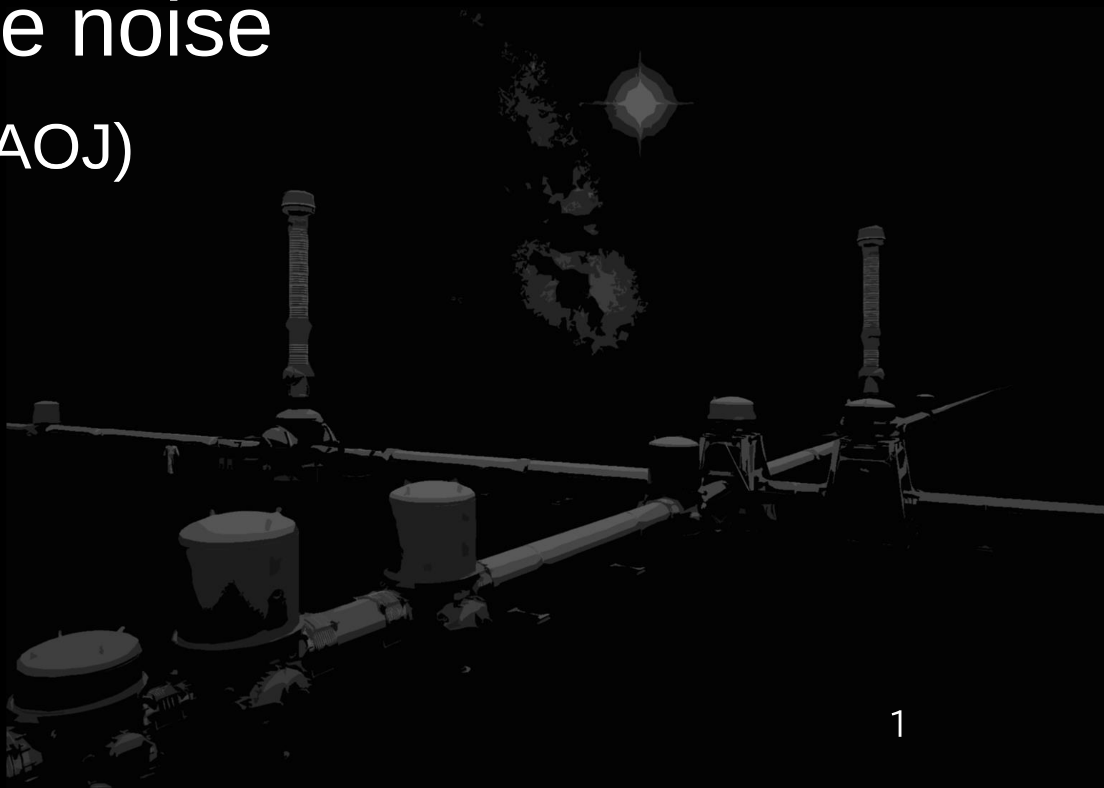
Speedmeter: advanced technique to reduce quantum radiation pressure noise

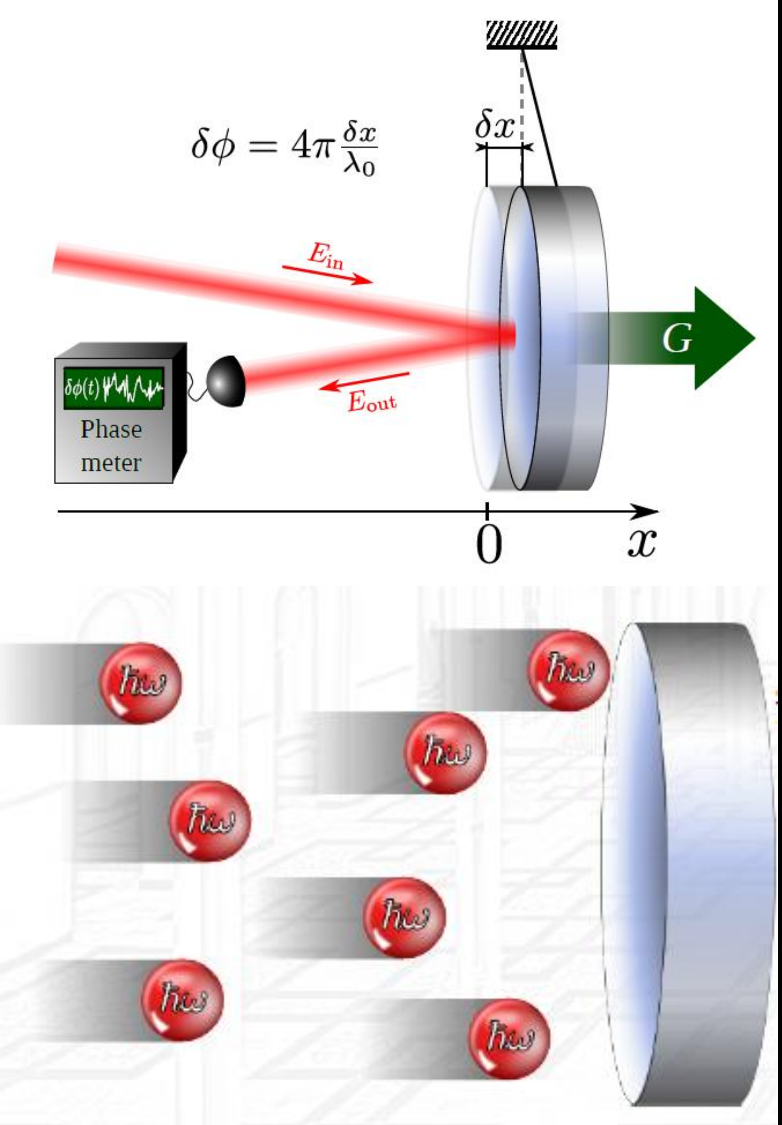
Yohei Nishino (NAOJ)



Introduction

Quantum Noise

S. Danilishin, GRASS 2018

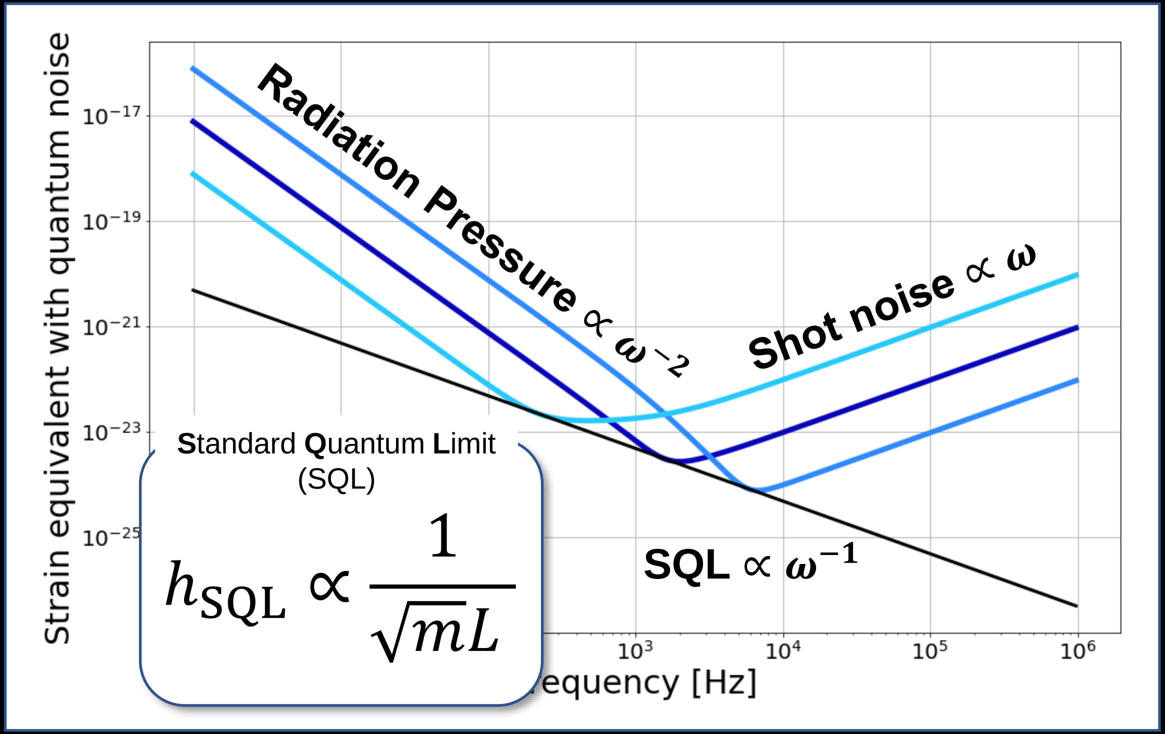


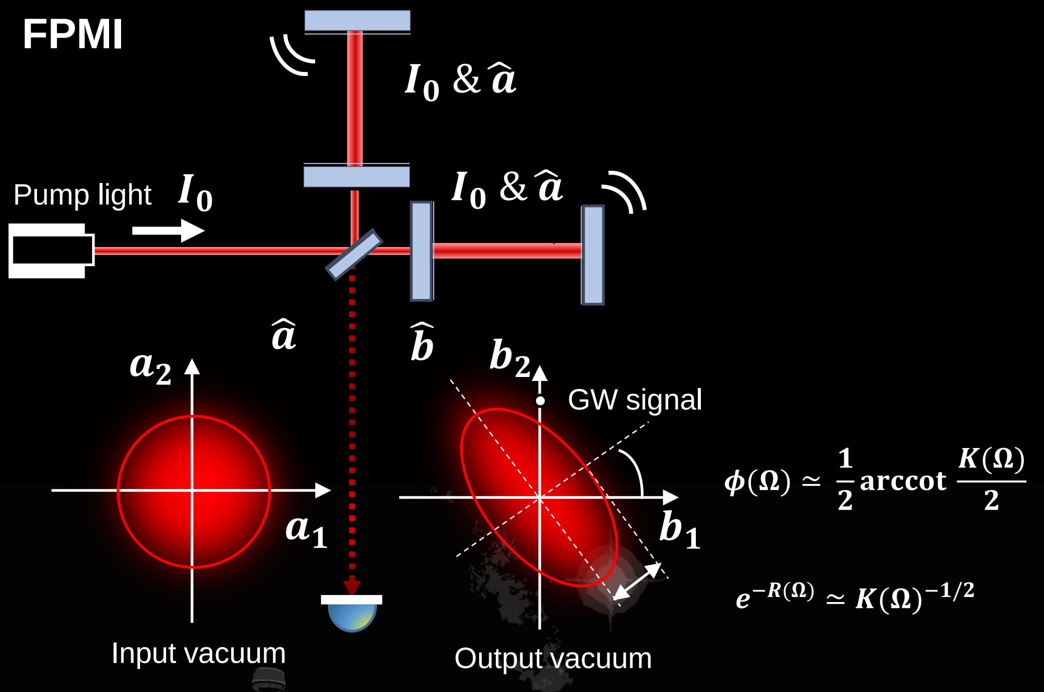
- ✓ GW detector is a precise displacement detector
- ✓ Increasing the laser power (P) will reduce shot noise and improve S/N ratio proportional to $\sqrt{P}$
- ✓ Are we able to perform infinite accurate position measurement with infinite laser power? ⇒ No, we cannot avoid back action of measurement.
- ✓ According to uncertainty principal, you cannot make a infinite precise measurement for both position and momentum.

$$\epsilon(x)\eta(p) \geq \frac{\hbar}{2} \text{ (Heisenberg's uncertainty principal)}$$

- ✓ The more accurate the position information is ($\epsilon(\mathrm{x}) \to 0$), the more disturbance you put on the mirror is ($\eta(p) \to \infty$)
- ✓ This is called Measurement-Disturbance-Relation (MDR)
- ✓ There exists a trade off between precision of position measurement and back action, and consequently there is a wall that we cannot overcome (naturally), called 'SQL'.

Quantum Noise





Shot noise QRPN GW signals

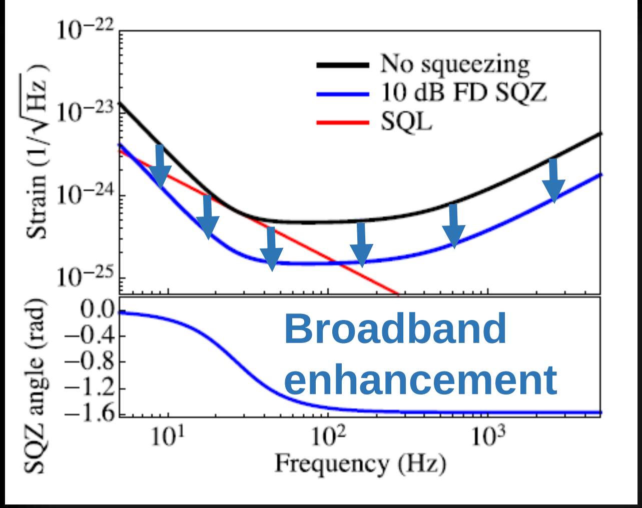
$$b_2 = \underbrace{a_2 e^{2j\beta}}_{\text{Shot noise}} - \underbrace{K(\Omega) a_1 e^{2j\beta}}_{\text{QRPN}} + \underbrace{\sqrt{2K(\Omega)}\frac{h}{h_{SQL}} e^{j\beta}}_{\text{GW signals}}$$

K: Optomechanical coupling factor

- ✓ Standard Quantum Limit is derived from MDR
- ✓ It is defined for a free test mass ($-\omega^2 x(\omega) = F$)
- ✓ It is defined only by the test mass and arm length
- ✓ Shot noise is dominant at high frequencies, while radiation pressure noise is dominant at low frequencies
- ✓ Source of both noise is a vacuum fluctuation injected from the AS port.
- ✓ Interference between carrier and amplitude fluctuation of vacuum shakes test masses differentially.

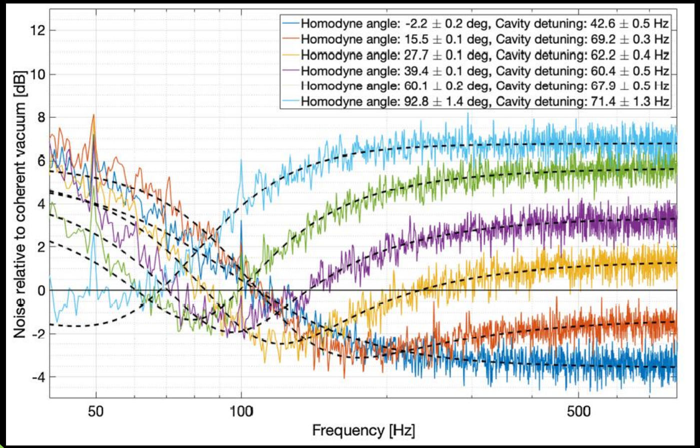
Quantum **N**on-**D**emolition measurement (QND)

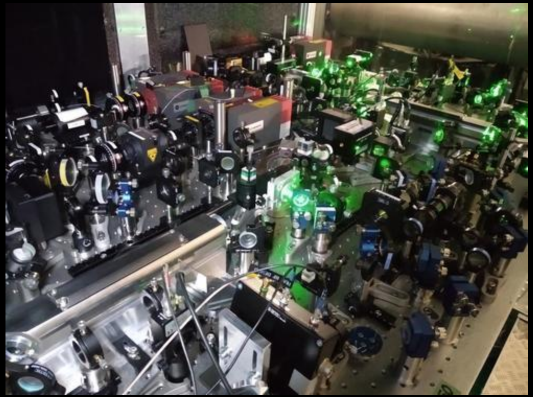
A lot of techniques have been investigated to beat SQL (ex. Frequency dependent squeezing)



S. Danilishin *et al.* 2019

TAMA 300 filter cavity experiments

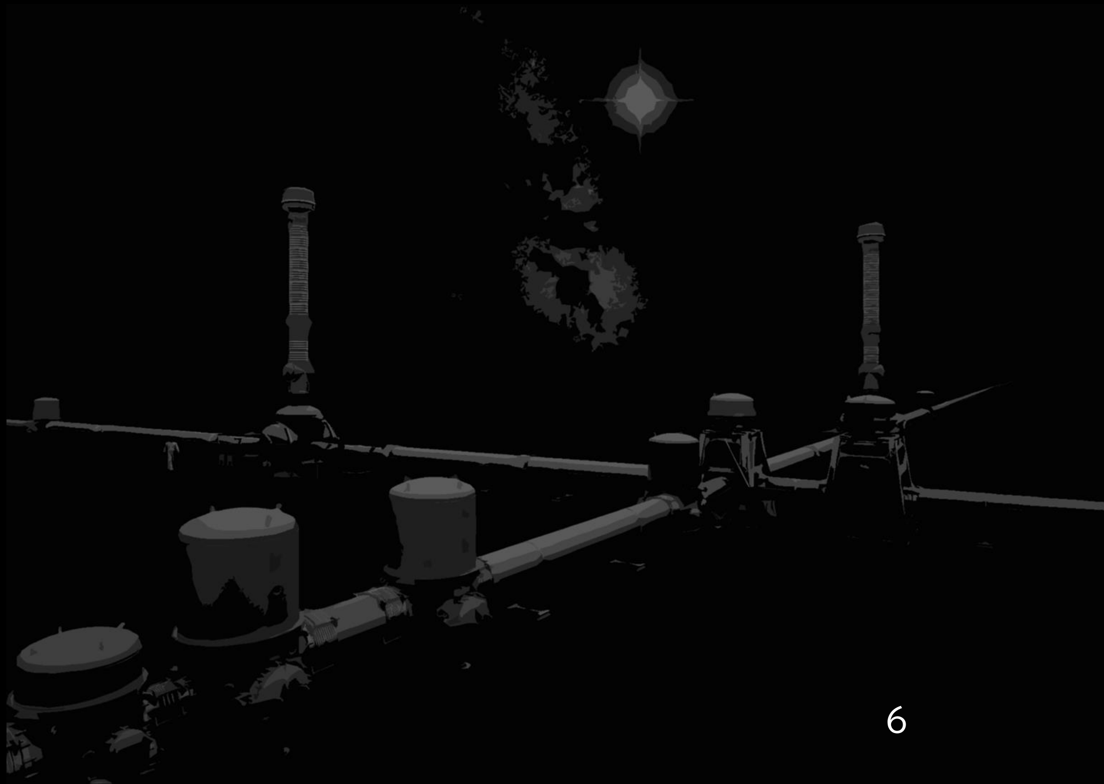




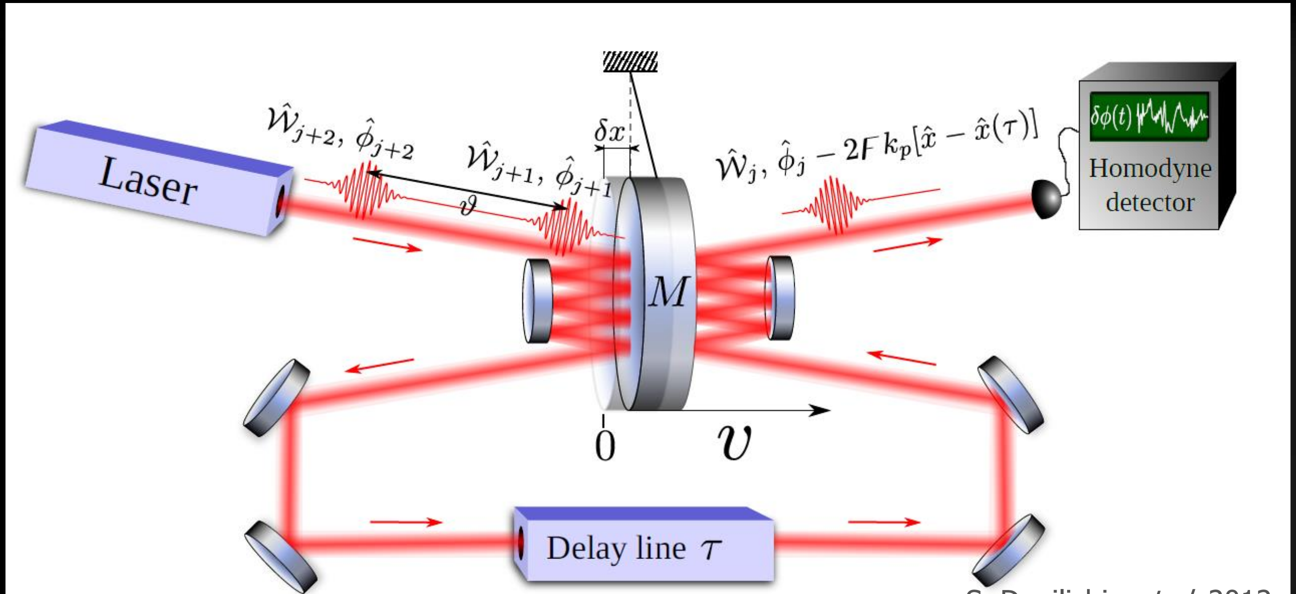
Y. Zhao *et al.* 2020

- ✓ Frequency dependent squeezing improves the sensitivity broadbandly
- ✓ It will be performed in 2G detectors
- ✓ One needs high finesse cavity ⇒ we are struggling with losses.
- ✓ Mode matching among squeezer, filter cavity and the IF is also critical
- ✓ Needs ~100-1000m scale cavity; needs a wide space

Speedmeter



Another observable: Momentum (speed)



S. Danilishin *et al.* 2012

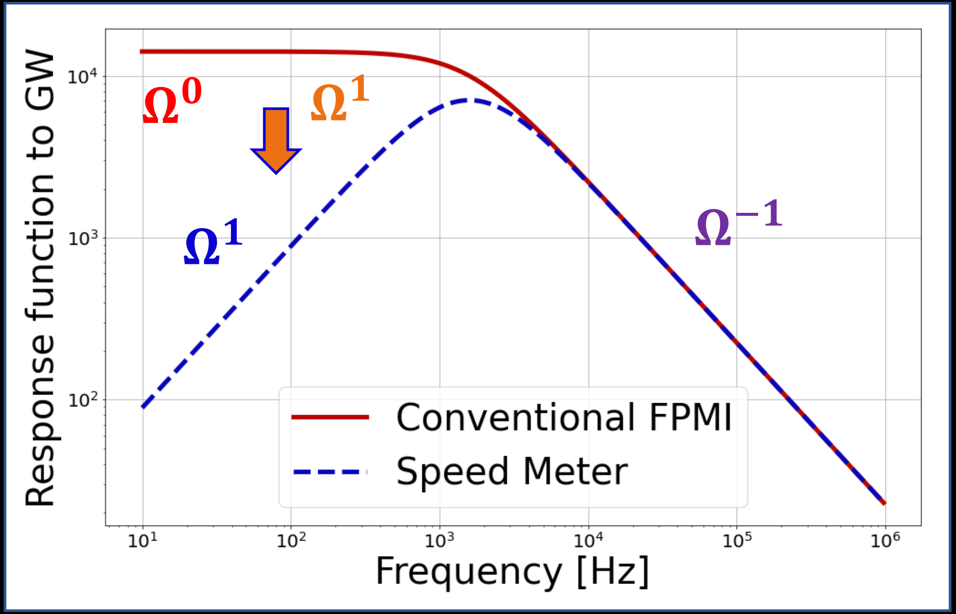
John von Neumann

$$[\hat{p}(\mathrm{t}), \hat{p}(t')] = 0$$

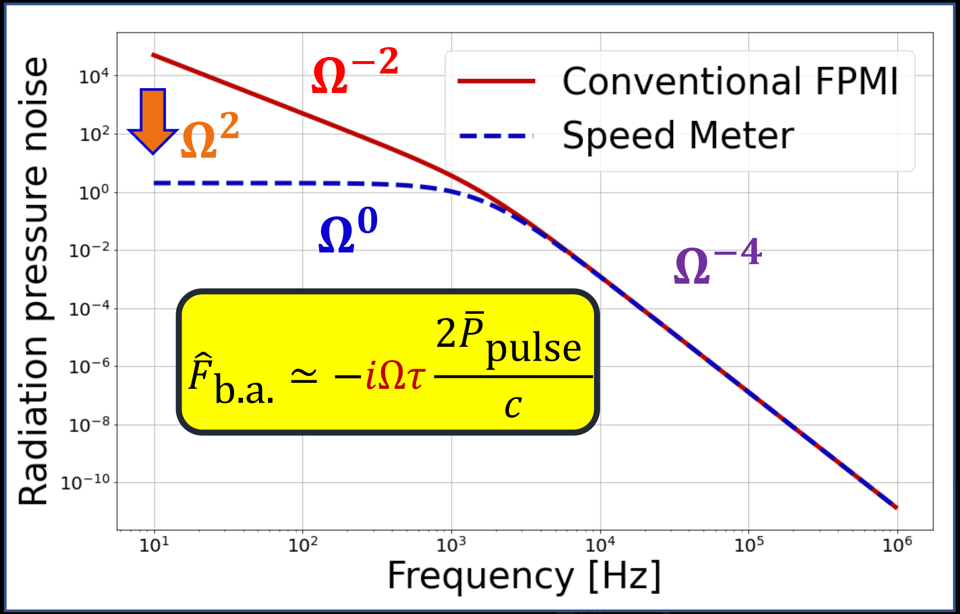
- ✓ Another way to beat SQL is to use other observables which do not encounter uncertainty principal, **momentum** for example.
- ✓ Momentum (↔ Speed) measurement at a time t will not affect the momentum of the mirror at t'
- ✓ One needs to satisfy two key features to realize speed meter
  1. Probe must interact with a test mass twice retaining its coherence
  2. Those two interaction Hamiltonians must have opposite sign
- ✓ The illustration above well describes these two features

How does it reduce QRP noise?

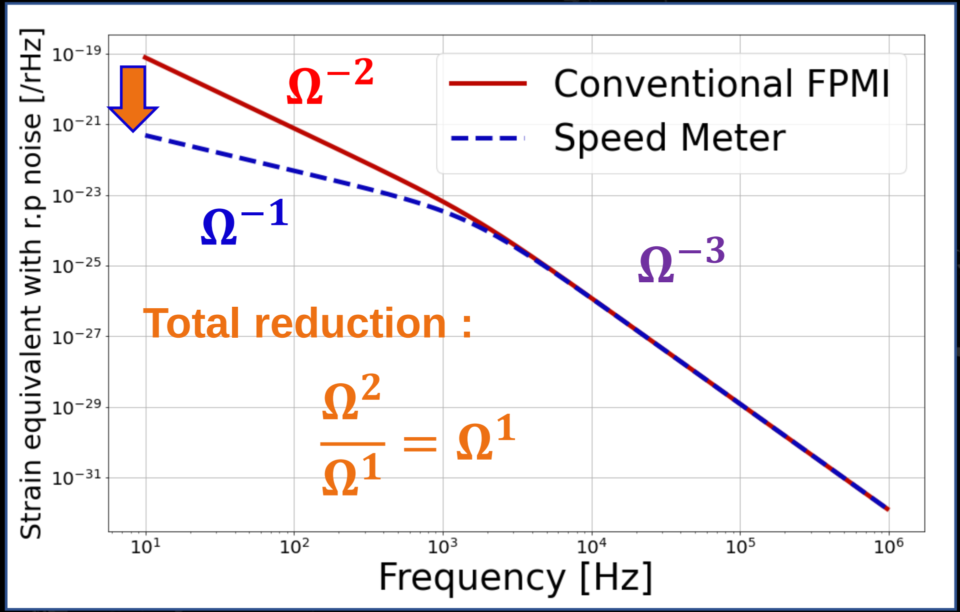
(A)



(B)



(B)÷(A)

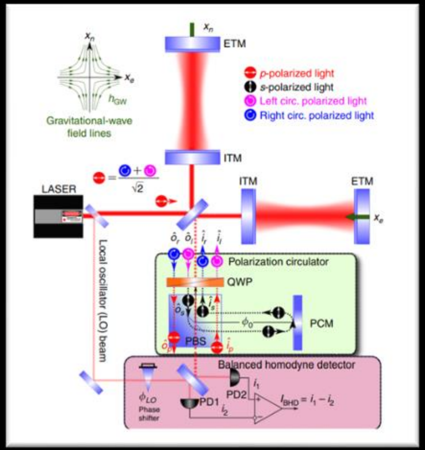


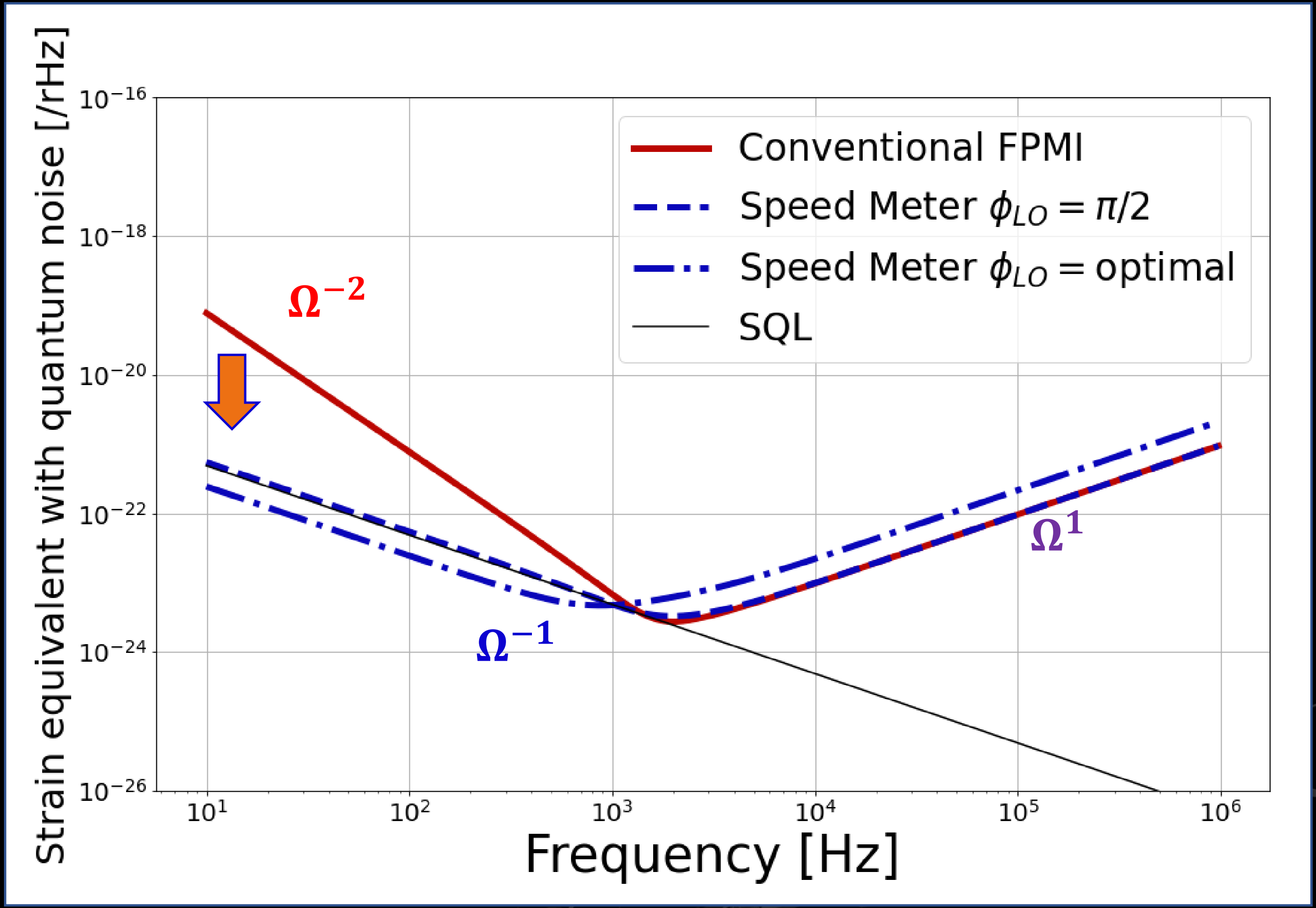
A) Response function to GW will be reduced by $1/\Omega$ $(\Omega < \gamma)$.

B) The amplitude of radiation pressure noise will be reduced by $1/\Omega^2$

➡ (B)/(A) Signal-Noise ratio will be improved by $\propto \Omega$

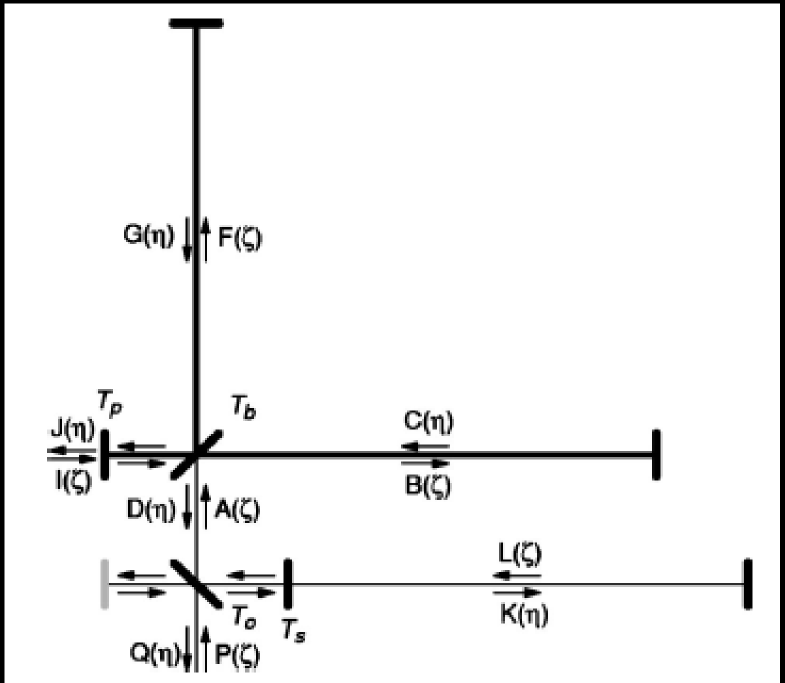
Benefits of Balanced Homodyne Detection



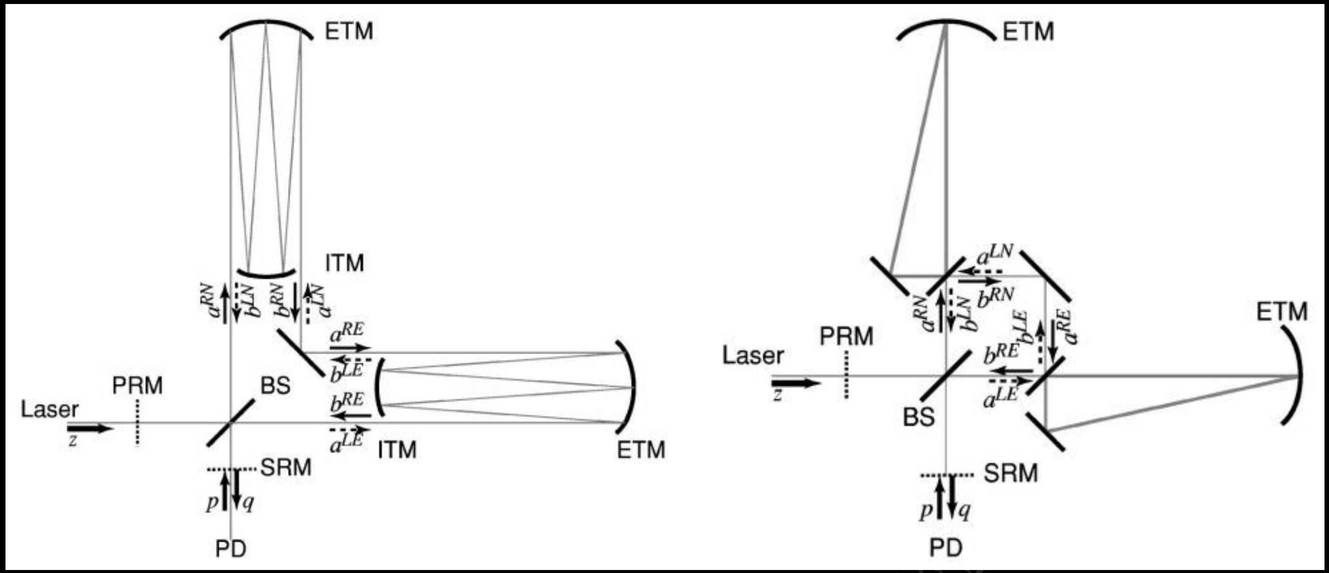


- ✓ Speedmeter itself will not overcome the SQL
- ✓ But with BHD it goes below the SQL
- ✓ The biggest advantage is it shows broadband noise reduction with a fixed homodyne angle ⇒ no need for additional cavities (cf. filter cavity, variational readout…)
- ✓ All QND process happens inside the interferometer.

Practical Implementation of speedmeter (1)



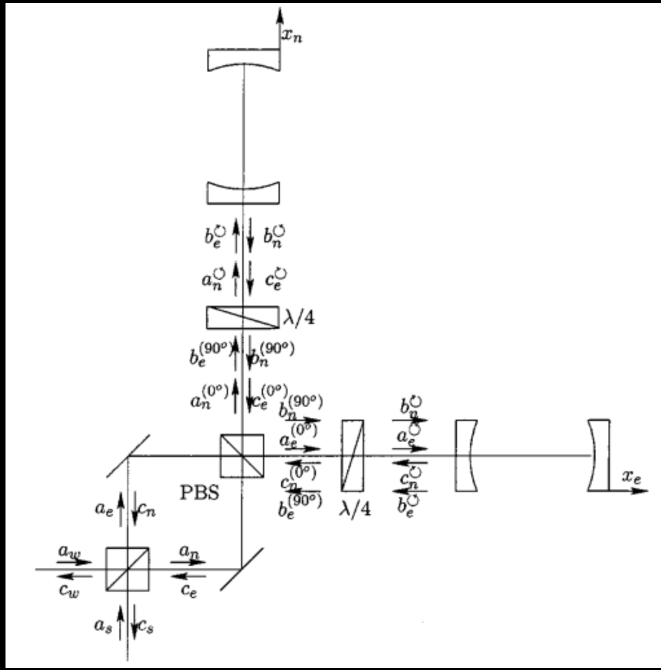
V. Braginsly *et al. Phys. Rev. D* **61,** 044022 (2000)
Purdue & Chen *Phys. Rev. D* **66**, 122004 (2002)



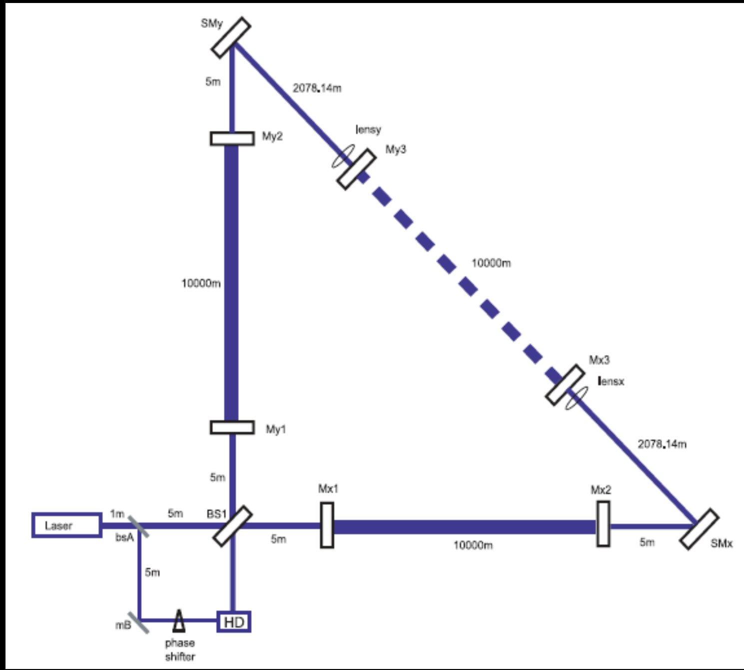
Y. Chen *Phys. Rev. D* **67**, 122004 (2003)

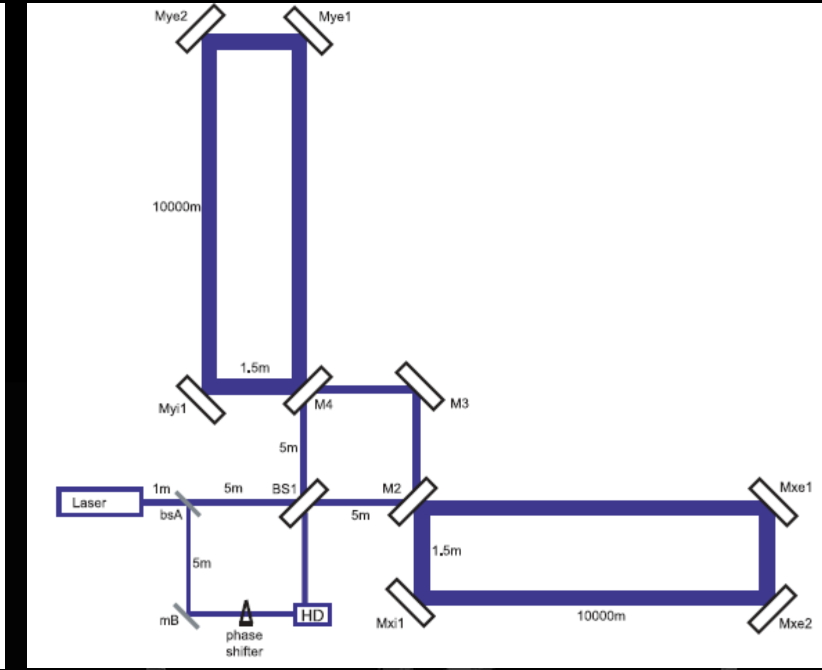
- ✓ First speedmeter concept with Michelson Interferometer is proposed by Braginsly *et al*. in 2000.
- ✓ Purdue and Chen further developed a sloshing type design in 2002
- ✓ Chen proposed Sagnac type designs in 2003

Practical Implementation of speedmeter (2)



S. Danilishin *Phys. Rev. D* **69**, 102003 (2004)

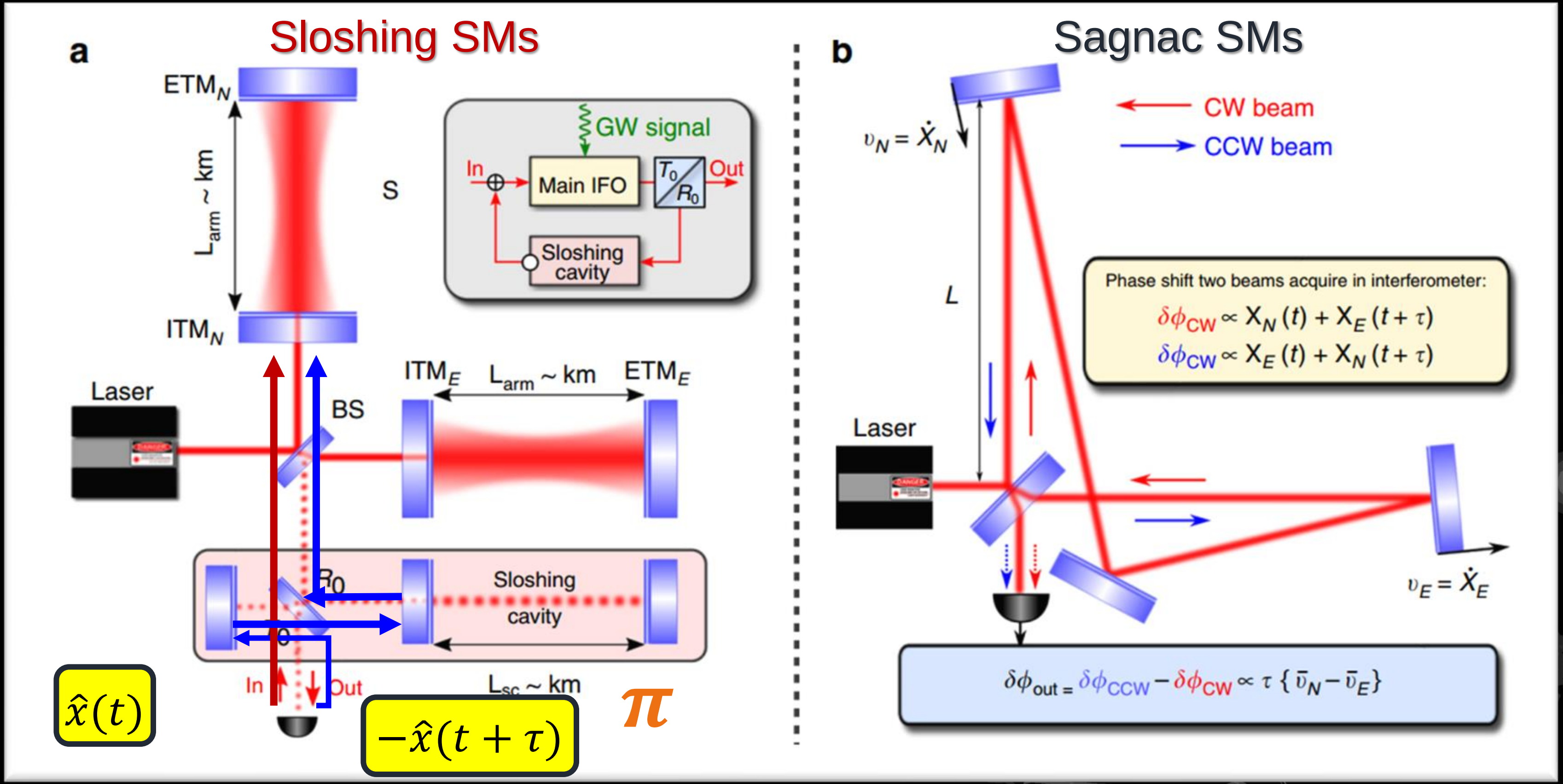




S. Huttner CQG 34, 024001 (2017)

- ✓ S. Danilishin proposed polarization-based speedmeter in 2004
- ✓ S. Huttner proposed a possible sloshing and Sagnac type design for Einstein telescope in 2017
- ✓ There are other many types of design, including “EPR speedmeter”

Design and Mechanism



S. Danilishin *et al.* 2017

Part of signal is reflected to the IF with opposite sign.

× We need additional km-scale cavity

× Hard to control the sloshing cavity

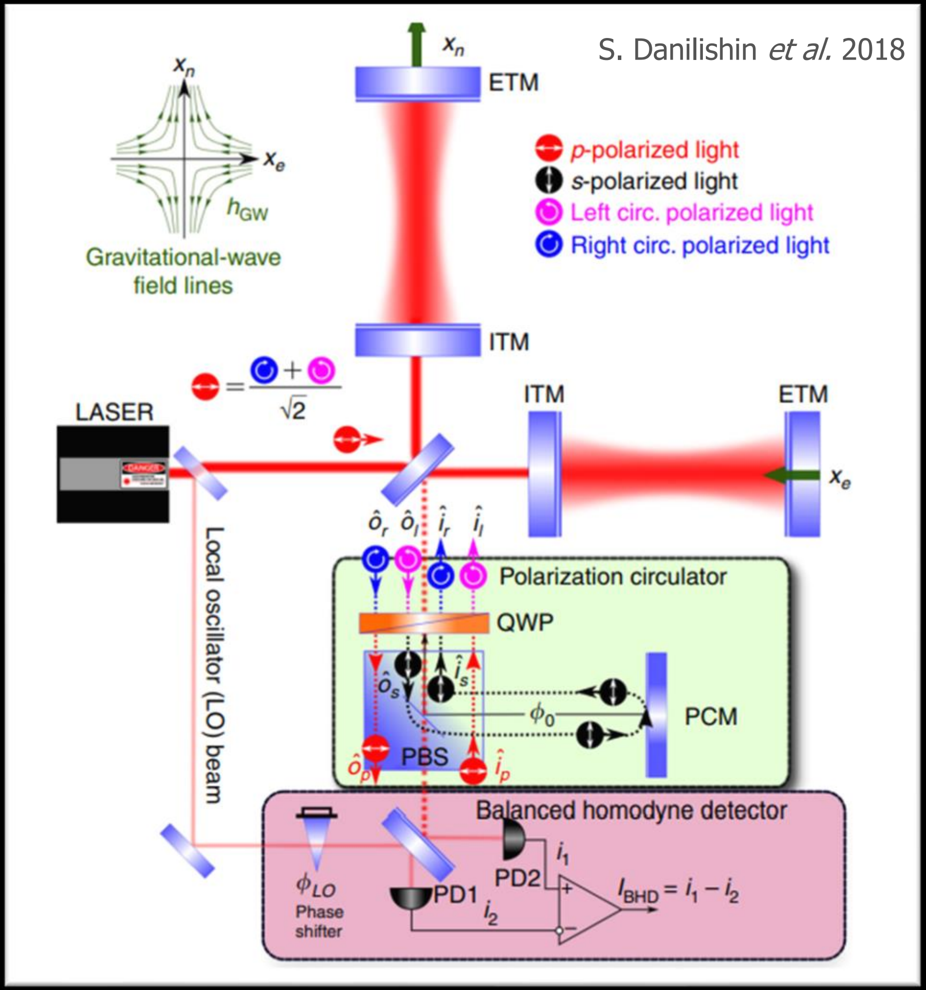
Carrier circulate the ring cavity in clockwise and counter-clockwise and the output interferes.

× Scattering light produces a lot of noise (in Glasgow's experiments)

Polarization Circulation SpeedMeter

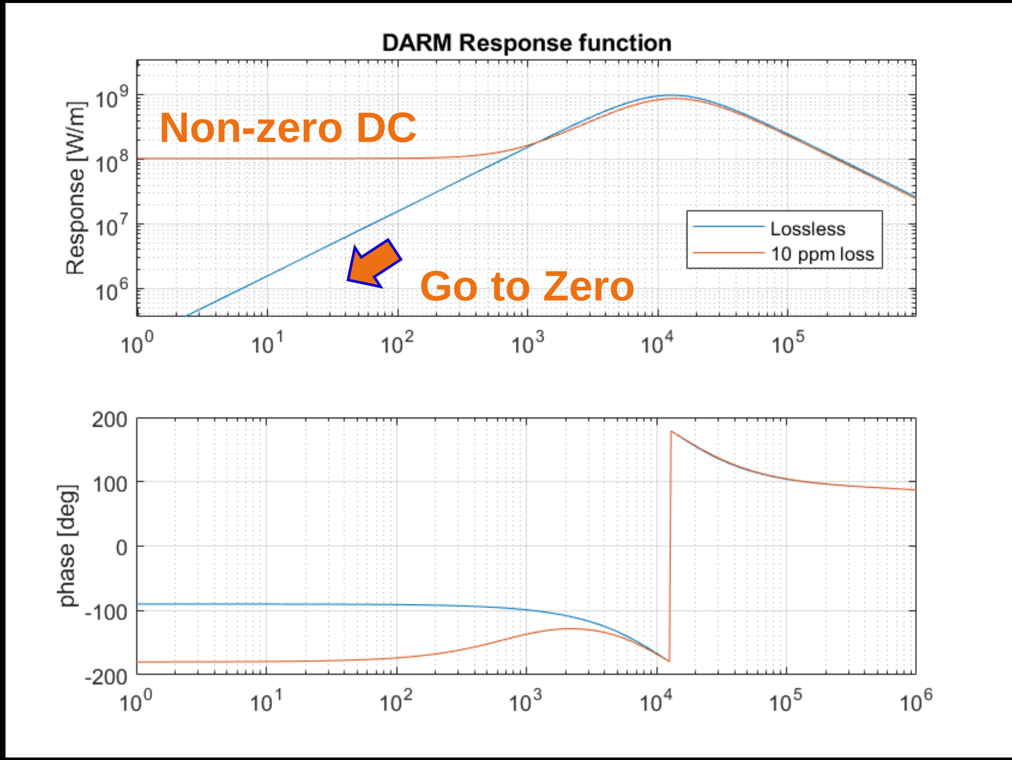
Polarization Circulation Speed Meter (PCSM)

A new polarization-based scheme is proposed by S. Danilishin *et al.* in 2018



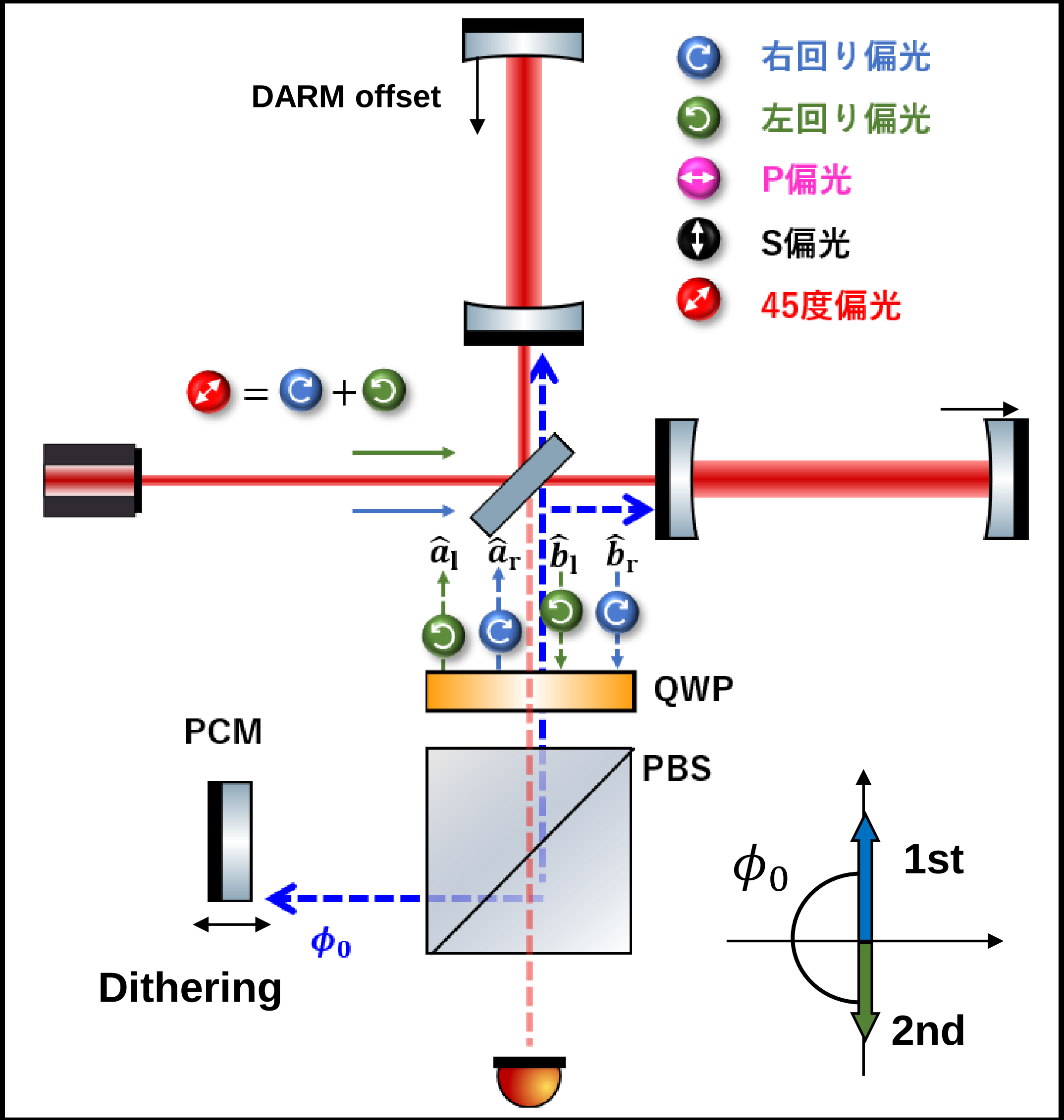
- How it works:
  - A quarter waveplate (QWP) in the AS port will change the polarization from linear to circular (from *s* to *r*, *p* to *l* for example.)
  - Only *p*-pol passes the PBS and reflected *s*-pol will go back to the interferometer
  - We control the length of **P**olarization **C**irculation **C**avity (**PCC**) formed by PCM, PBS, QWP and ITM so that the round-trip phase shift becomes $\phi_0 = \pi$
  - Vacuum field, which enters as *p*-pol, will hit the mirrors twice with opposite signs and comes out as *p*-pol.
- Benefits:
  - *Latest incarnation of speedmeter concept* (cit. S. Hild *et al*. ET symposium 2017)
  - No need to touch the central interferometer
  - No need for additional cavities ⇒ minimal hardware changes
  - What we need is reconstruction of the AS port ⇒ can switch to normal FPMI in situ.
- Problems: How to control it?
  - Especially how to control the phase shift π in PCC?
  - How to obtain DC signals?

How to obtain DARM signal?

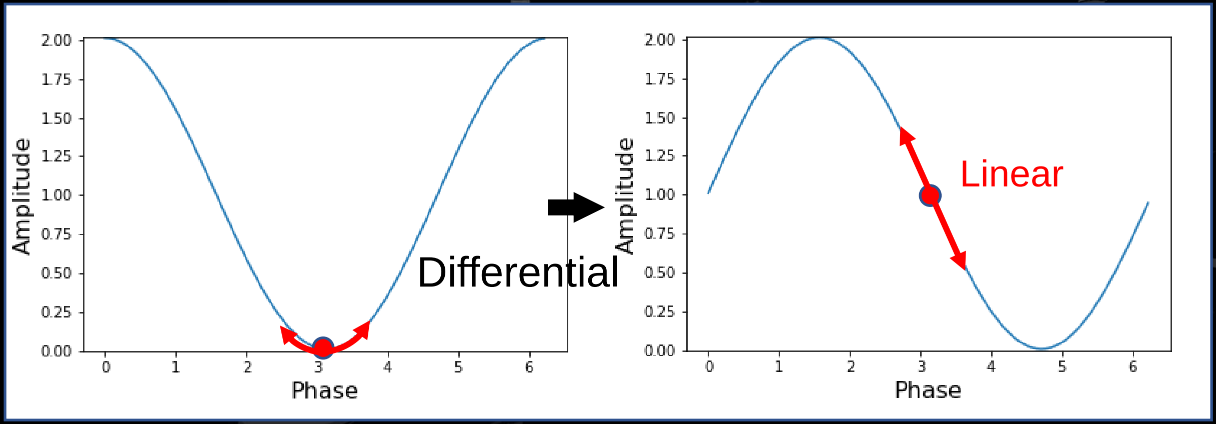


- ✓ DC signal of DARM will be zero in “ideal” Speedmeters
- ✓ We need to add a loss to steal DC signals.
- ✓ Imperfection will give us DC information
  - ✓ Arm cavity loss
  - ✓ Loss of QWP, PBS, PCM
  - ✓ PCM misalignment
  - ✓ PCC mode-mismatching
- ✓ We can exploit losses by making optimal servo filters

How to control the **P**olarization **C**irculation **C**avity?

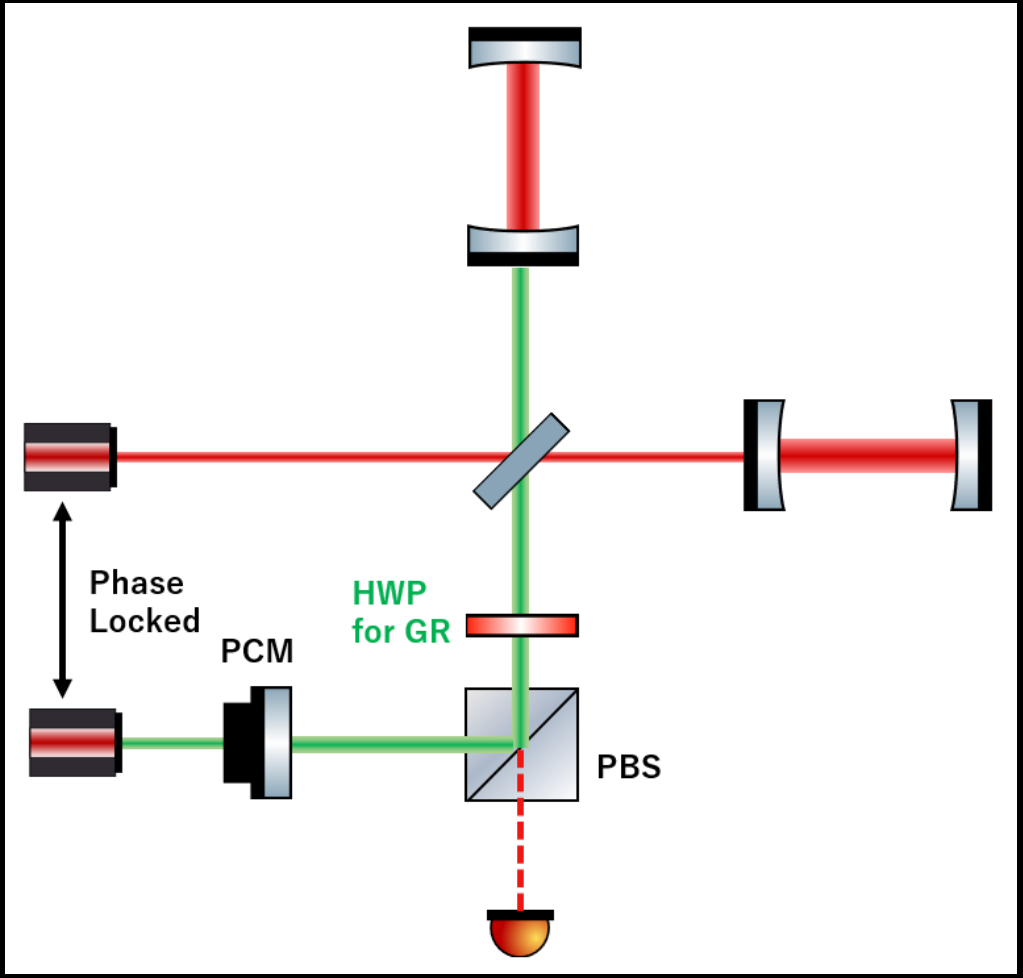


- ✓ The round-trip phase shift of PCC (ϕ_0) should be kept to π
- ✓ Control scheme:
  1. Putting DARM offset, and some amount of DC offset will be leaked to the AS port
  2. The optimal PCM position is where DARM offset becomes minimum
  3. We can get error signals by dithering PCM
- ✓ Problems:
  1. Dithering will introduce a lot of noise
  2. Though DARM offset is not necessary when we adopt BHD, we still need it in this scheme.



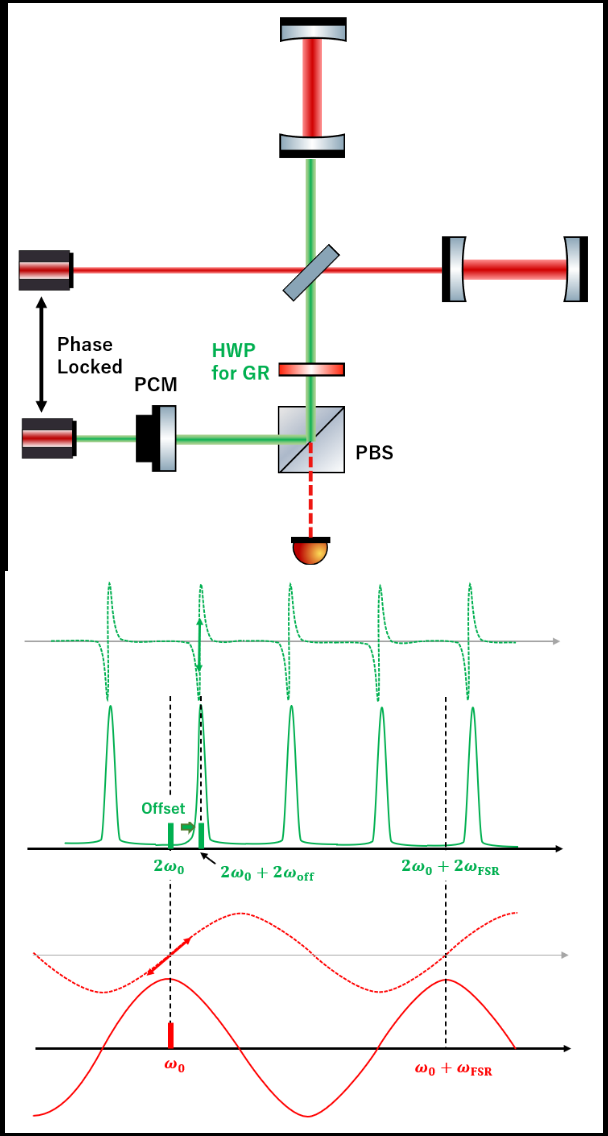
How to control the **P**olarization **C**irculation **C**avity?

We propose another scheme “dual waveplate scheme”



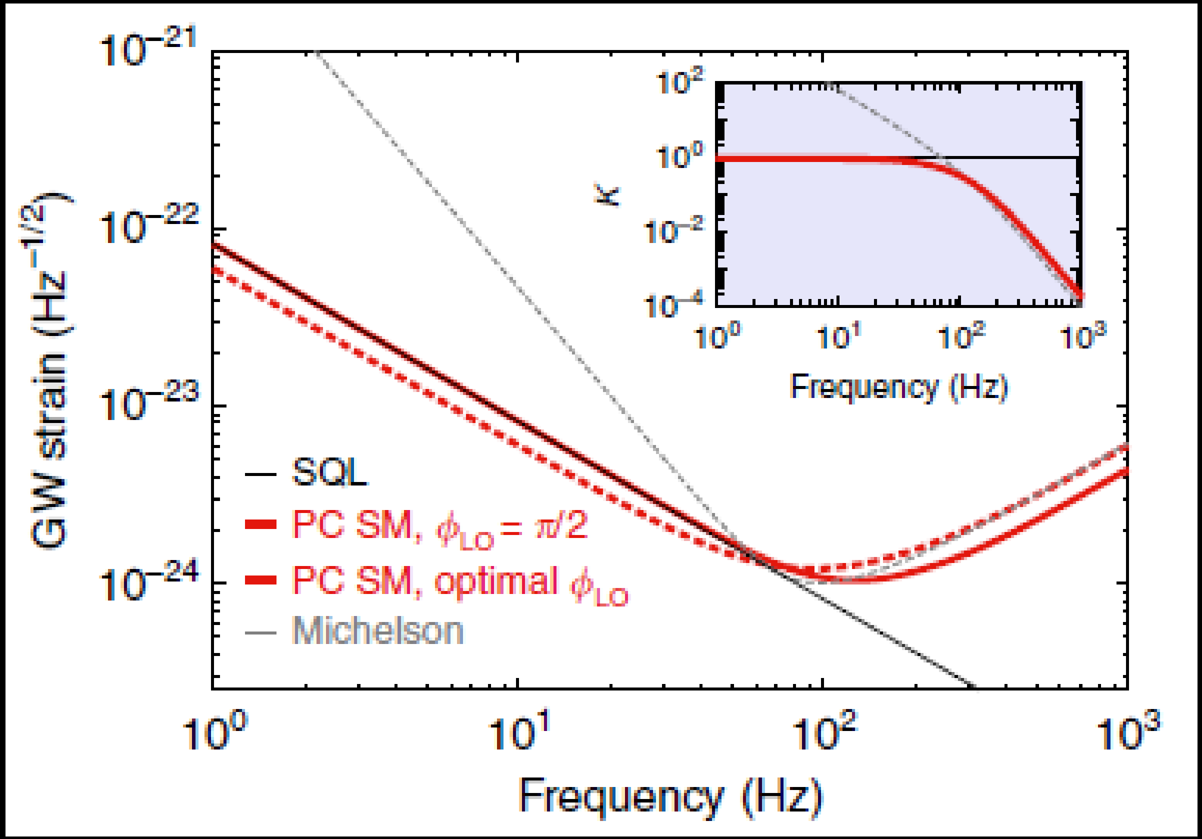
- ✓ The problem was we cannot perform the PDH method to PCC for 1064nm, because carrier will circulate in it **twice at most**. (⇒Finesse is **~ 0**)
- ✓ Here is another scheme using an auxiliary laser.
- ✓ Basic Idea:
  - ✓ When light passes a QWP twice, its polarization will be changed to its counter-quadrature (like *p* to *s* or *r* to *l*)
  - ✓ If the waveplate is HWP, it will not change the polarization.
  - ✓ Let’s make a dual wavelength waveplate that perform as a HWP in another wavelength.
  - ✓ Ex.) Thorlabs: WPDM05M-532H-1064Q

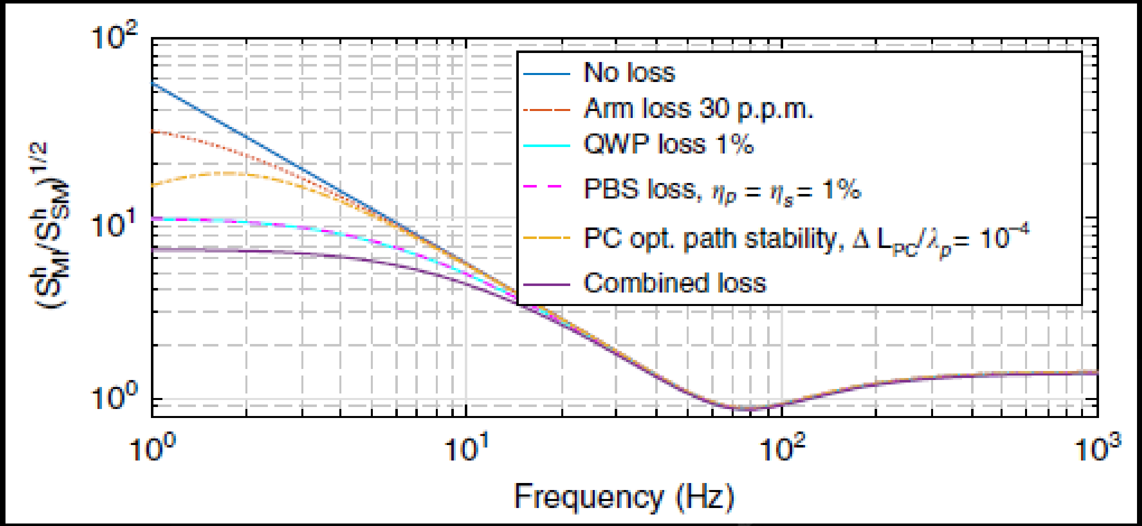
How to control the **P**olarization **C**irculation **C**avity?



- ✓ Lock acquisition:
  1. Make a dual wavelength waveplate which acts as a QWP for 1064 nm and acts as a HWP for 532 nm
  2. Prepare an auxiliary GR laser phase locked to the main IR.
  3. Inject it from back of PCM.
  4. Put DARM offset and dither PCM to find the best position
  5. Put frequency offset to GR and lock the cavity by PDH method.
  6. Once the frequency offset is fixed, the PCC error signal can be switched from dithering to GR PDH (which is generally stronger than dithering signal)
- ✓ Benefits:
  - ✓ Can use stronger error signal than dithering.
  - ✓ DARM offset is not needed anymore. (Once you switch the error signal to GR PDH, you can offload the DARM offset.)
  - ✓ Can perform Wave Front Sensing
- ✓ Concerns
  - ✓ Doesn’t it conflict with the current ALS scheme?
  - ✓ GR will enter the arm cavity to some amount ⇒ classical radiation pressure noise?
  - ✓ Is the offset value stable? How often do we need to check it?

Quantum-Noise-Limited Sensitivity (QNLS)

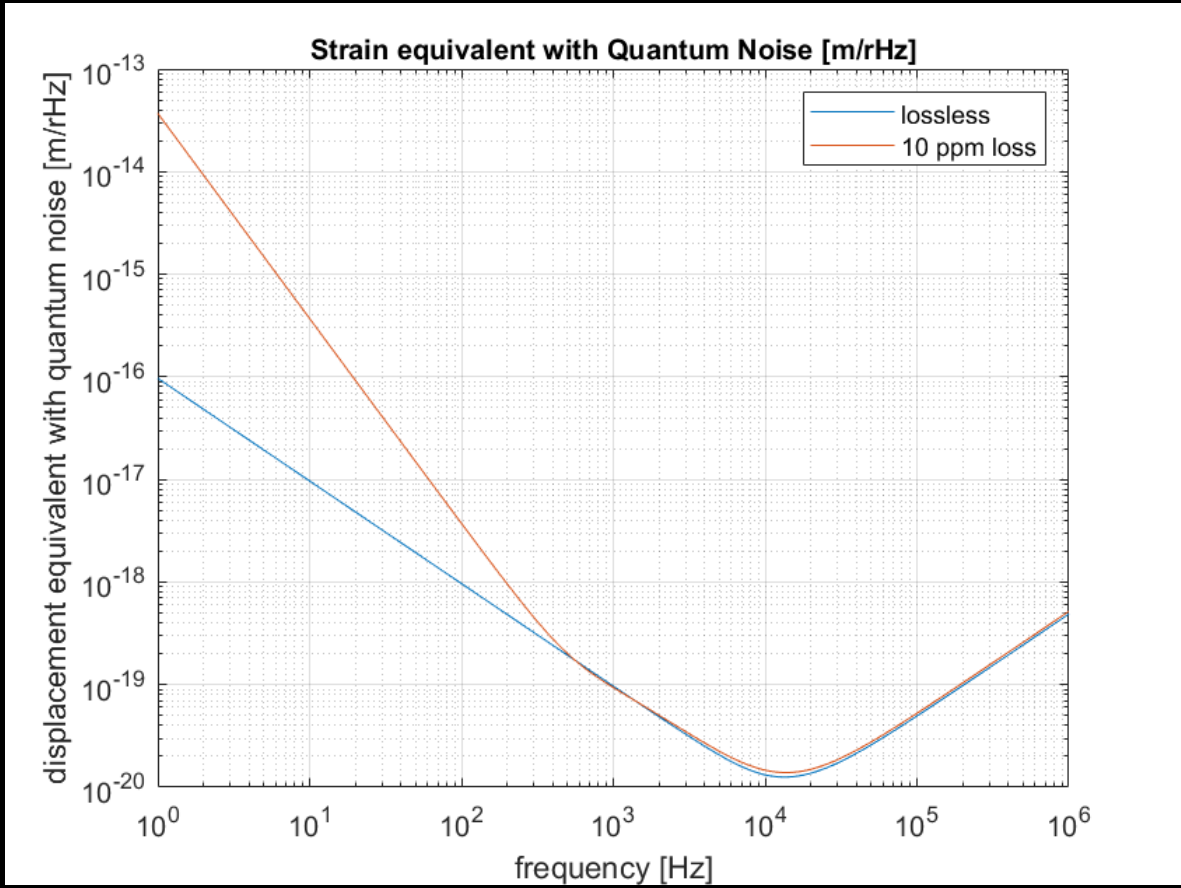




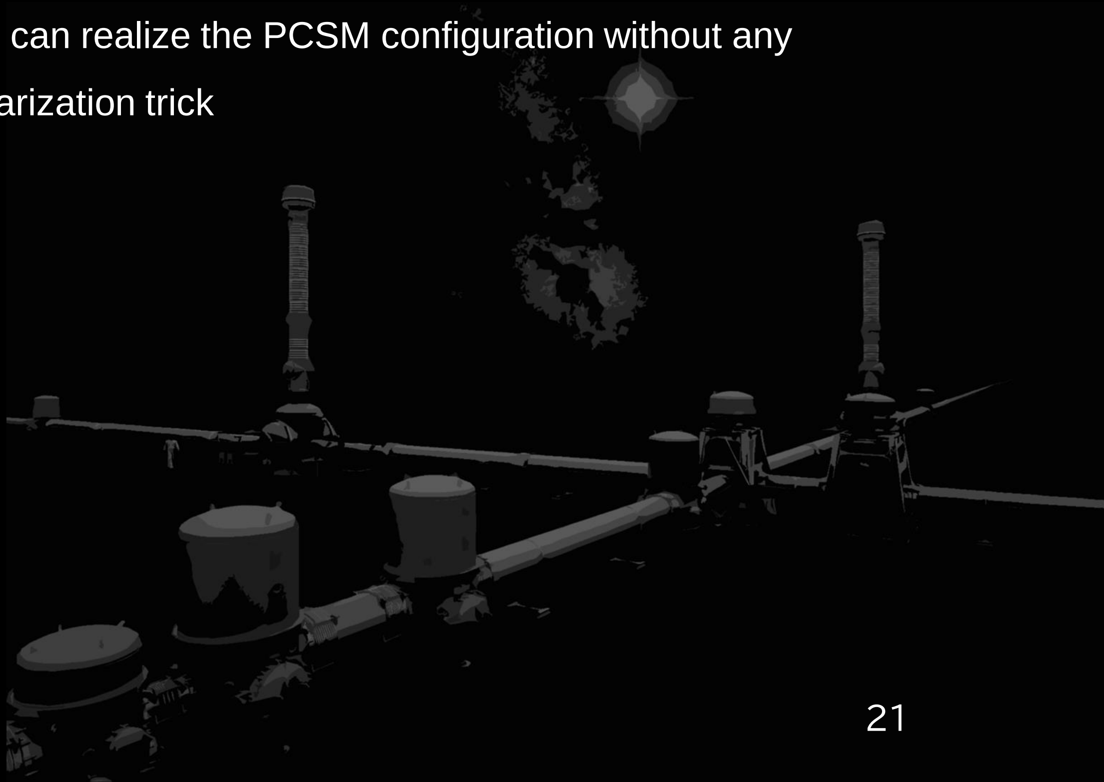
S. Danilishin *et al.* 2018

- ✓ Danilishin et al. (2018) has analyzed loss contribution from optics and PCC length instability
- ✓ They did not include a retardation error of QWP and leakage of PBS
- ✓ We have re-analyzed loss contribution including these two components (in prep.)

Simulation by Optickle2 (in prep.)

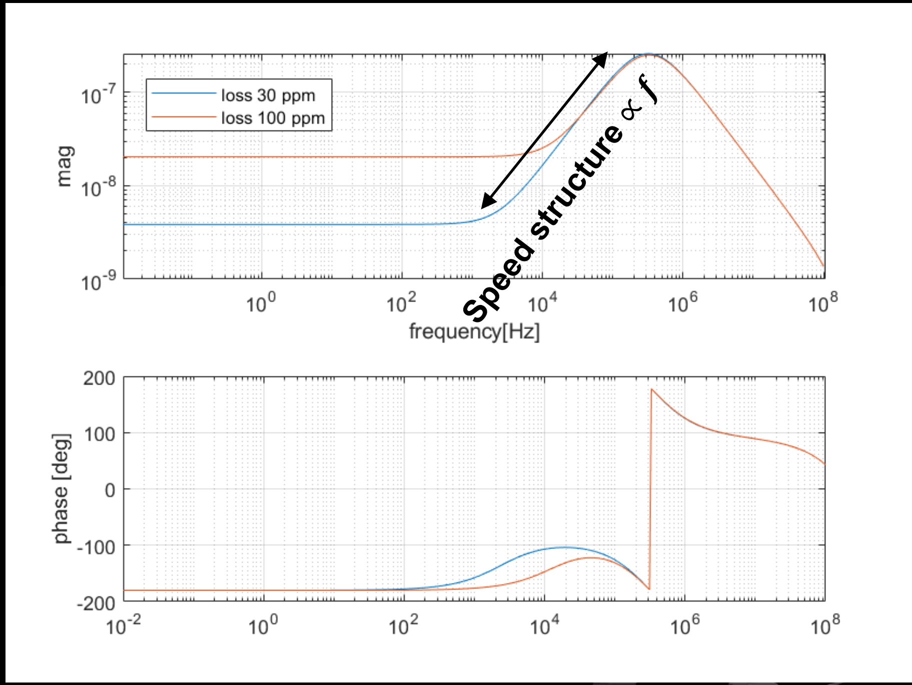


- ✓ Polarization optics, like QWP and PBS, are available in Optickle2 (cf. Finesse)
- ✓ We can realize the PCSM configuration without any polarization trick



Proof of principal experiment at NAOJ (in prep.)

- ✓ We are planning a new speed meter experiment
- ✓ Phase1: Control demonstration
  - ✓ 15 cm prototype
  - ✓ Rigid cavity
  - ✓ Inject phase modulated beam from ETM and measure a transfer function
  - ✓ Check if it realizes $\propto f$ structure at low frequencies
  - ✓ Check the stability of the dual waveplate scheme
- ✓ Phase2: Proof of principal experiment:
  - ✓ 20 m meter prototype (or TAMA300?)
  - ✓ Suspended cavity
  - ✓ Light mirrors (~1g)
  - ✓ Inject amplitude modulated laser from the AS port (= fake radiation pressure noise) and see noise reduction.



Speedmeter + Signal Recycling

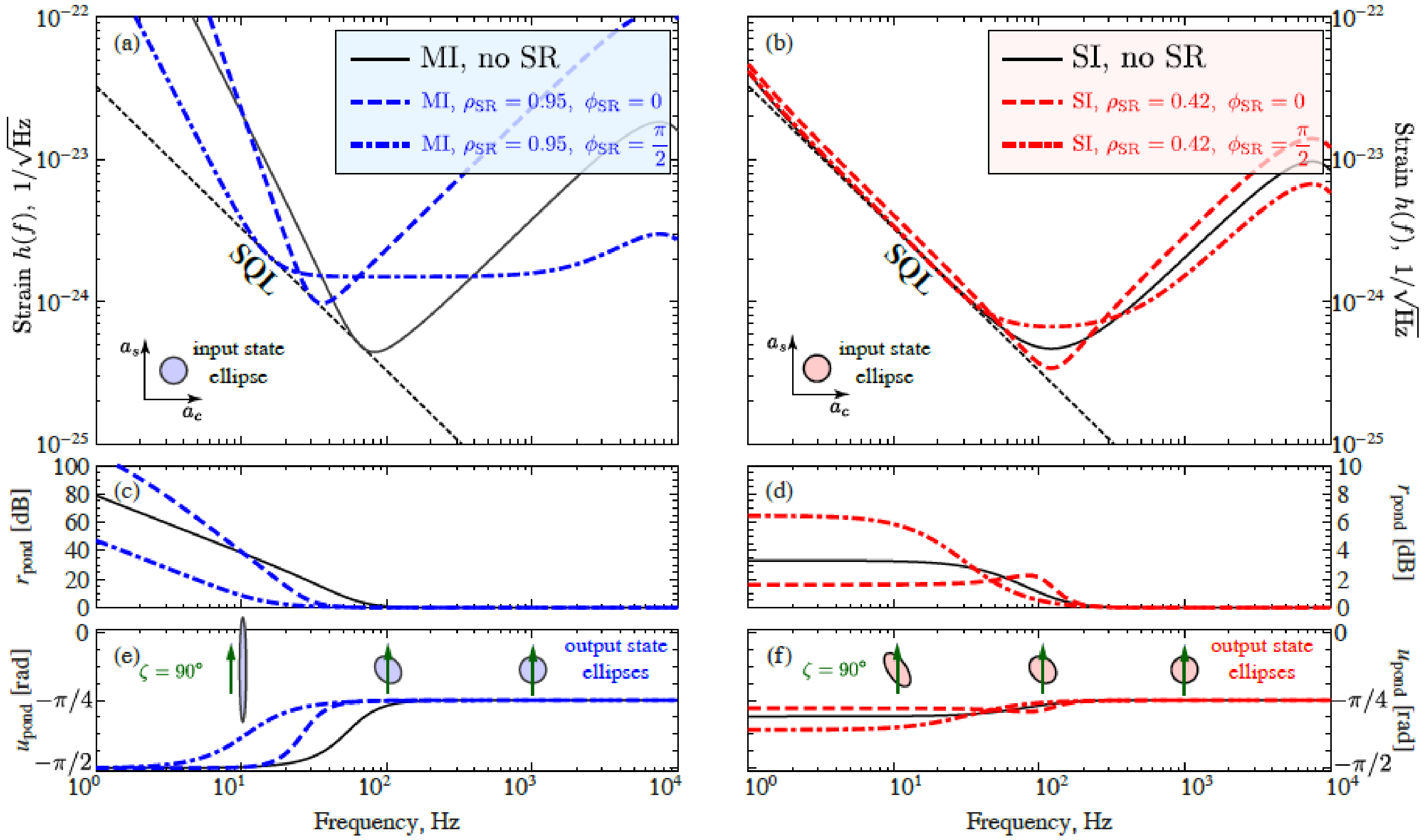


FIG. 5: Effect of signal recycling on Michelson (left) and Sagnac (right) interferometers quantum noise sensitivity (first row, panels (a) and (b)), ponderomotive squeezing strength (middle row, panels (c) and (d)) and quantum state rotation angle, u_{pond} (bottom row, panels (e) and (f)). Plots are drawn for ET typical parameters: arms length $L = 10$ km, mirrors mass, $m = 200$ kg, arm circulating power, $P_{\text{arm}} = 3$ MW, phase quadrature readout, $\zeta = \pi/2$. ITM power transmissivity for Michelson is equal to $T_{\text{ITM}} = 5.2\%$, and for Sagnac is $T_{\text{ITM}} = 9.1\%$. Light quantum state transformation by an interferometer (w/o signal recycling) is illustrated by noise ellipses. Circles on panels (a) and (b) stand for injected vacuum noise ellipse. Ellipses on panels (e) and (f) demonstrate quantum state of the outgoing light transformed by ponderomotive squeezing at different frequencies (10, 100, and 1000 Hz). Green arrows point at the direction of readout quadrature, $\zeta = \pi/2$.

Voronchev *et al.* 2015

Speed meter + Squeezing

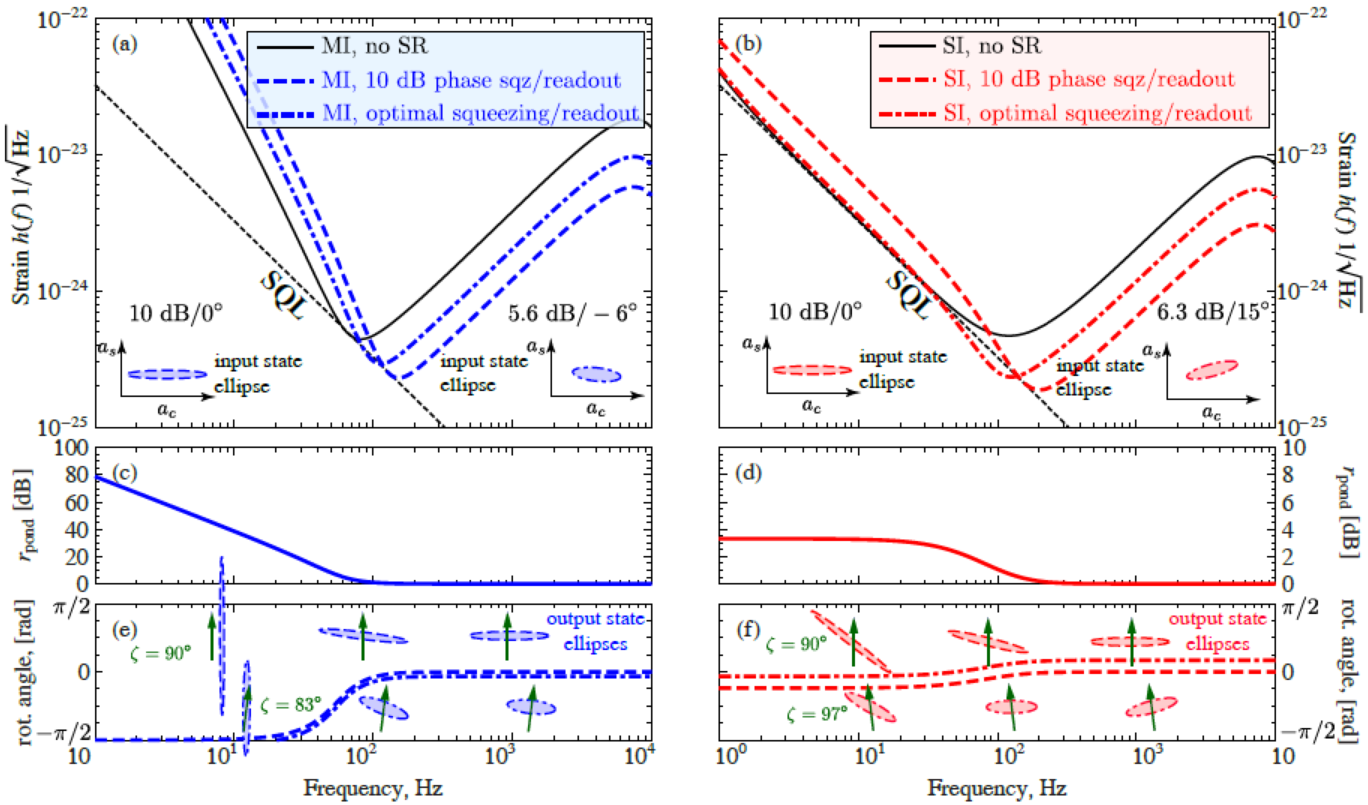


FIG. 6: Quantum noise sensitivity of Michelson (left, panel (a)) and Sagnac (right, panel (b)) interferometers quantum in case of constant phase squeezed vacuum injection. Panels (c) and (d) show ponderomotive squeezing factor, $r_{\rm pond}(\Omega)$, while panels (e) and (f) show quantum noise ellipse overall rotation angle, *i.e.* rot. angle $= \lambda + u_{\rm pond} + v_{\rm pond}$ of Michelson and Sagnac interferometers, respectively. Solid black lines of quantum noise sensitivity of bare interferometers (w/o recycling and squeezing) are given for reference. Dashed lines demonstrate the effect of constant phase squeezing ($r = 10$ dB, $\lambda = 0$) with phase quadrature readout ($\zeta = \pi/2$), dash-dotted lines show quantum noise for optimised squeezing angle and readout quadrature. Parameters used for these plots are given in Table II. Light's quantum state transformation by an interferometer with squeezed vacuum injection is illustrated by noise ellipses. Ellipses on panels (a) and (b) stand for injected squeezed vacuum noise ellipses (left one for 10 dB phase squeezed input, right one for optimised squeezed input). Ellipses on panels (e) and (f) demonstrate quantum state of the outgoing light transformed by ponderomotive squeezing at different frequencies (10, 100, and 1000 Hz). Green arrows point at the direction of readout quadrature, ζ. An upper row of ellipses on both lower panels refers to the 10 dB phase squeezed vacuum injection case. A lower row stands for the optimised fixed angle squeezed vacuum injection case.

Voronchev *et al.* 2015

Speedmeter + Filter Cavity

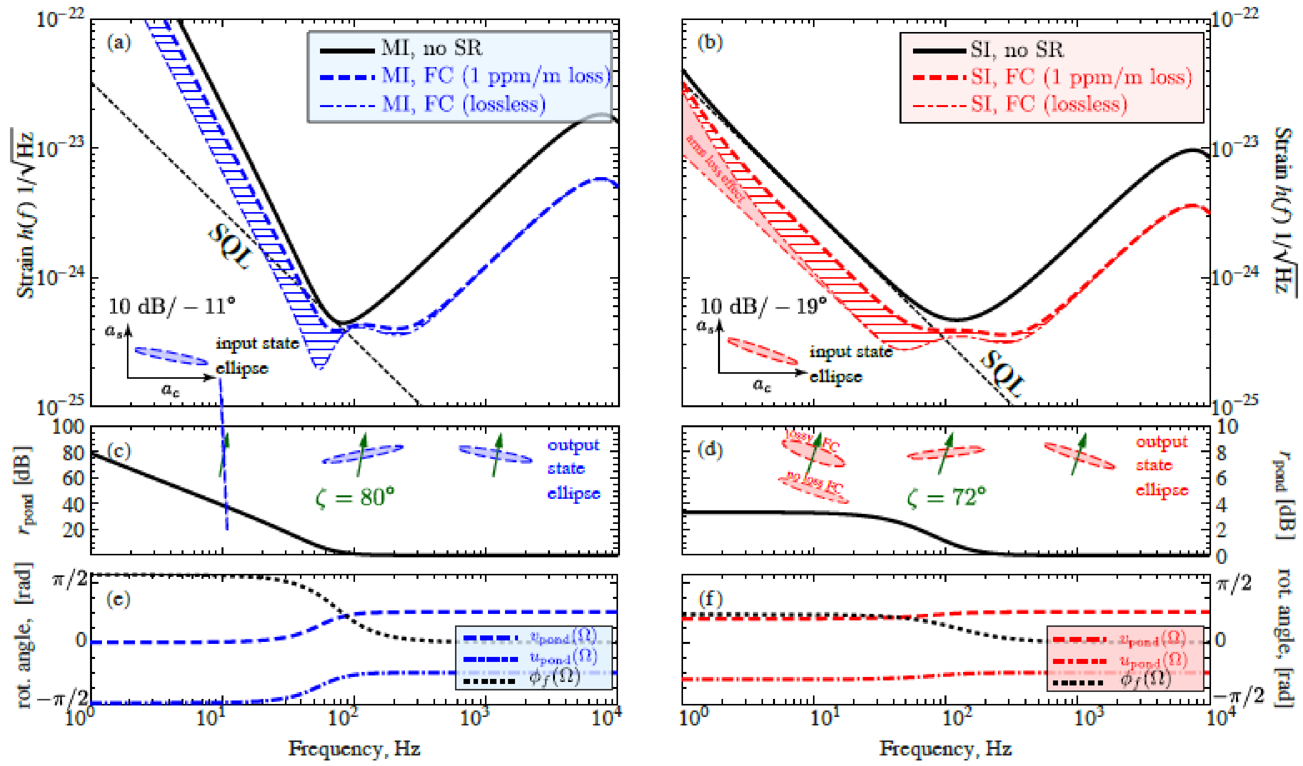


FIG. 7: Quantum noise of Michelson (left, panel (a)) and Sagnac (right, panel (b)) interferometers with frequency dependent squeezing injection: solid black lines show quantum noise without squeezing, thin dash-dotted lines show quantum noise with lossless single filter cavity with parameters given in Table III, and thick dashed lines show quantum noise with account for optical loss in the FC. Hatched regions demonstrate sensitivity deterioration due to FC loss. Panels (c) and (d) show ponderomotive squeezing factor vs. frequency, and panels (e) and (f) illustrate frequency dependent phase space rotation of the light noise ellipse in the interferometer at all stages, *i.e.* before the ponderomotive squeezing is applied (dashed lines), after it (dash-dotted lines), and the overall rotation angle (black dotted lines). Corresponding output noise ellipses are shown for both interferometers in panels (c) and (d) at 3 different frequencies (10, 100 and 1000 Hz). Readout quadrature direction, given by angle ζ, is illustrated by green arrows. Quantum noise at each frequency can be conveniently represented by a projection of the corresponding noise ellipse on the readout quadrature direction. These plots show that a single filter cavity is able to provide only a quasi-optimal phase rotation. The effect of this deviation from optimal dependence is most pronounced near the medium frequencies (around 100 Hz). Effect of optical loss in the arms is not negligible for Sagnac interferometer and shown by pink colour-filled area at low frequencies ($T_{\rm ETM}$ = 40 ppm).

Voronchev *et al.* 2015

Speedmeter + Signal Recycling + Filter Cavity

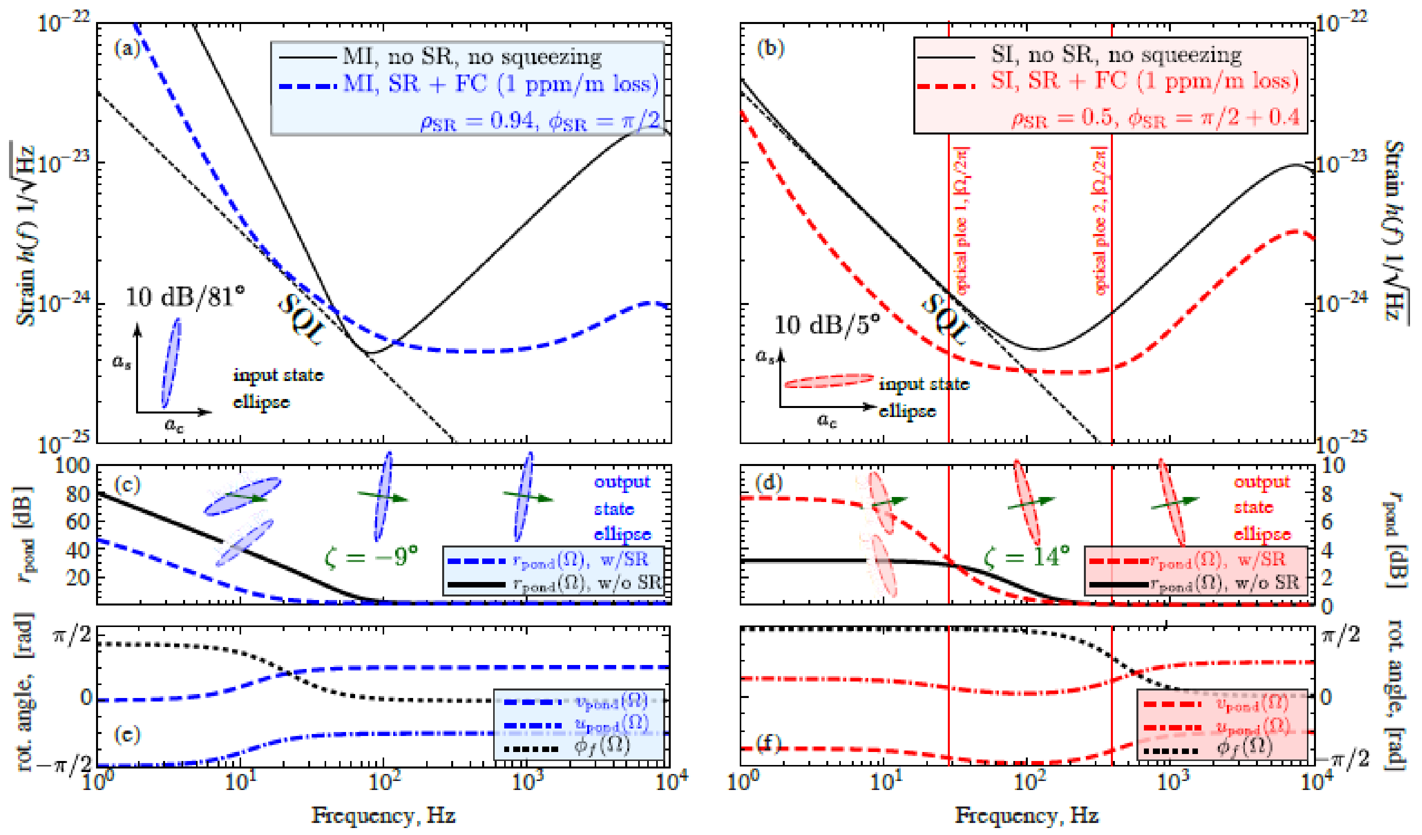


FIG. 8: Quantum noise sensitivity of Michelson (left, panel (a)) and Sagnac (right, panel (b)) interferometers in case of combined frequency dependent squeezed vacuum injection and optimal signal recycling. Red vertical lines denote the location of two optical poles of the SI defined in Eq. (64). Solid black lines in panels (c) and (d) show ponderomotive squeezing in interferometers w/o signal recycling mirror, while red dashed lines demonstrate how it changes if an optimally detuned signal-recycling is employed. Panels (e) and (f) show frequency dependence of ponderomotive angles (red lines) and the optimal FC phase shift (black dashed curve) for a detuned signal-recycled interferometer. Light quantum state transformation by an interferometer with squeezed vacuum injection is illustrated by noise ellipses. Ellipses on panels (a) and (b) stand for injected squeezed vacuum noise ellipses for a 10 dB optimally squeezed vacuum. Ellipses on panels (c) and (d) demonstrate quantum state of the outgoing light transformed by ponderomotive squeezing at different frequencies (10, 100, and 1000 Hz). Green arrows point at the direction of readout quadrature, ζ. Lower ellipse at 10 Hz represents a would-be output state, were there no optical loss in the filter cavity. All the relevant parameters for these plots are given in Table IV.

Voronchev *et al.* 2015

Summary

- ✓ QND measurement is one of the biggest topics in GW detector development
- ✓ Frequency dependent squeezing gives a broadband enhancement in sensitivity and filter cavities have already been implemented in 2G detectors.
- ✓ Speedmeters give us a great reduction of quantum radiation pressure noise.
- ✓ Speedmeters do not need additional cavities, and everything happens inside the interferometer.
- ✓ Many designs have been proposed, but most of them need a huge hardware change.
- ✓ Polarization Circulation Speed Meter, proposed by S. Danilishin, require minimal hardware change from the current 2G detectors.
- ✓ PCSM could be a design of ET (high frequency?)
- ✓ But its control scheme has not been investigated.
- ✓ We propose a new scheme using a dual wavelength waveplate and an auxiliary laser
- ✓ We are planning to start a new experiment in NAOJ
- ✓ It will be also beneficial for KAGRA once it reaches QNL