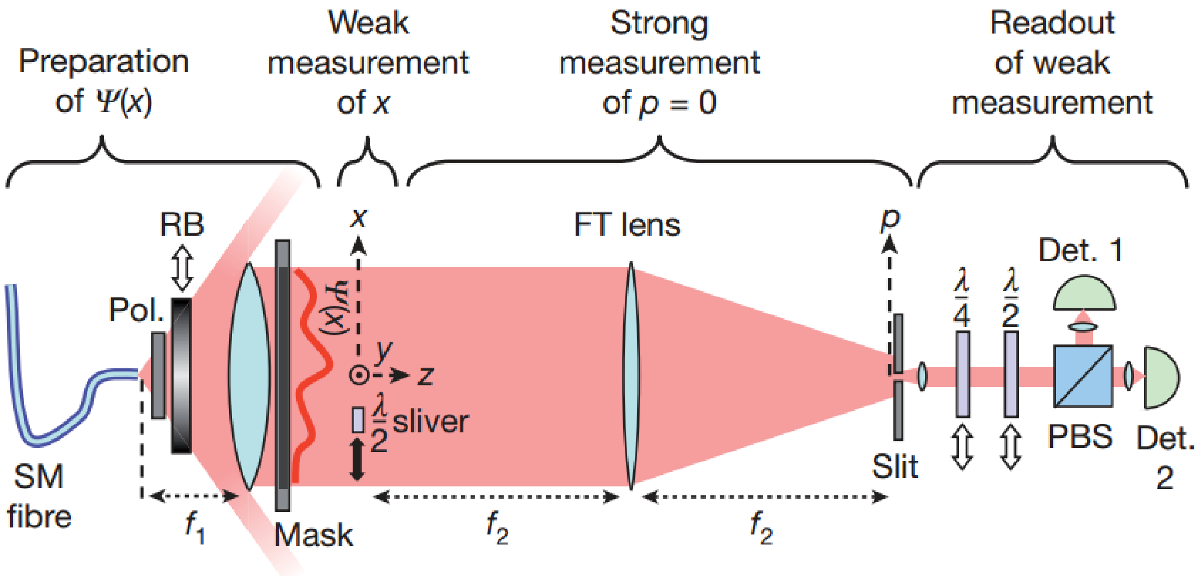

Figure 1 | Direct measurement of the photon transverse wavefunction. To begin with photons having identical wavefunctions, we transmit them through an optical fibre (Nufern PM780-HP) that allows only a single mode (SM) to pass. This mode is approximately Gaussian, with a nominal $1/e^2$ diameter of $5.3 \pm 1.0\ \mu m$. The photons emerge from the fibre and pass through a micro-wire polarizer (Pol.; Edmund Optic NT47-602) to be collimated by an achromatic lens ($f_1 = 30$ cm, diameter 5 cm, Thorlabs AC508-300-B), one focal length (f_1) away from the fibre. The lens was masked off with a rectangular

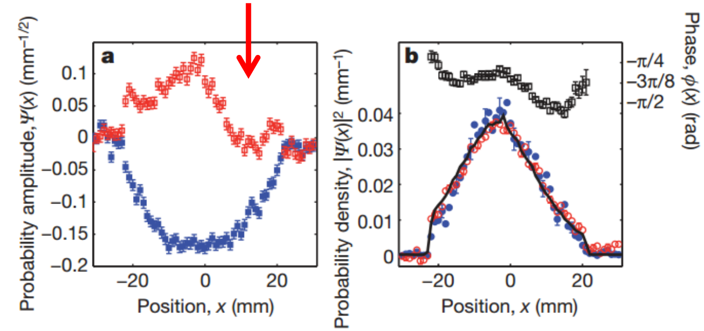

Figure 2 | The measured single-photon wavefunction, $\Psi(x)$, and its modulus squared and phase. a, Re$\Psi(x)$ (solid blue squares) and Im$\Psi(x)$ (open red squares) measured for the truncated Gaussian wavefunction. **b**, Using the data in **a** we plot the phase $\phi(x) = \arctan(\mathrm{Re}\Psi(x)/\mathrm{Im}\Psi(x))$ (open squares; right axis) and the modulus squared $|\Psi(x)|^2$ (solid blue circles; left axis). There is good agreement between the latter and a strong measurement of the x probability distribution Prob(x) (solid line; left axis) conducted by scanning a detector along x in the plane of the sliver. The phase is relatively flat, as expected from the fibre mode. The slight variation is consistent with the manufacturer specification of the first lens and the phase curvature measured with a shear plate. We also removed the slit completely. In this case, there is no post-selection and the weak value $\langle\pi_x\rangle$ becomes equal to the standard expectation value $\langle\Psi|\pi_x|\Psi\rangle = |\Psi(x)|^2$. We plot the measured Re$\langle\pi_x\rangle$ (open red circles; left axis) after it is normalized so that $\int \mathrm{Re}\,\Psi(x)dx = 1$ and find it is in good agreement with Prob(x). We find that Im$\langle\pi_x\rangle$ is ten times smaller, making $\langle\pi_x\rangle$ largely real, as expected. Error bars are ± 1 s.d. found from statistics in repeated scans. In **b**, only every third error bar is shown for clarity.

その他の波動関数測定例

- J. Z. Salvail+: Nature Photonics 7, 316 (2013)

nature photonics
ARTICLES
PUBLISHED ONLINE: 3 MARCH 2013 | DOI: 10.1038/NPHOTON.2013.24

Full characterization of polarization states of light via direct measurement

Jeff Z. Salvail[1]*, Megan Agnew[1], Allan S. Johnson[1], Eliot Bolduc[1], Jonathan Leach[1] and Robert W. Boyd[1,2]

- M. Malik+: arXiv:1306.0619

Direct Measurement of Quantum State Rotations

Mehul Malik,[1*] Mohammad Mirhosseini,[1] Martin P. J. Lavery,[2]
Jonathan Leach,[3,4] Miles J. Padgett,[2] Robert W. Boyd[1,4]

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[4] *Department of Physics, University of Ottawa, Ottawa, ON K1N 6N5 Canada*

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弱測定に対する否定的意見

- 例えば A. J. Legget: [PRL 62, 2325 (1989)]
- 始状態を決めているので測定と言えるのか
- 複素量？？
- $\langle \phi_f | \phi_i \rangle$を小さくすると弱値は大きくなるが、成功確率は減る

- 評価する意見
  - 時間対称な量子論の枠組を与えている
  - 一般の測定を包含
  - 精密測定に実際に使えている

弱値増幅の利点はない

- G. C. Knee & E. M. Gauger: arXiv:1306.6321
- 成功確率が減るので分解能もランダム誤差も改善しないと主張

Weak-value amplification offers no advantage for overcoming technical imperfections

George C. Knee*
Department of Materials, University of Oxford, Oxford OX1 3PH, United Kingdom

Erik M. Gauger
Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543 and Department of Materials, University of Oxford, Oxford OX1 3PH, United Kingdom
(Dated: June 27, 2013)

The combination of a weak quantum measurement with postselection enables the phenomenon of weak-values, where the average displacement of the meter wavefunction may significantly exceed the eigenspectrum of the measured observable. Employing the Fisher Information metric, we argue that the effect offers no metrological advantage due to the necessarily reduced probability of success. We analyze a situation where the detector has only finite resolution and when the measuring device is afflicted by random displacements. Surprisingly, weak-value amplification continues to provide no benefit when these imperfections are introduced.

計算してみよう

- 分子研から帰ってきてからの話
- 詳しくは
  「通常の測定と弱測定でのQPDによる位置検出の量子限界」
  http://granite.phys.s.u-tokyo.ac.jp/michimura/document/noteQPD.pdf
- パルスはよくわからないがQPDによる位置検出なら散射雑音の計算は容易
- QPDに入射する光強度と位置ずれに対する応答から位置ずれ等価散射雑音が計算できる

$$\delta x_{\mathrm{shot}} = \delta P_{\mathrm{shot}} \left(\frac{\partial P_{\mathrm{diff}}}{\partial(\delta x)} \right)^{-1}$$

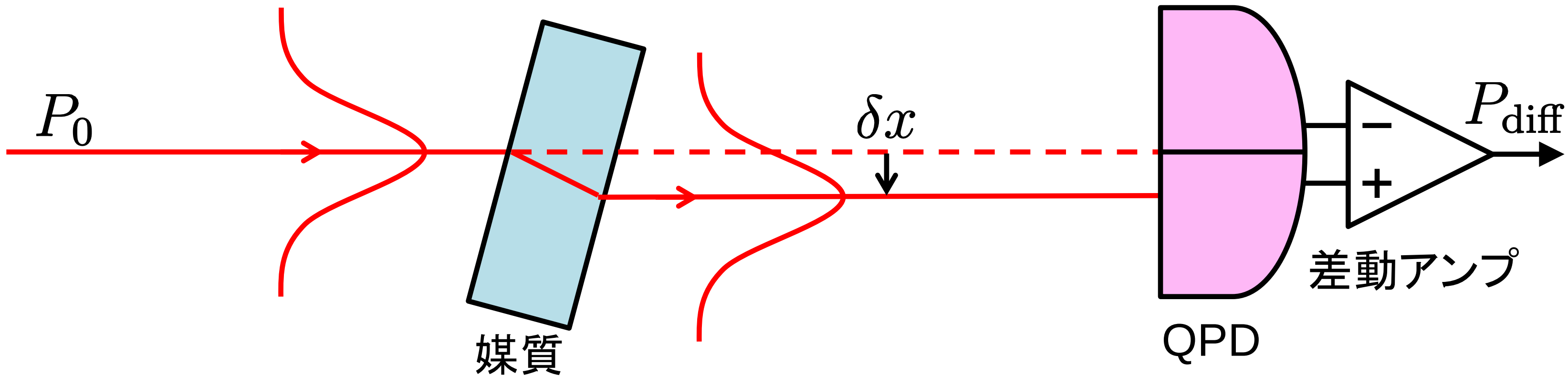
光強度変化の検出限界 (W/rtHz)

$$\delta P_{\mathrm{shot}} = \sqrt{2h\nu P_{\mathrm{tot}}}$$

QPD出力の応答 (W/m)

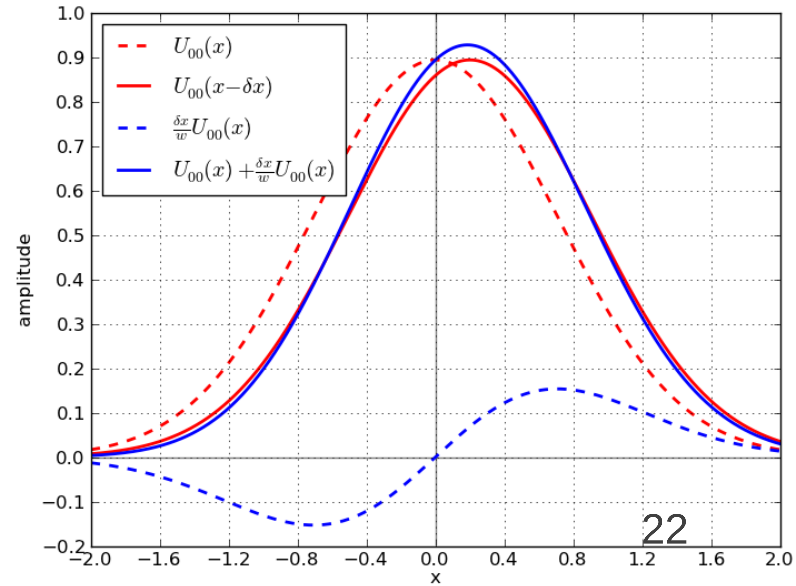
通常の測定

- 屈折による位置ずれをQPDで測定するような系を考える



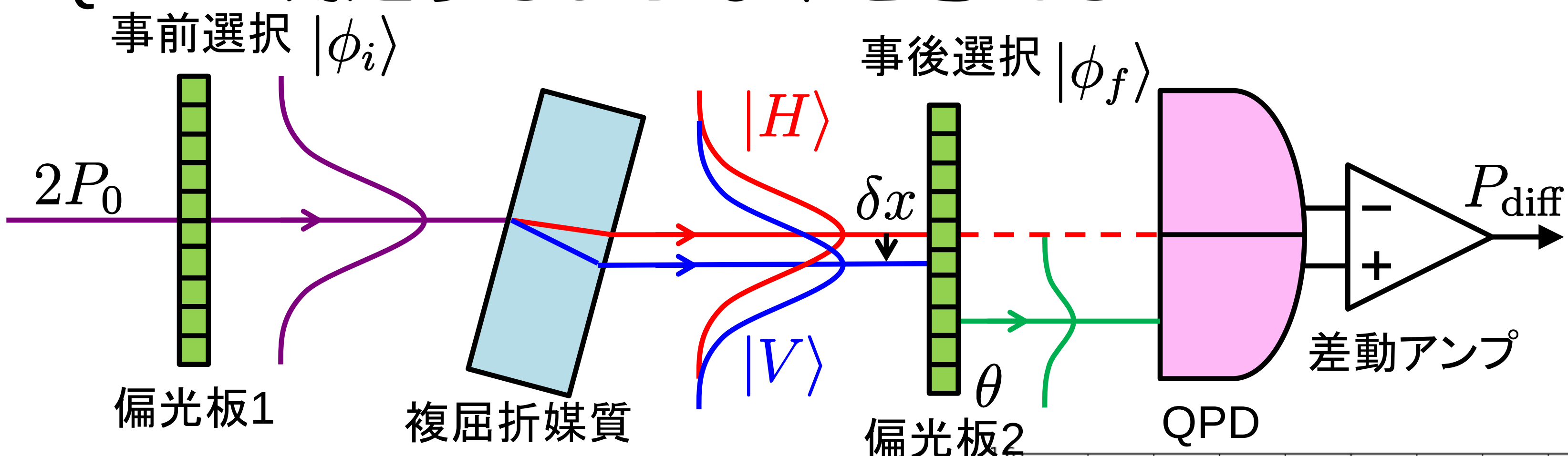
- QPD上での電場分布

$$E(x) = E_0 U_{00}(x - \delta x)$$



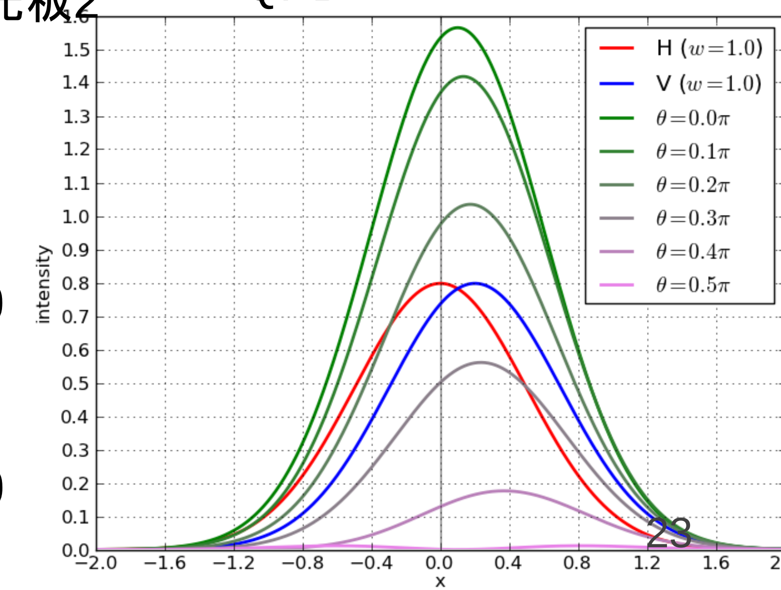
弱測定

- 複屈折によるH偏光とV偏光の位置ずれの差をQPDで測定するような系を考える



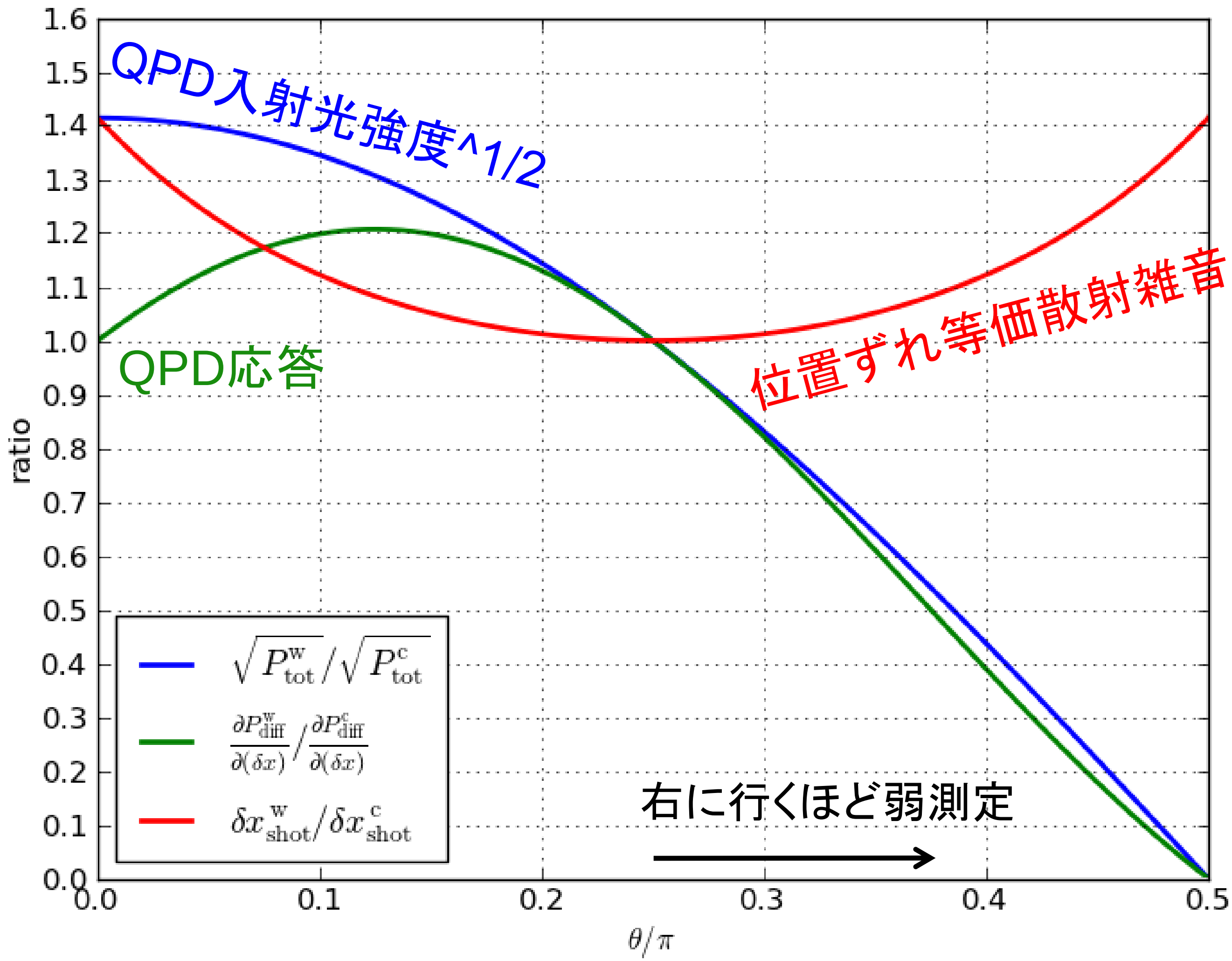
- QPD上での電場分布

$$E(x) = \cos\left(\frac{\pi}{4} + \theta\right)U_{00}(x)E_0$$
$$+ \cos\left(\frac{\pi}{4} - \theta\right)U_{00}(x - \delta x)E_0$$



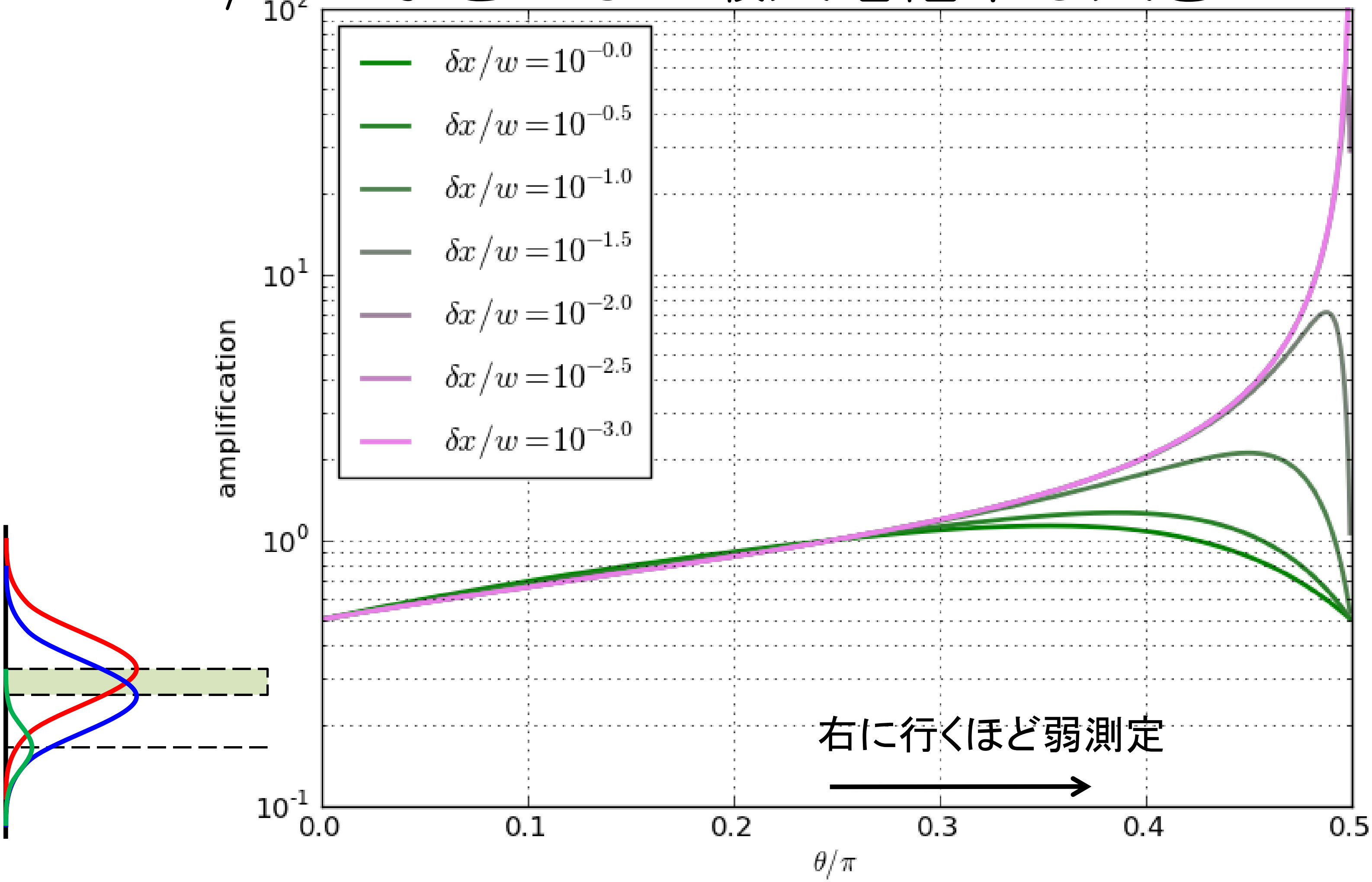
通常の測定と弱測定の比

- 散射雑音は改善しない(むしろ悪化)



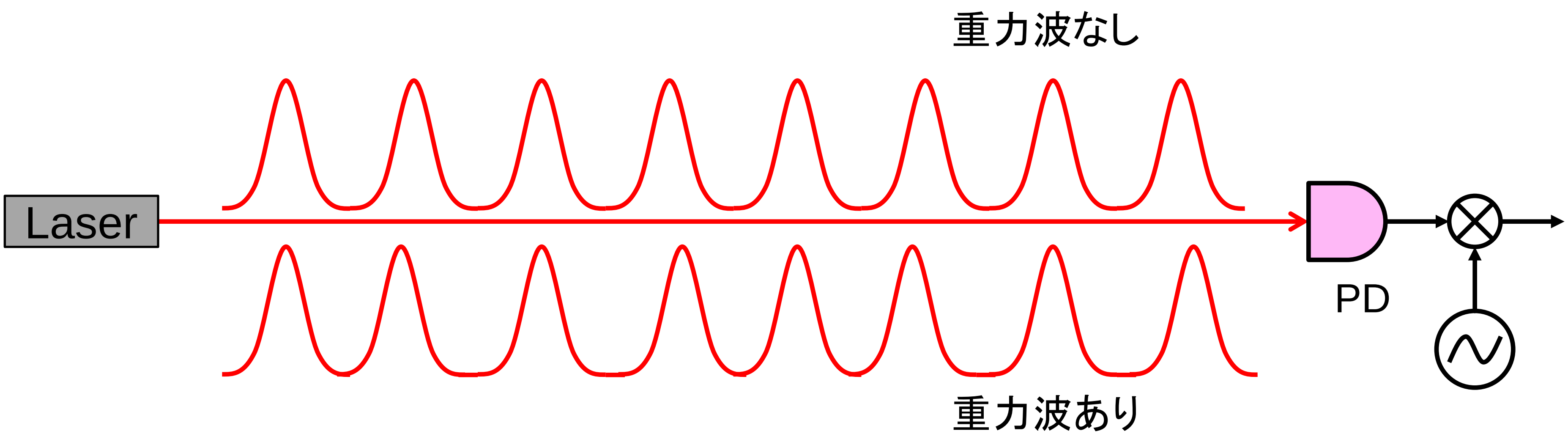
弱測定での増幅率

- 輝度中心の位置は δx より大きくなり得る
- $\delta x/w$が小さいほど最大増幅率は大きい



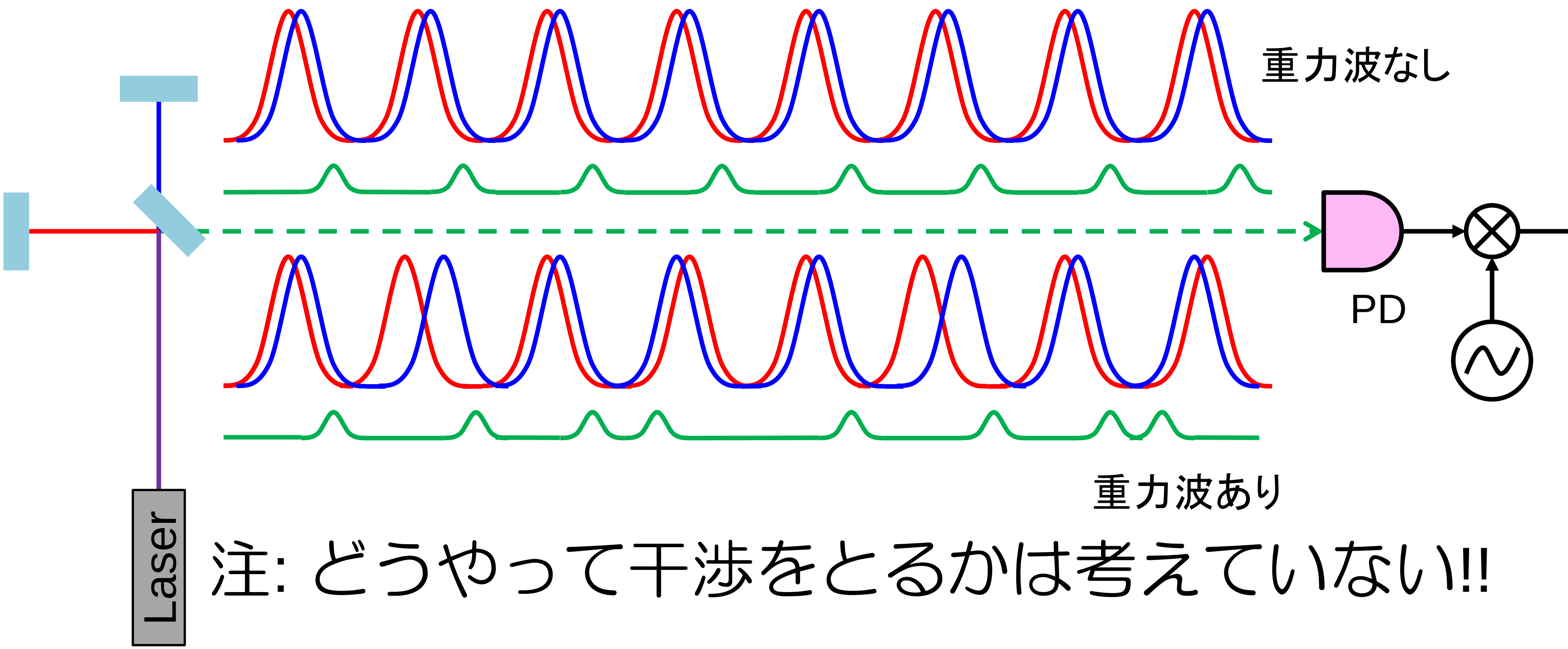
重力波検出器への応用？

- 干渉計型重力波検出器では位置ずれではなく、時間ずれをみたい
  →パルスの到着間隔の変化
- 単純なセットアップでは難しい



パルス間隔の変化を増幅

- Michelson干渉計(または腕の長さを合わせるためにSagnac干渉計)で弱測定によりパルス間隔の変化を増幅させることは可能
- 腕の非対称性、パルス幅で増幅率が決まる

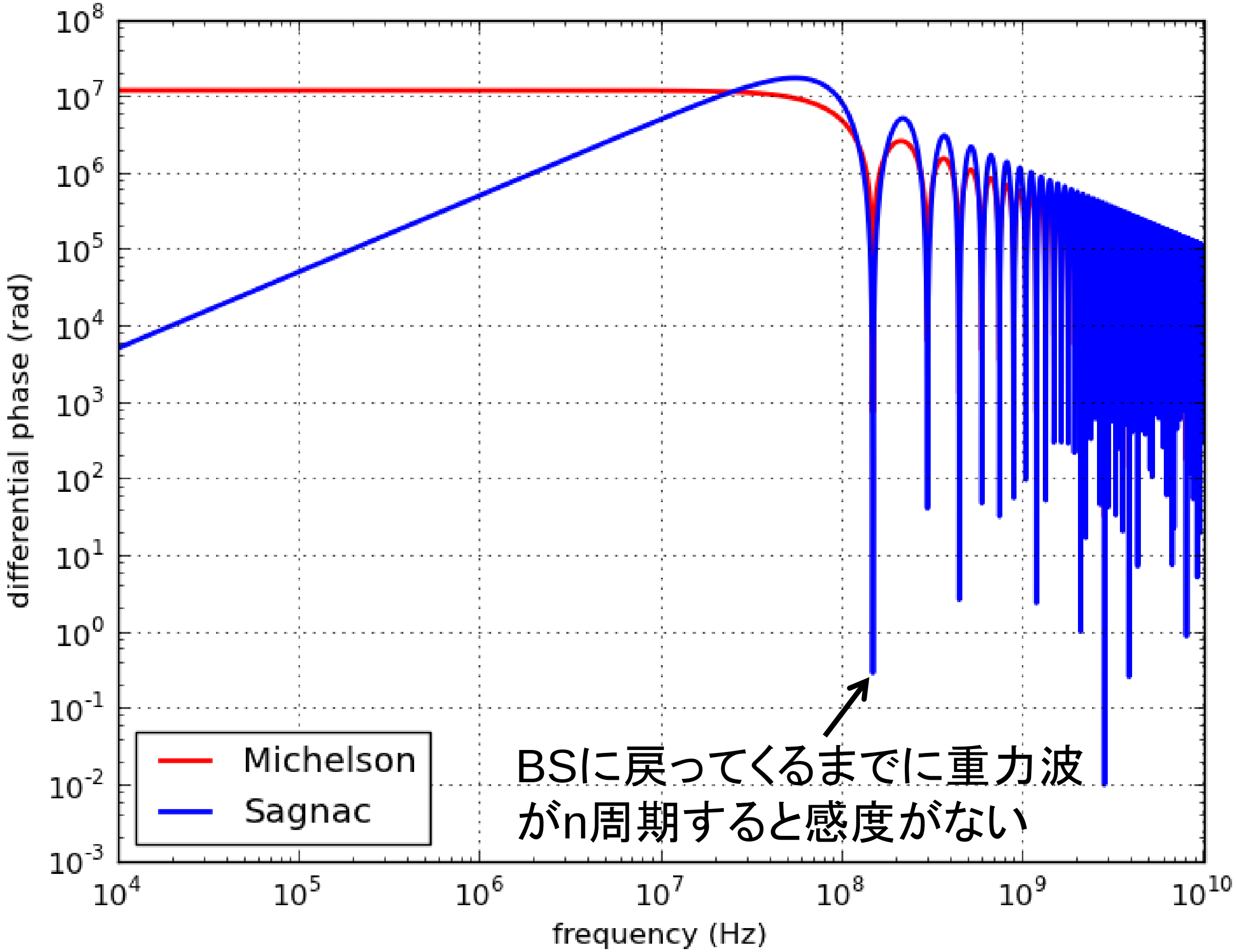


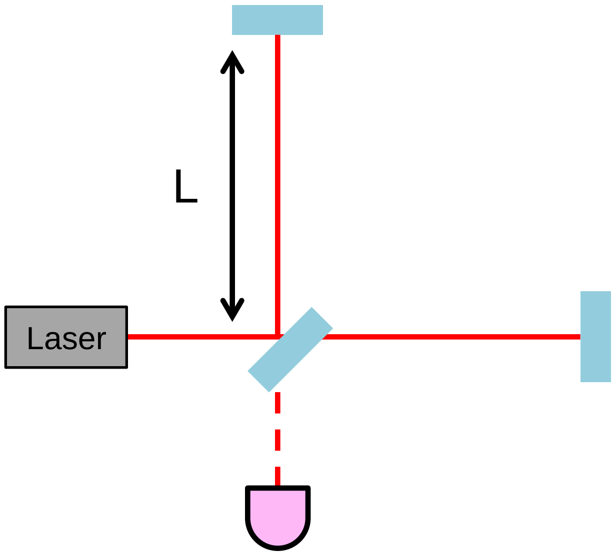
注: どうやって干渉をとるかは考えていない!!

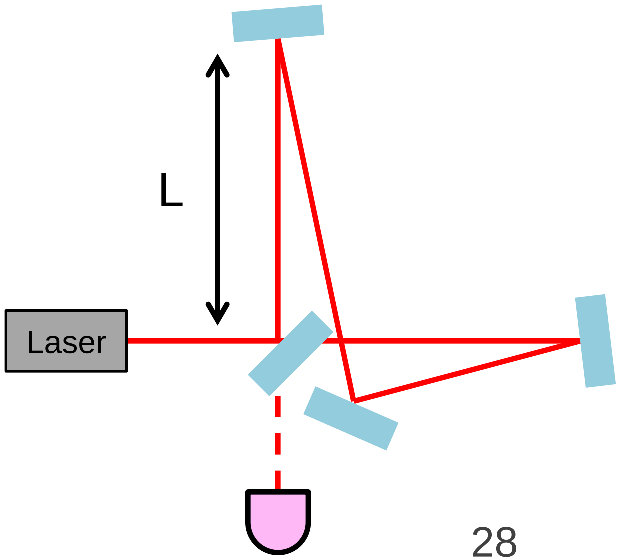
Michelson or Sagnac

- Sagnacの方が弱測定は容易

重力波h (/rtHz)が来た時に生じる位相差
CWレーザー, λ=1064nm, L=1m







計算が必要

- Nishizawa2012とはたぶん違う
  A. Nishizawa+: PRA 85, 062108 (2012)
- Nishizawa2012は重力波によるパルス幅の変化(周波数分布の変化)を見る、僕のはパルス間隔の変化を見る
- 結局強度変調がかかった重力波検出器と同じ？
- パルス間隔の変化は群速度で決まるが、干渉具合は位相速度で決まる
  → Sagnacの低周波化ができる？？
  → 真空中は分散がないのでだめ

でも重力波に対する応答は波長依存性があるからOK？？

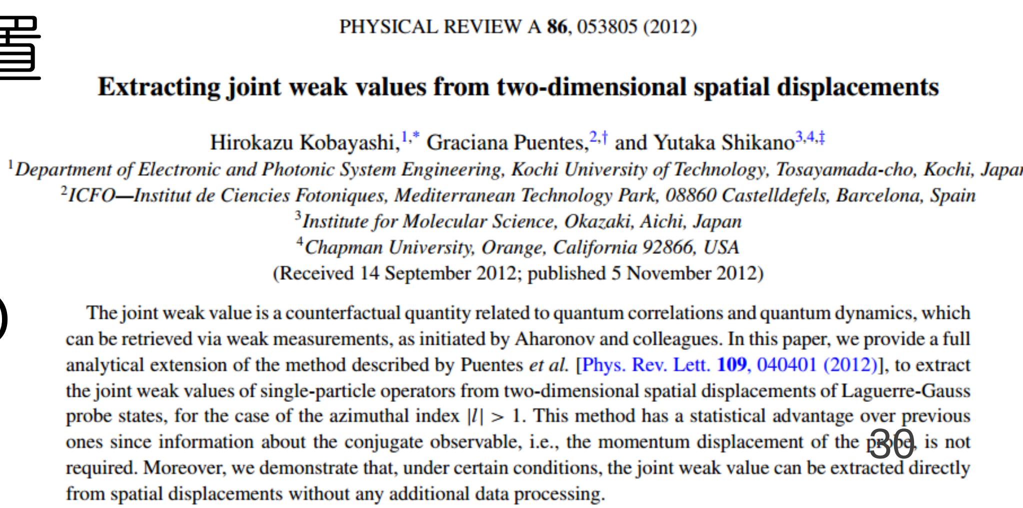
- ざっくり 1m で h=1e-11 /rtHz@300MHz の感度
  → だめだった

参考: パルス間隔の測定精度　3e-20 sec/rtHz
F. Quinlan+: Nature Photonics 7, 290 (2013)

結合弱値の話

Hardyのパラドクスの実証

- J. S. Lundeen+: PRL 102, 020404 (2009)
- K. Yokota+: New J. Phys. 11, 033011 (2009)
- K. Resch & A. Steinberg: PRL 92, 130402 (2004)
- G. Puentes+: PRL 109, 040401 (2012)
- H. Kobayashi+: PRA 86, 053805 (2012)
- 結合弱値 $\langle AB \rangle_w$ の取得に相互作用 $gAB \otimes P_x$ を用意するのは困難だが、$g(A \otimes P_x + B \otimes P_y)$ なら容易。その代わり位置と運動量の測定が必要。しかしLGを使うと2次元の位置ずれの測定だけでよい！



PHYSICAL REVIEW A **86**, 053805 (2012)

Extracting joint weak values from two-dimensional spatial displacements

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[3] *Institute for Molecular Science, Okazaki, Aichi, Japan*
[4] *Chapman University, Orange, California 92866, USA*

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The joint weak value is a counterfactual quantity related to quantum correlations and quantum dynamics, which can be retrieved via weak measurements, as initiated by Aharonov and colleagues. In this paper, we provide a full analytical extension of the method described by Puentes *et al.* [Phys. Rev. Lett. **109**, 040401 (2012)], to extract the joint weak values of single-particle operators from two-dimensional spatial displacements of Laguerre-Gauss probe states, for the case of the azimuthal index $|l| > 1$. This method has a statistical advantage over previous ones since information about the conjugate observable, i.e., the momentum displacement of the probe, is not required. Moreover, we demonstrate that, under certain conditions, the joint weak value can be extracted directly from spatial displacements without any additional data processing.

Hardyのパラドクス

- L. Hardy: PRL 68, 2981 (1992)
- 対消滅でも独立に干渉でもない場合がある

VOLUME 68, NUMBER 20 PHYSICAL REVIEW LETTERS 18 MAY 1992

Quantum Mechanics, Local Realistic Theories, and Lorentz-Invariant Realistic Theories

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(Received 22 January 1992)

First, we demonstrate Bell's theorem, without using inequalities, for an experiment with two particles. Then we show that, if we assume realism and we assume that the "elements of reality" corresponding to Lorentz-invariant observables are themselves Lorentz invariant, we can derive a contradiction with quantum mechanics.

- Y. Aharonov+: Phys. Lett. A 301, 130 (2002)
  e^+ も e^- もPを通らない確率は-1
- 大阪大学の横田らが光子で実証

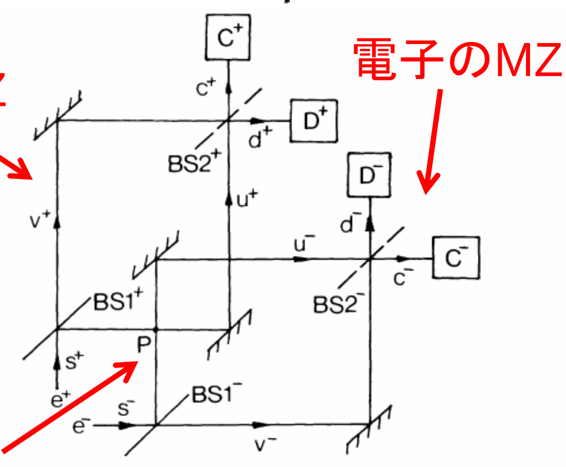
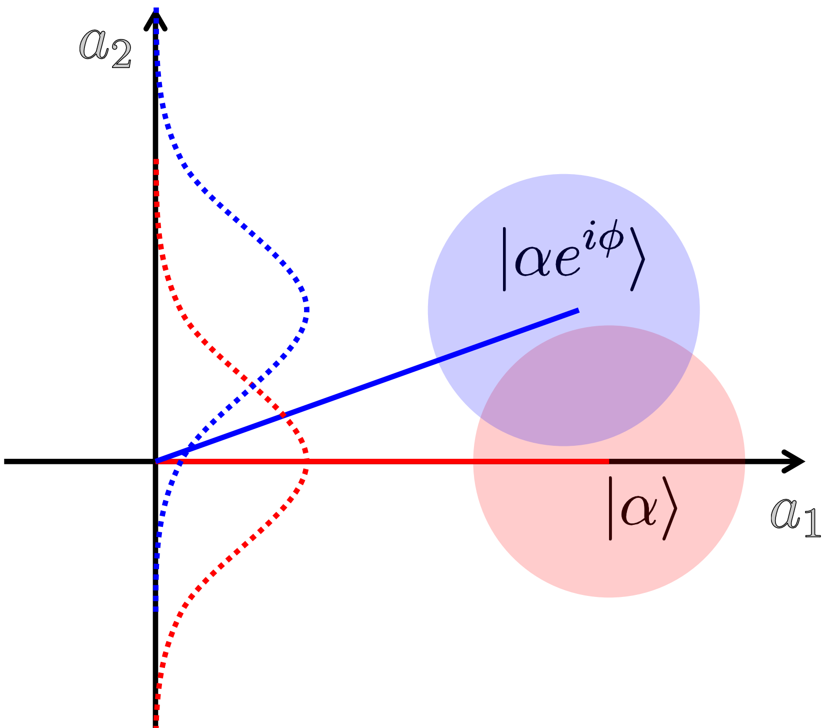
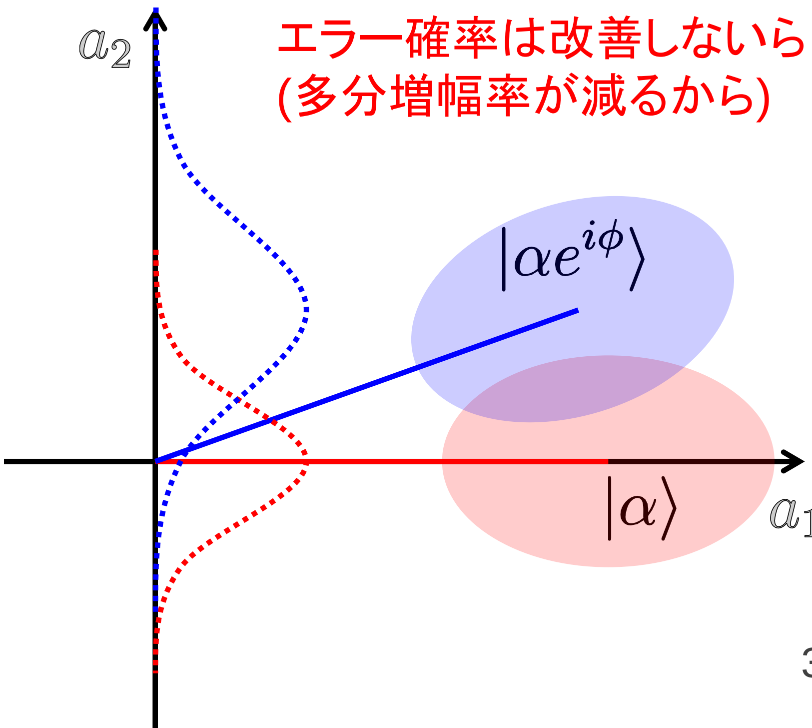


FIG. 1. Two Mach-Zehnder-type interferometers, one for positrons and one for electrons, arranged such that if a positron takes path u^+ and an electron takes path u^- then they will meet at point *P* and annihilate one another.

信号識別の話

- 位相シフトしたかどうかホモダイン測定
- その時のエラー確率を減らしたい
  → 弱値増幅を利用
  A. Feizpour+: PRL 107, 133603 (2011)
- さらにスクイーズド光を使えば成功確率も改善





エラー確率は改善しないらしい
(多分増幅率が減るから)

単一光子レベルでのKerr効果測定

- N. Matsuda+: Nature Photonics 3, 95 (2009)

nature photonics

LETTERS

PUBLISHED ONLINE: 25 JANUARY 2009 | DOI: 10.1038/NPHOTON.2008.292

Observation of optical-fibre Kerr nonlinearity at the single-photon level

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Optical fibres have proved to be an important medium for manipulating and generating light in applications including soliton transmission[1], light amplification[2], all-optical switching[3] and supercontinuum generation[4]. In the quantum regime, fibres may prove useful for ultralow-power all-optical signal processing[5] and quantum information processing[6]. Here, we demonstrate the first experimental observation of optical nonlinearity at the single-photon level in an optical fibre. Taking advantage of the large nonlinearity and managed dispersion of photonic crystal fibres[7,8], we report very small (1×10^{-7} to $\sim 1 \times 10^{-8}$ rad) conditional phase shifts induced by weak coherent pulses that contain one or less than one photon per pulse on average. We discuss the feasibility of quantum information processing using optical fibres, taking into account the observed Kerr nonlinearity, accompanied by ultrafast response time and low induced loss.

The photon, the quantum unit of light, has much less interaction with its environment than other quanta (for example, electron spin, superconducting current) and for this reason it is an outstanding carrier of information in quantum communication and has earned the name the 'flying qubit'. This lack of interaction also means that photons may not be suitable for computations that require strong unitary interaction between qubits. The fabrication of optical nonlinear media providing sufficiently strong interaction between photons has therefore been under intense study. Cavity quantum electrodynamics-based devices have performed nonlinear Kerr phase shifts of a few tens of degrees at the single-photon level[9,10]. Another approach to quantum-optical information processing (QOIP) is to apply the weak nonlinearity that is inherent in currently existing media. Recent proposals[11,12] have indicated that such

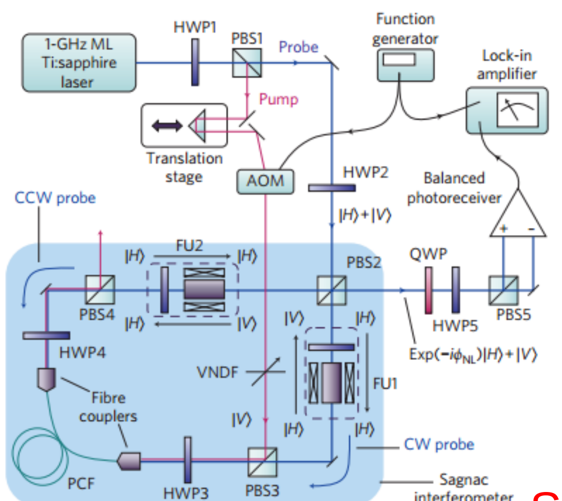

Figure 1 | Experimental set-up. PBS, polarizing beam splitter; HWP, half-wave plate; QWP, quarter-wave plate; AOM, acousto-optic modulator; VNDF, variable neutral density filter; PCF, photonic crystal fibre; FU, Faraday unit, each consisting of a 45° Faraday rotator and a half-wave plate; $|H\rangle$ and $|V\rangle$, horizontal and vertical polarizations, respectively; CW and CCW, clockwise and counter-clockwise. The thick red and blue lines represent optical connections, and the thin black arrowed curves are electronic connections.

量子論理ゲート

光子が来たか来てないかの判定XPM(cross phase modulation)に使えるらしい

このKerr効果を増幅させたいというのが元々の動機

Sagnac干渉計

弱測定の数理の話

- 弱測定の本質は相互作用が弱いことではない
- J. Lee & I. Tsutsui: arXiv:1305.2721

Uncertainty of Weak Measurement and Merit of Amplification

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(Dated: May 14, 2013)

Aharonov's weak value, which is a physical quantity obtainable by weak measurement, admits amplification and hence is deemed to be useful for precision measurement. We examine the significance of the amplification based on the uncertainty of measurement, and show that the trade-offs among the three (systematic, statistical and nonlinear) components of the uncertainty inherent in the weak measurement will set an upper limit on the usable amplification. Apart from the Gaussian state models employed for demonstration, our argument is completely general; it is free from approximation and valid for arbitrary observables A and couplings g.

弱測定の数理の話

- 通常の測定と弱測定を結ぶ式

$$\sum_{|\phi_f\rangle\in\mathcal{B}} r(\phi_i \to \phi_f)\cdot \Delta^w_X(g) = \Delta^c_X(g), \qquad (6)$$

成功確率　弱測定での測定値　通常の測定での測定値

where

$$r(\phi_i \to \phi_f) := \frac{\left\|(|\phi_f\rangle\langle\phi_f| \otimes \mathrm{Id})\, e^{-igA\otimes P}\phi_i \otimes \psi_i\right\|^2}{\left\|e^{-igA\otimes P}\phi_i \otimes \psi_i\right\|^2} \qquad (7)$$

- 系統誤差(分解能)は改善するが、統計誤差はあまり改善しない
- また、非線形の効果が出てくる(back-action とも言われる)

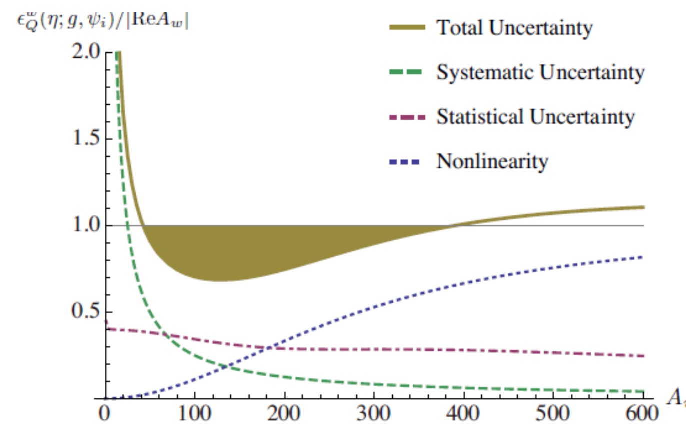


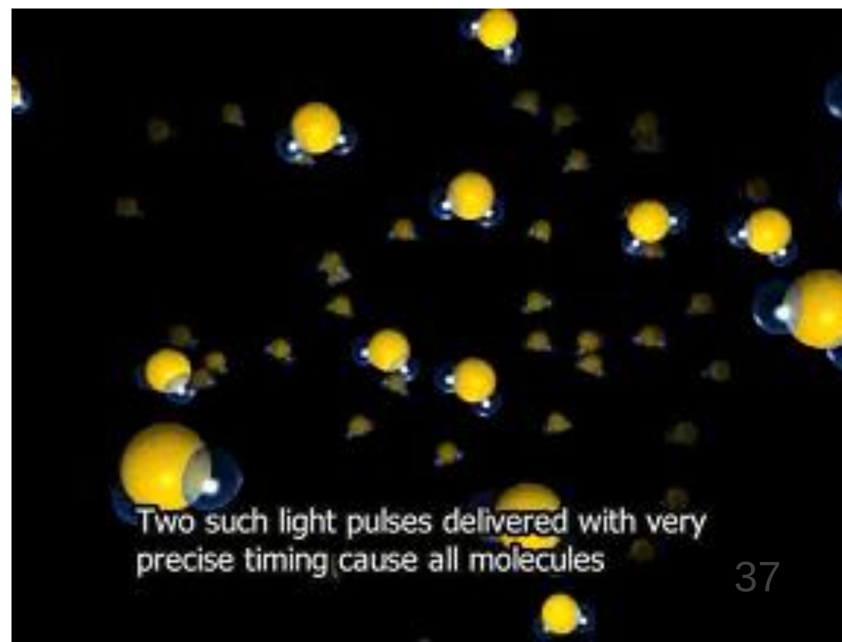
FIG. 1. Ratio of uncertainty $\epsilon^w_Q(\eta; g, d)$ to the real part of the weak value of the spin $S_z = \sigma_z/2$. By amplifying the weak value out of its numerical range $[-1/2, 1/2]$ to $(S_z)_w \approx 100$, the significance condition (15) is attained with confidence $\eta = 0.95$. (Parameters: $\delta_Q = 1/2$, $N_0 = 10^7$, $g = 1/50$ and $d = 4$.)

一般確率論の話

- generalized probability theory
- 量子力学と古典確率論の統合
- ティッシュ箱の長さの測定はStern-Gerlachの実験より難しいという話

大島グループ見学

- [大島グループHP](#)　[YouTube](#)
- 分子の運動状態を調べるためにパルスレーザーを開発している
- レーザー分光のために広く周波数掃引が可能で、かつ安定なCWレーザーを開発している
- パルス光は安定度がよくない



まとめ

- 思ったよりハードで、刺激的だった
- 弱測定、無相互作用測定、スクイージングって全部似てる(一方を犠牲にする感じが)
- 重力波検出器への関心は高い

- 散射雑音と戦う実験では弱測定は利点がなさそう
- 長時間測定したところで、分解能的に足りていない実験への応用はないか？
  (でもわざとランダムに動かすことで分解能を上げることもできますよね……)
- 弱測定でないと説明がつかない実験は今のところないらしい？