Proof-of-principle experiment for polarization circulation speed meter

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On behalf of

National Astronomical Observatory of Japan

Contents:

- Speed meter
- Review of polarization circulation speed meter
- Control idea
- Experiment

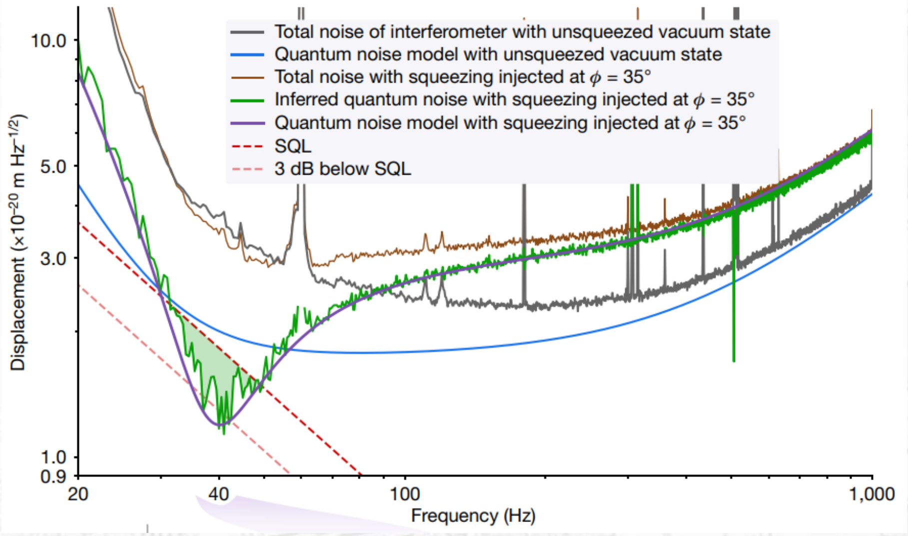
Speed meter

Quantum radiation pressure noise in the 3G detectors

Quantum radiation pressure noise will be a dominant noise source in future detectors

Background and future perspective

- ✓ In the 3rd observation run (2019-2020), LIGO and Virgo has come to see the QRPN effects at low frequencies with squeezing.
- ✓ This is due to the improvement of thermal noises and suspension-control noise, and the implementation of the high-power laser.
- ✓ In the upcoming 3rd-generation (3G) detectors, the QRPN will be a dominant noise source at low frequencies.

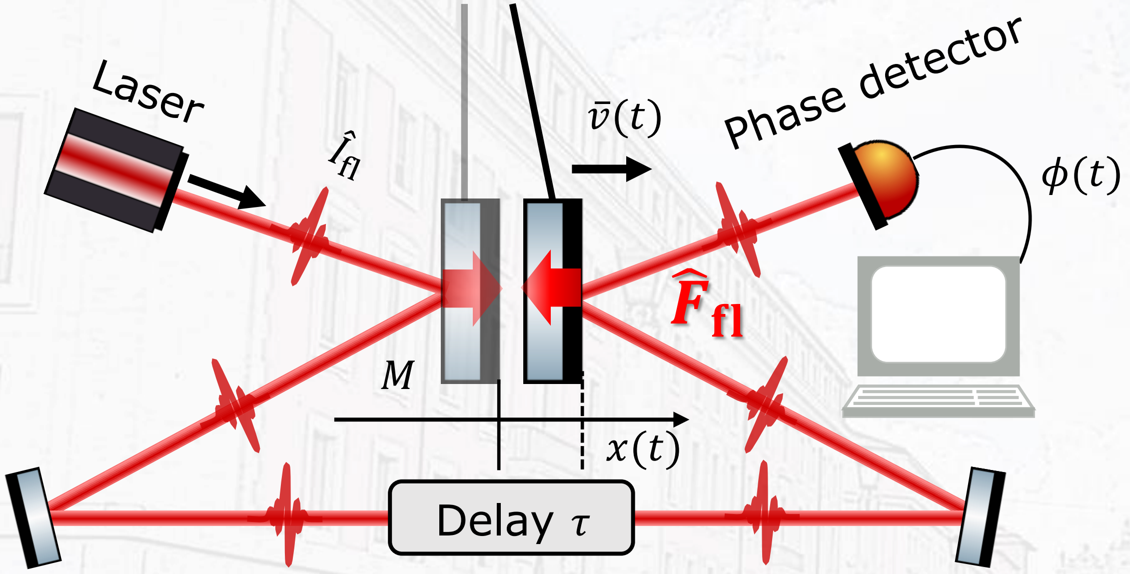


H. Yu *et al.*, Nature volume 583, pages43–47 (2020), Fig. 2

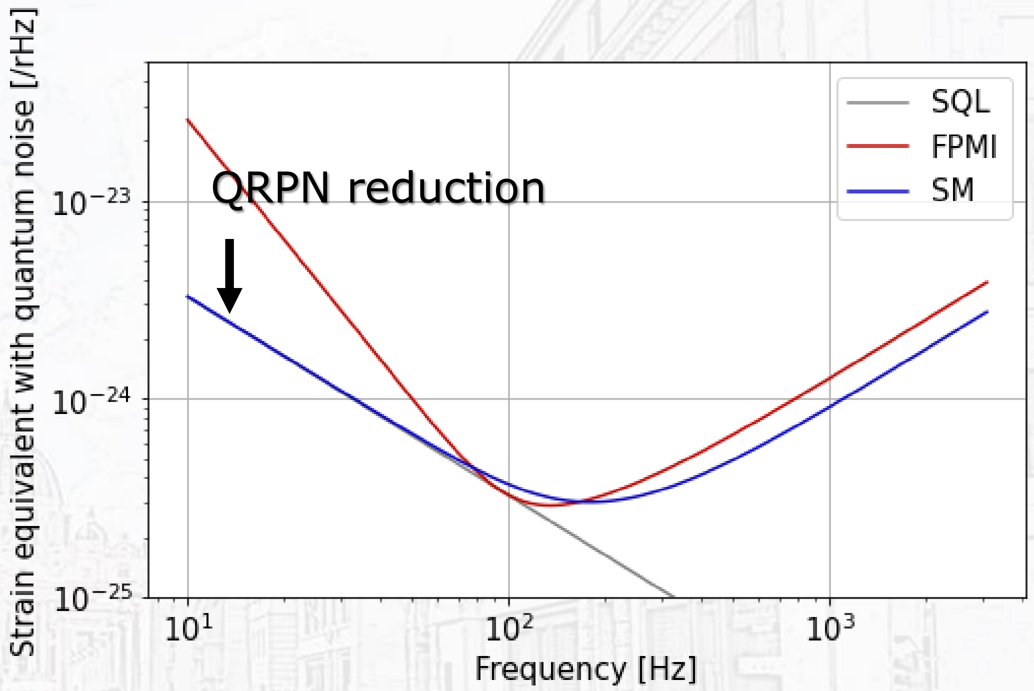
Speed meters are one of the solutions to reduce the QRPN

Speed meter

Key: speed measurement cancels out the back action of the measurement



Danilishin & Khalili, Living Reviews (2012).



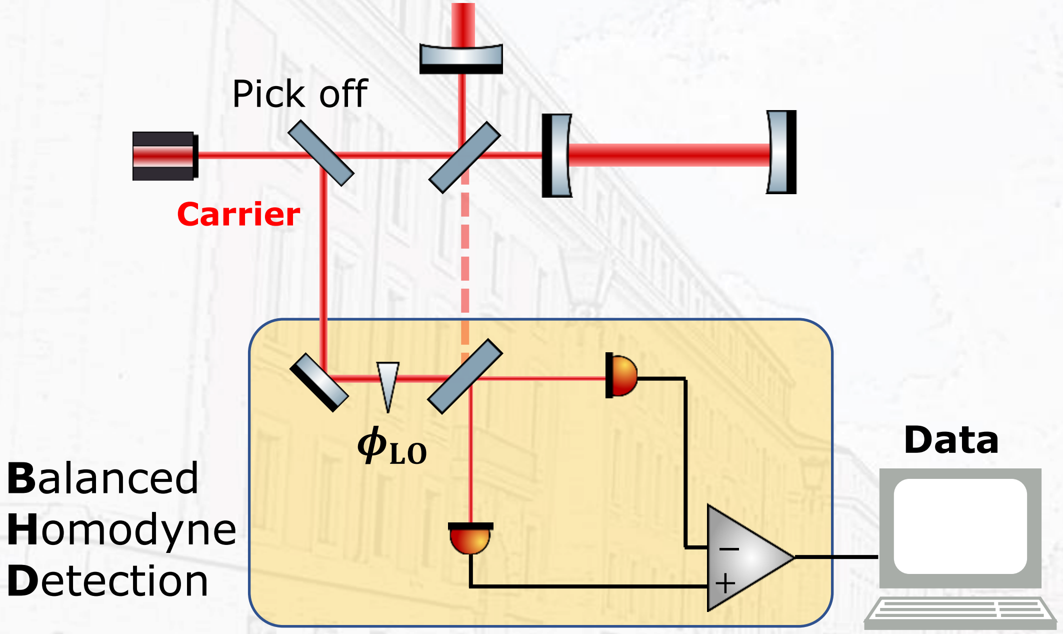
Amplitude fluctuation $\hat{\imath}_{\rm fl}$

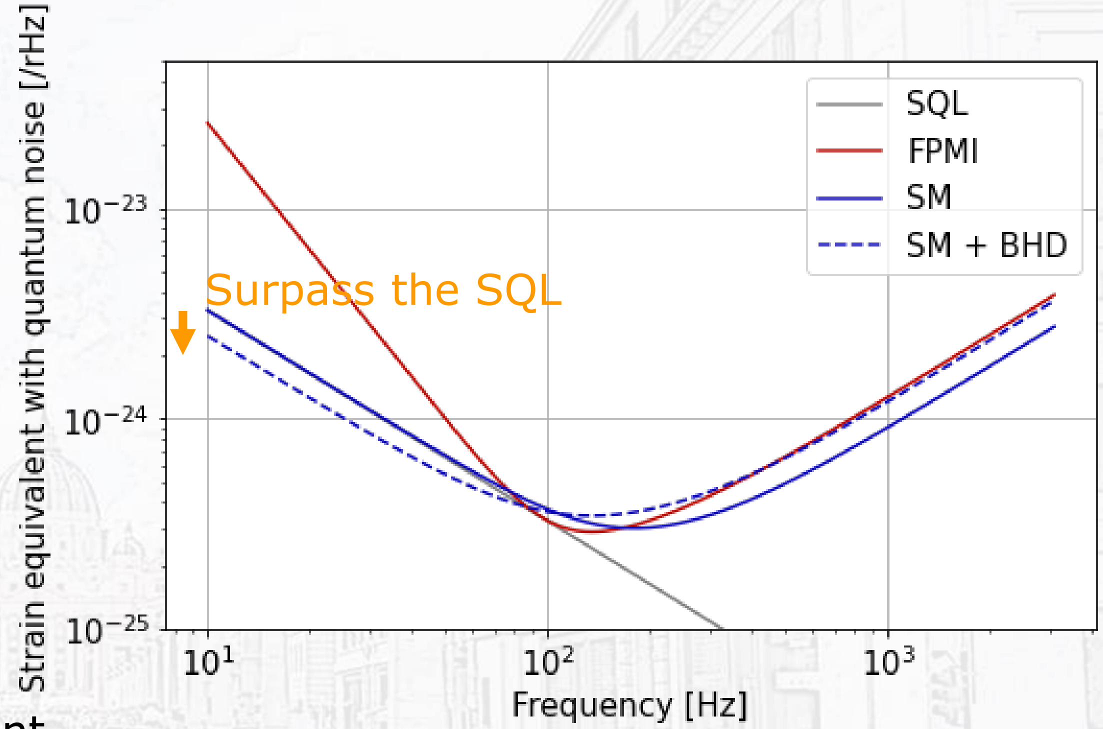
Back action: $\hat{F}_{\rm fl}(\Omega) \simeq -i\Omega\tau\frac{2\hat{\imath}_{\rm fl}}{c}$

Measured quantity: $\phi(t) \propto x(t) - x(t-\tau) \simeq \bar{v}(t)\tau$

Speed meters as a QND meter

Velocity measurement becomes a Quantum Non-Demolition (QND) measurement with the BHD

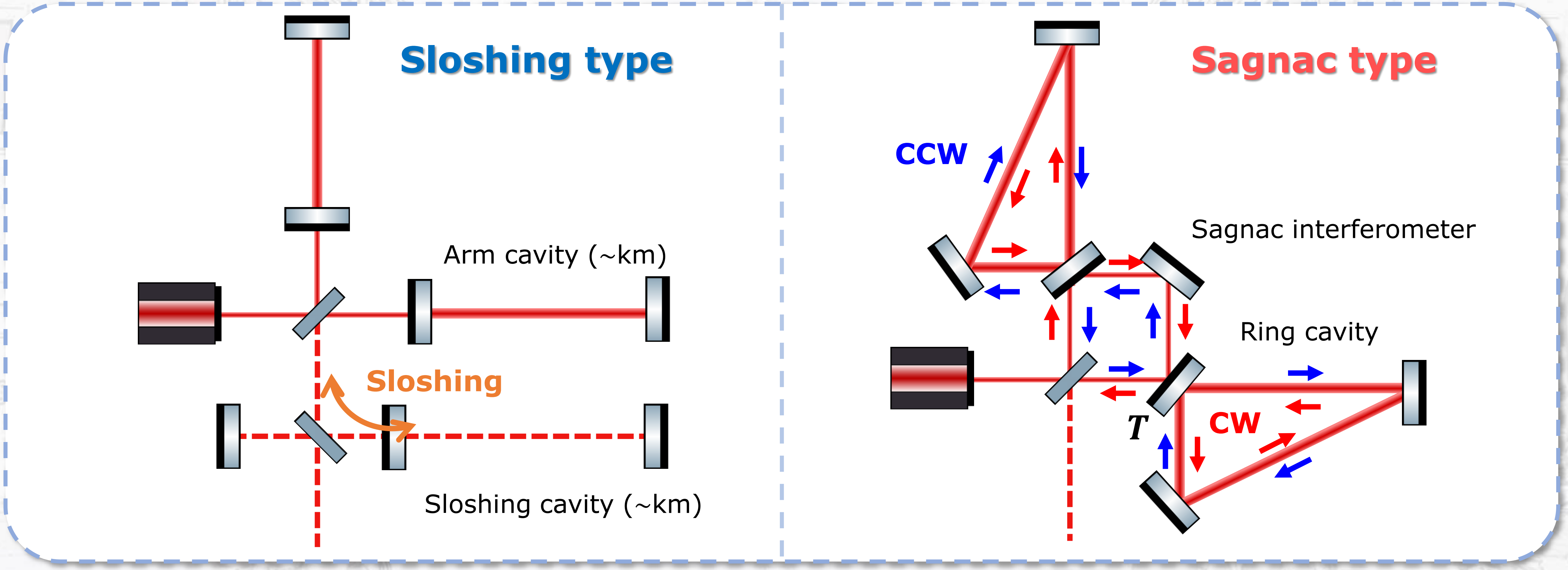




- ✓ One can get broad-band sensitivity improvement
- ✓ With the balanced homodyne detection, with a fixed homodyne angle, one can surpass the SQL
  ⇒ QND measurement
- ✓ “Fixed” means it doesn’t need filter cavities

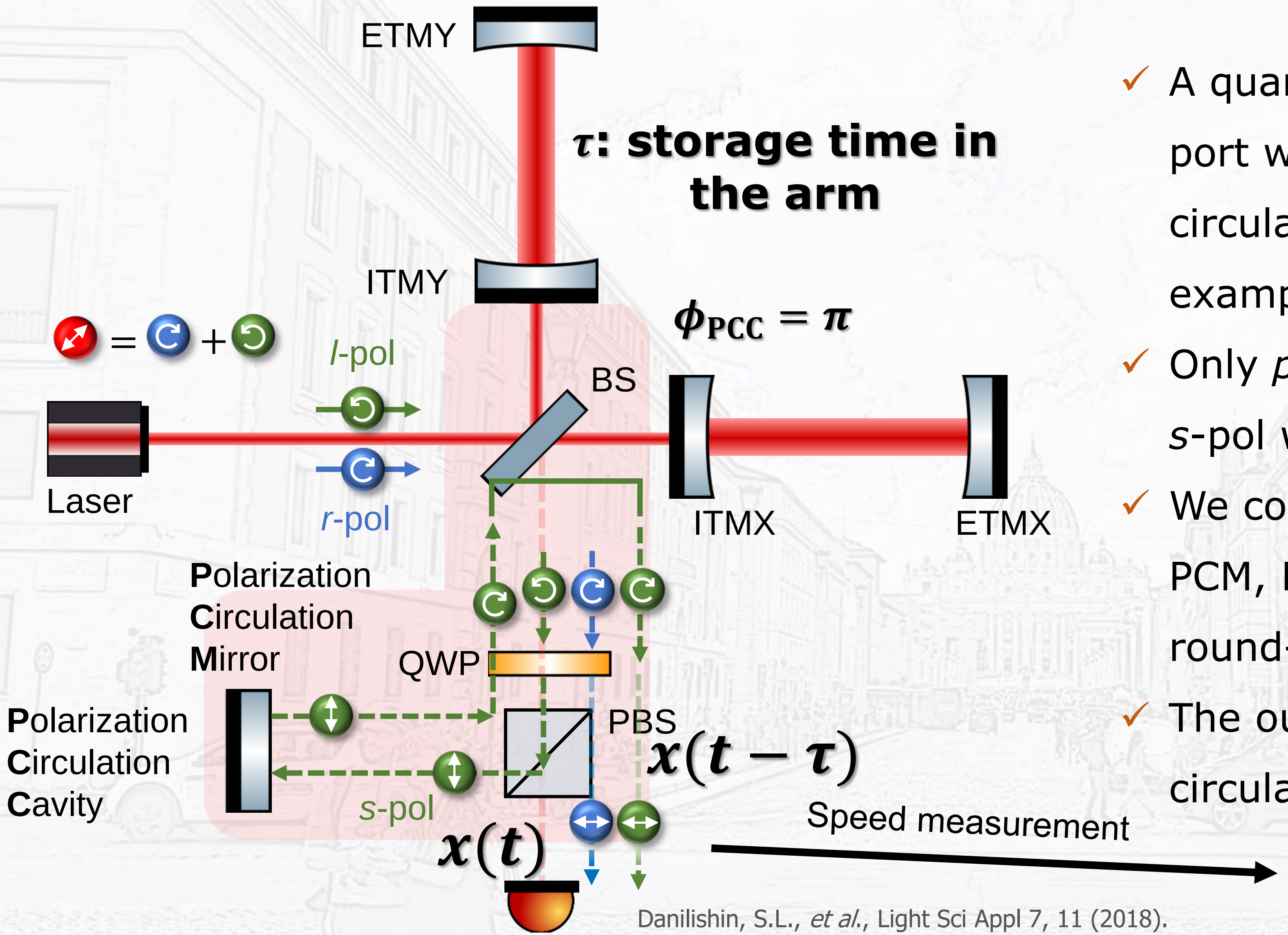
Proposed designs of speed meters

Two designs have been mostly investigated, but not realized in the real large-scale detectors



Review of polarization circulation speed meter

Polarization circulation speed meter – How it works?



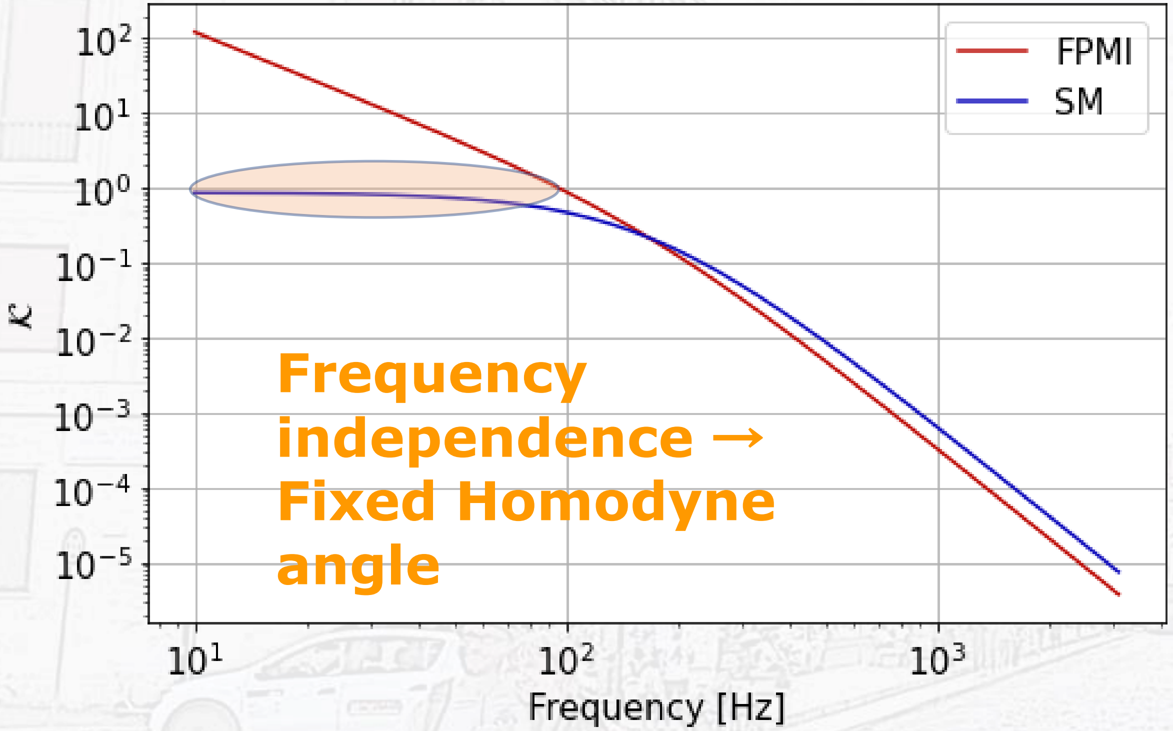
- ✓ A quarter waveplate (QWP) in the AS port will change the polarization from circular to linear (from *r* to *p*, *l* to *s* for example.)
- ✓ Only *p*-pol passes the PBS and reflected *s*-pol will go back to the interferometer
- ✓ We control the length of PCC formed by PCM, PBS, QWP and ITM so that the round-trip phase shift becomes $\phi_{\mathrm{PCC}} = \pi$
- ✓ The output is a subtraction of 1st and 2nd circulation:

$$x(t) - x(t-\tau) \simeq \bar{v}(t)\tau$$

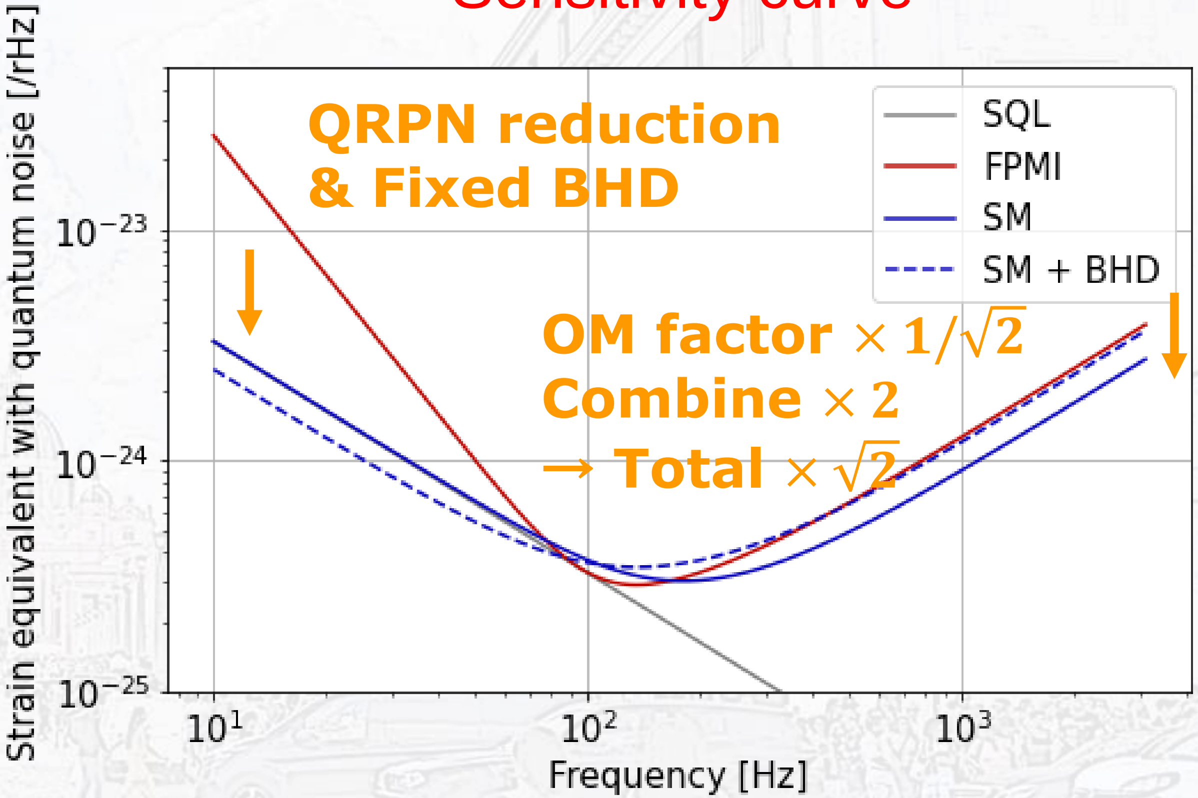
Danilishin, S.L., *et al.*, Light Sci Appl 7, 11 (2018).

Optomechanical coupling & sensitivity

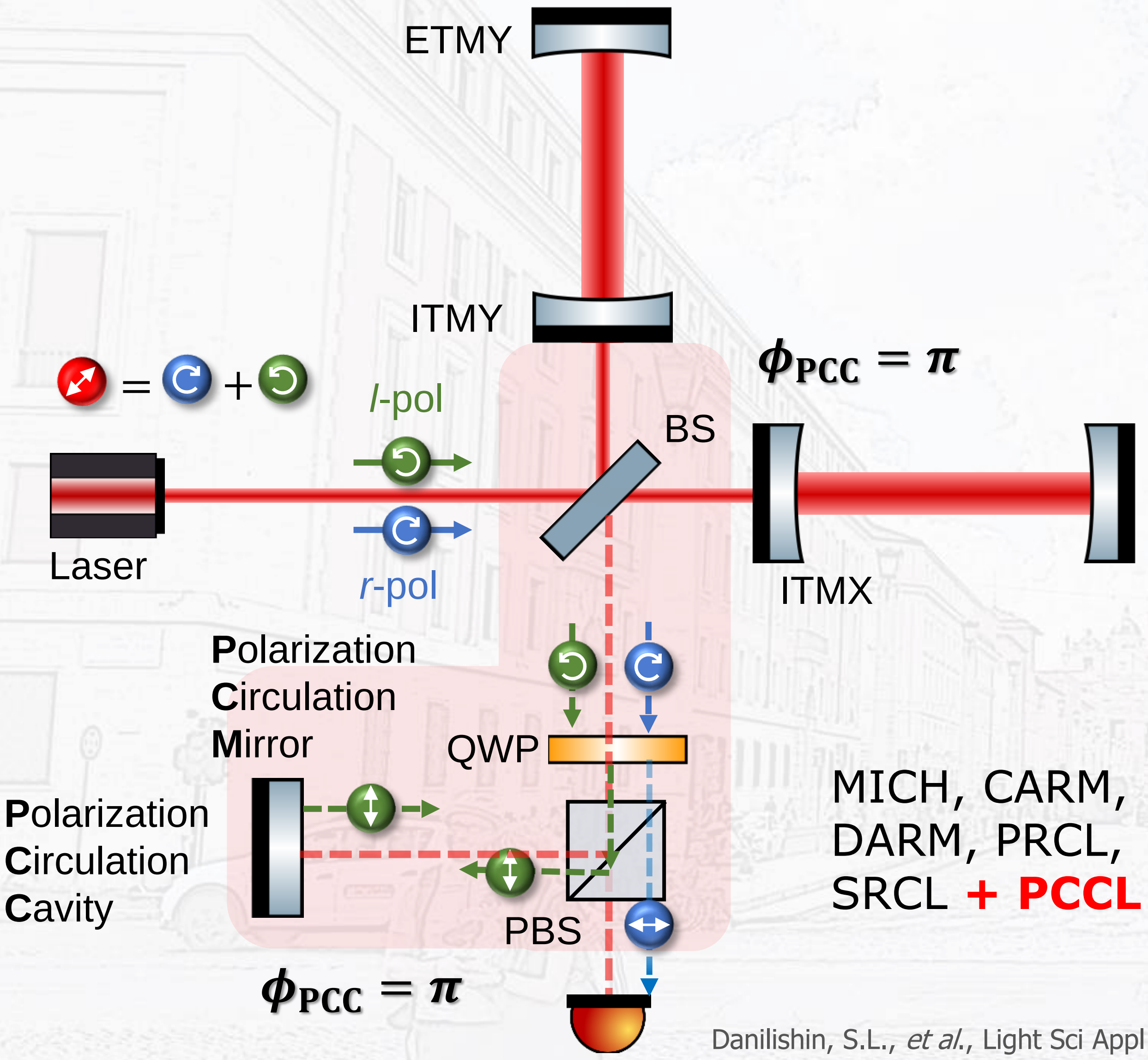
OM factor (κ)



Sensitivity curve



Polarization Circulation Speed Meter – Benefits & Problems



MICH, CARM, DARM, PRCL, SRCL **+ PCCL**

Benefits: **No need to touch the central interferometer**

- ✓ There were many speed meter designs, but they need drastic modification to the conventional position meters
- ✓ Can switch to the conventional position meter

Q. How to control?

- ✓ 6th degree of freedom = PCCL
- ✓ Carrier (also RF sidebands) does not resonate inside the polarization circulation cavity

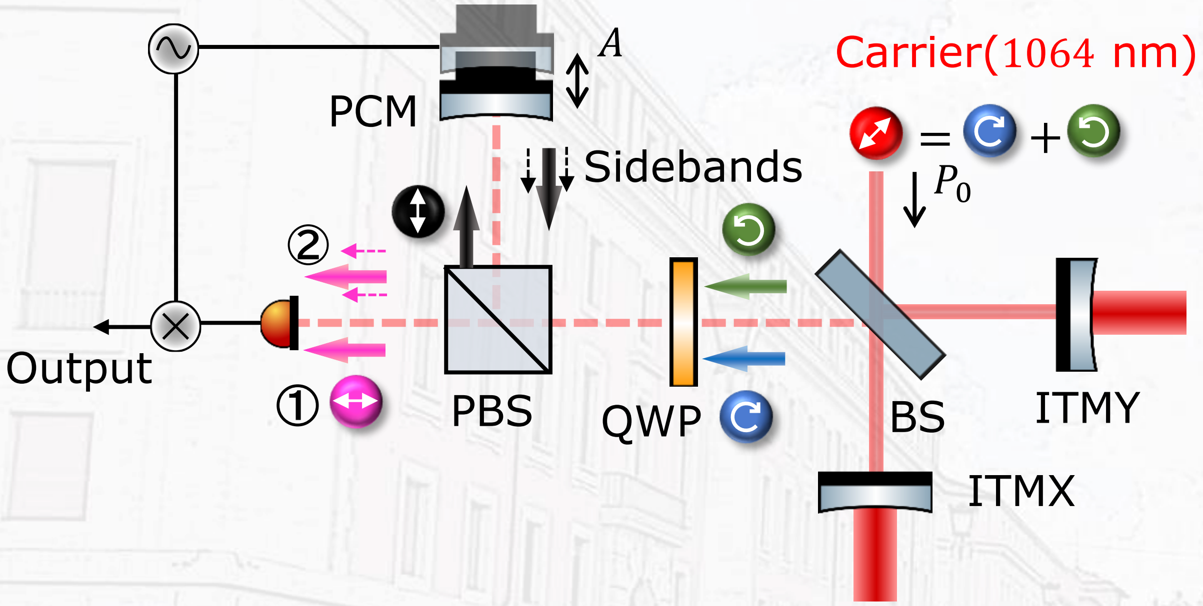
Danilishin, S.L., *et al.*, Light Sci Appl 7, 11 (2018).

Control idea

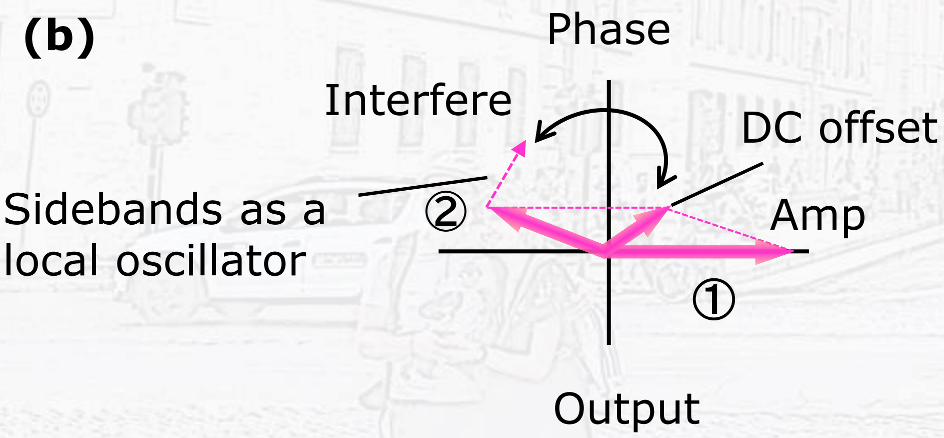
Mirror dithering?

Y. Nishino, *et al.*, Phys. Rev. D **107**, 084029 (2023).

(a)



(b)



- The round-trip phase shift in the PCC should be kept to π
  a. Modulating the position of the PCM, and demodulating the output of the PBS transmission
  b. Taking the beat between DC offset and generated sidebands, one can obtain a linear error signal
- Issues…
  - × Add mechanical oscillation
  - × No phase amplification
  - × Not sensitive to the alignment fluctuation
  - × DARM offset is needed

Mirror dithering?

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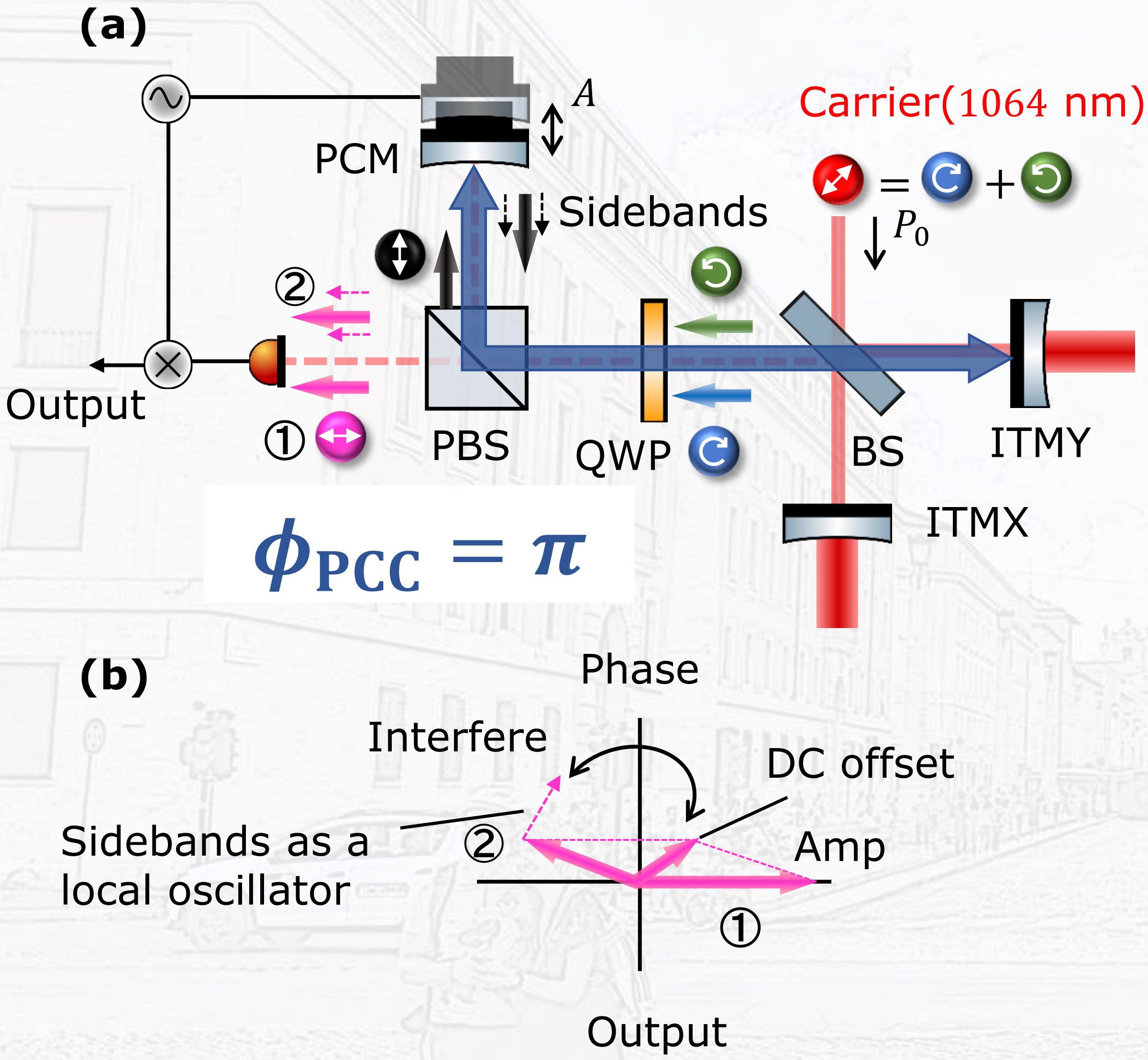

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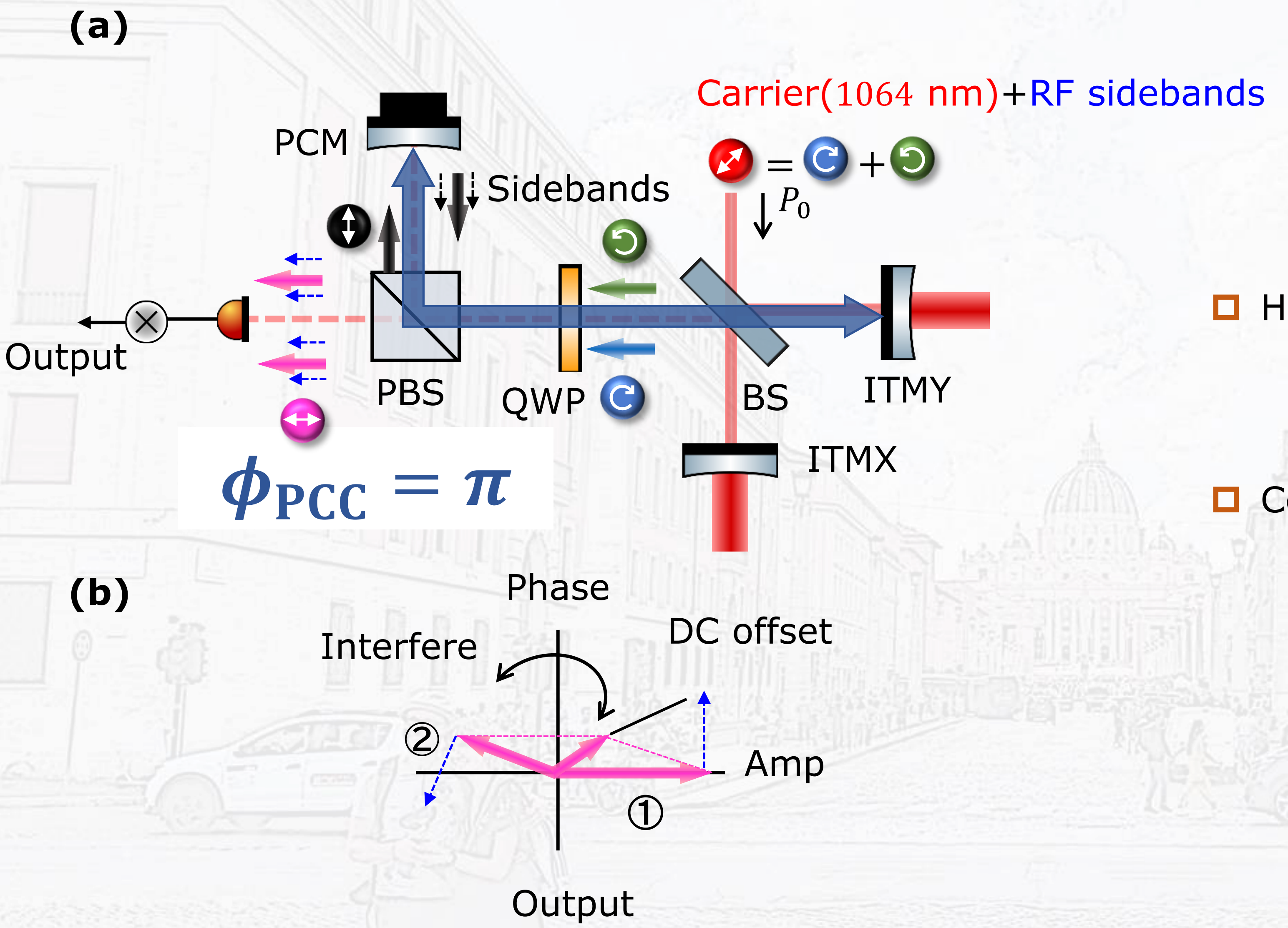
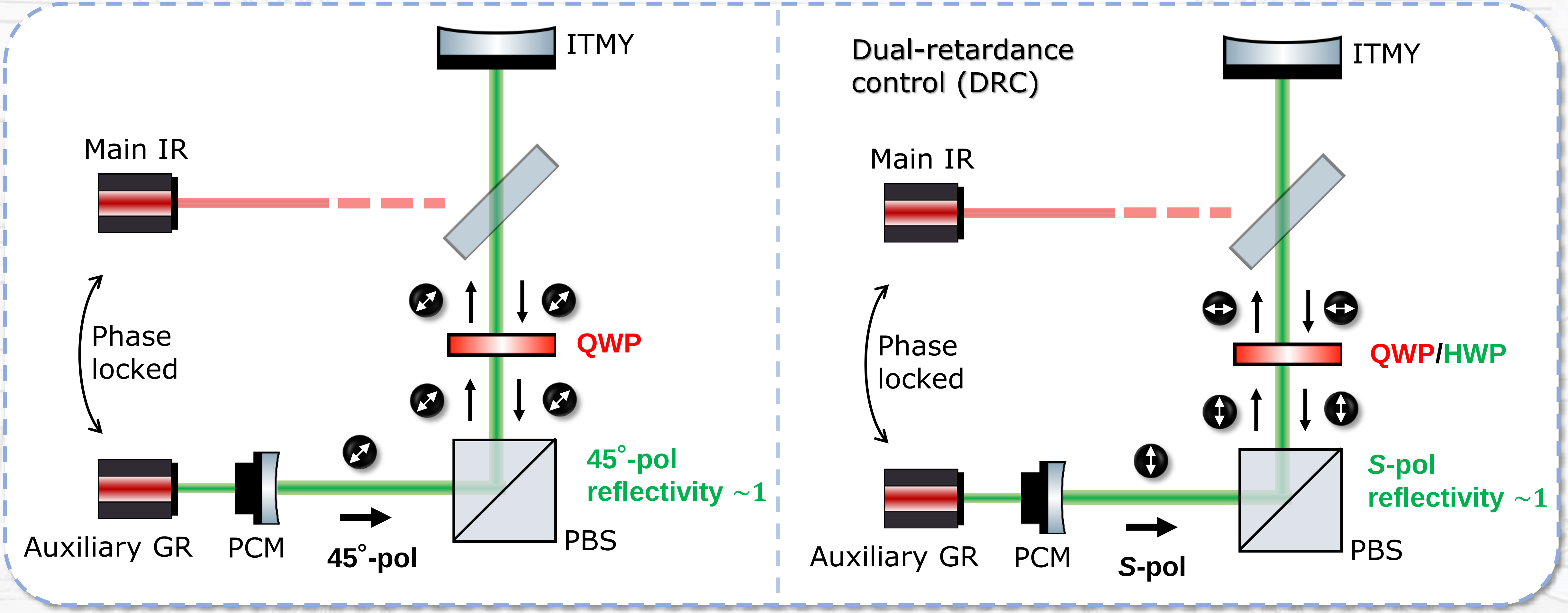
Using the RF sidebands?



- How about using existing sidebands?
  - ✓ Maybe feasible…
  - ✓ No need of mirror dithering
- Concerns…
  - ✓ Enough S/N?
  - ✓ No amplification
  - ✓ Need DARM offset

Control of the polarization circulation cavity



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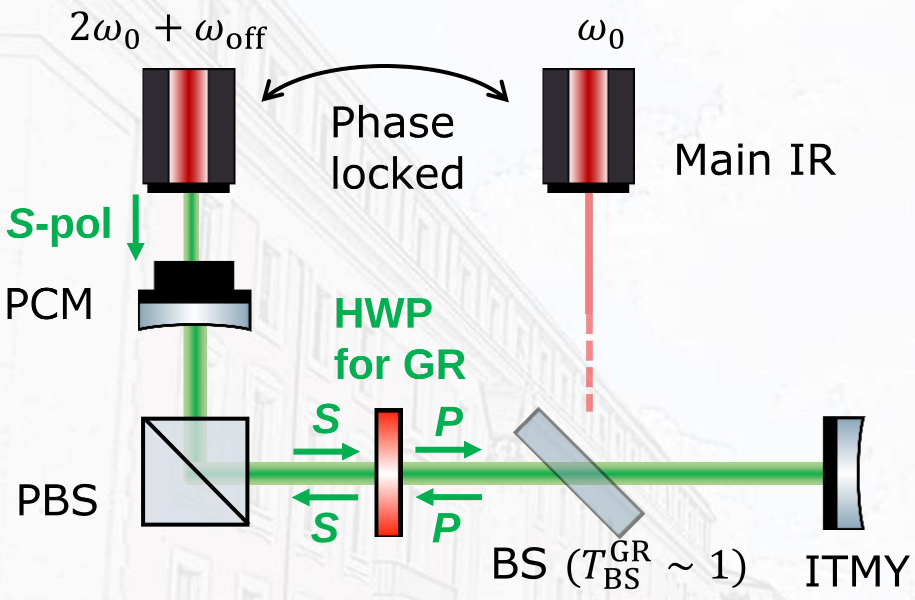
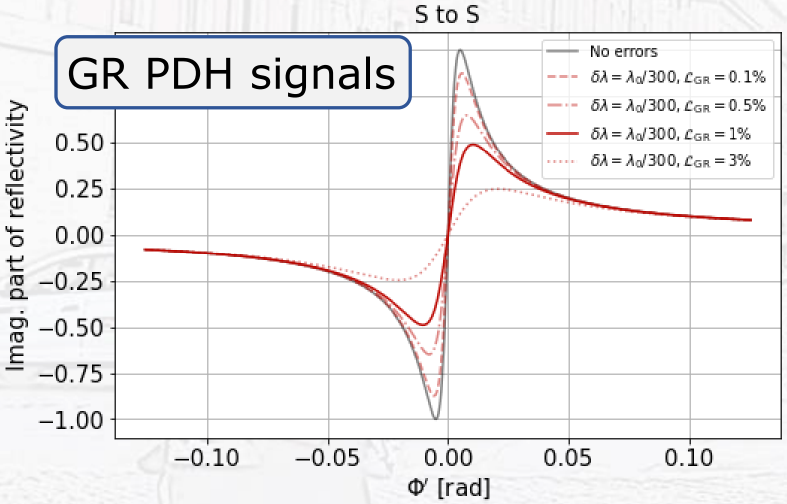
Dual-Retardance Control





Advantages:

- ✓ The error signal can have a high signal-to-noise ratio (10^4 times better than dithering)
- ✓ Wave-front sensing for the alignment control can be used
- ✓ Easier coatings @ 532 nm to the PBS and BS

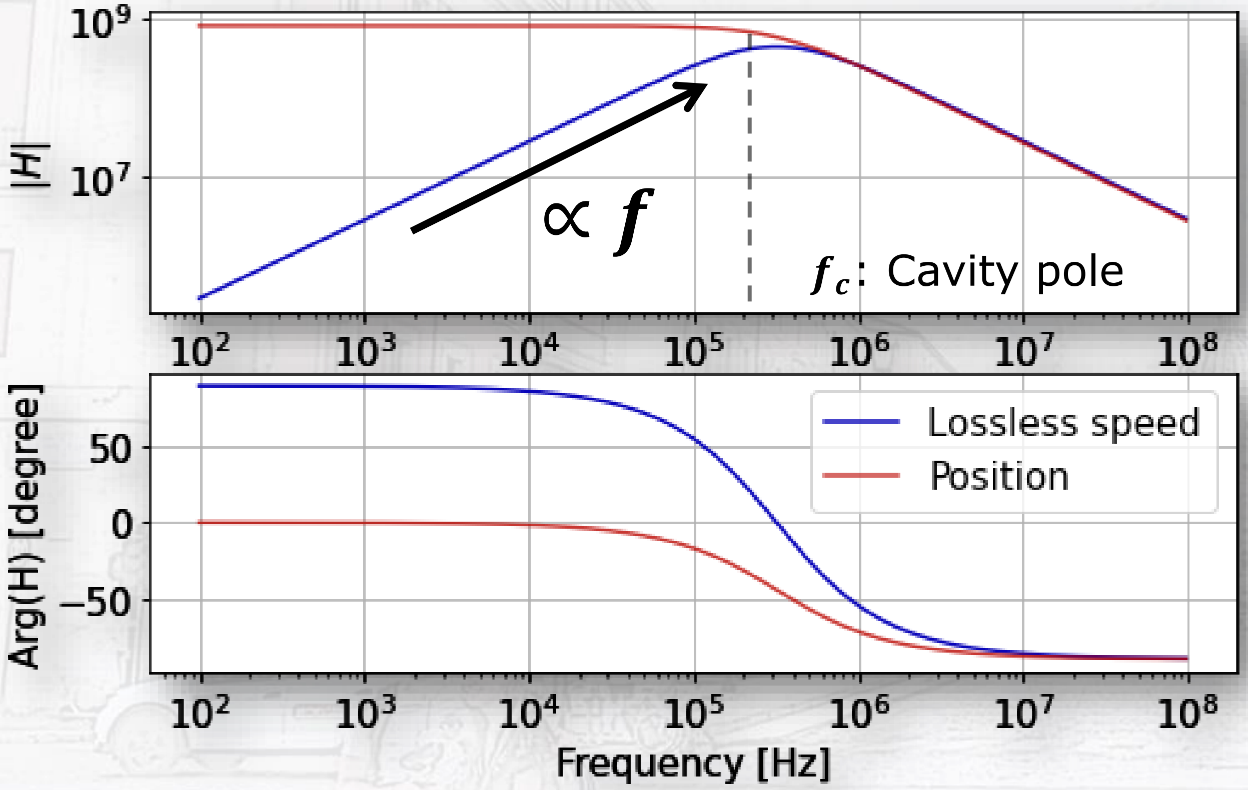
Stability?:

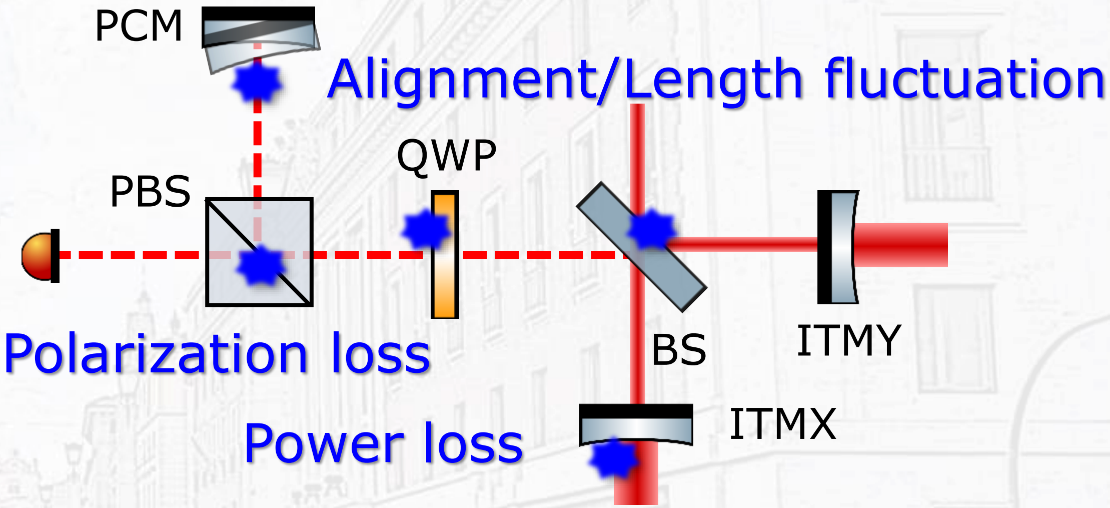
- Retardation drift
- Co-alignment of 532 & 1064 nm
- Couplings with other degrees of freedoms

Experiment

Loss effect on transfer function

There are several loss sources that narrow the f-proportional region in its transfer function





Loss-estimation formula

$$f_{\mathrm{cut}} = \frac{c}{8L\mathcal{F}}\left(\frac{\mathcal{F}\mathcal{L}_{\mathrm{arm}}}{\pi} + \mathcal{L}_{\mathrm{PCC}} + \mathcal{L}_{\mathrm{align}} + \mathcal{L}_{\mathrm{mis}} + \frac{(\delta\phi_{\mathrm{PCC}})^2}{2}\right)$$

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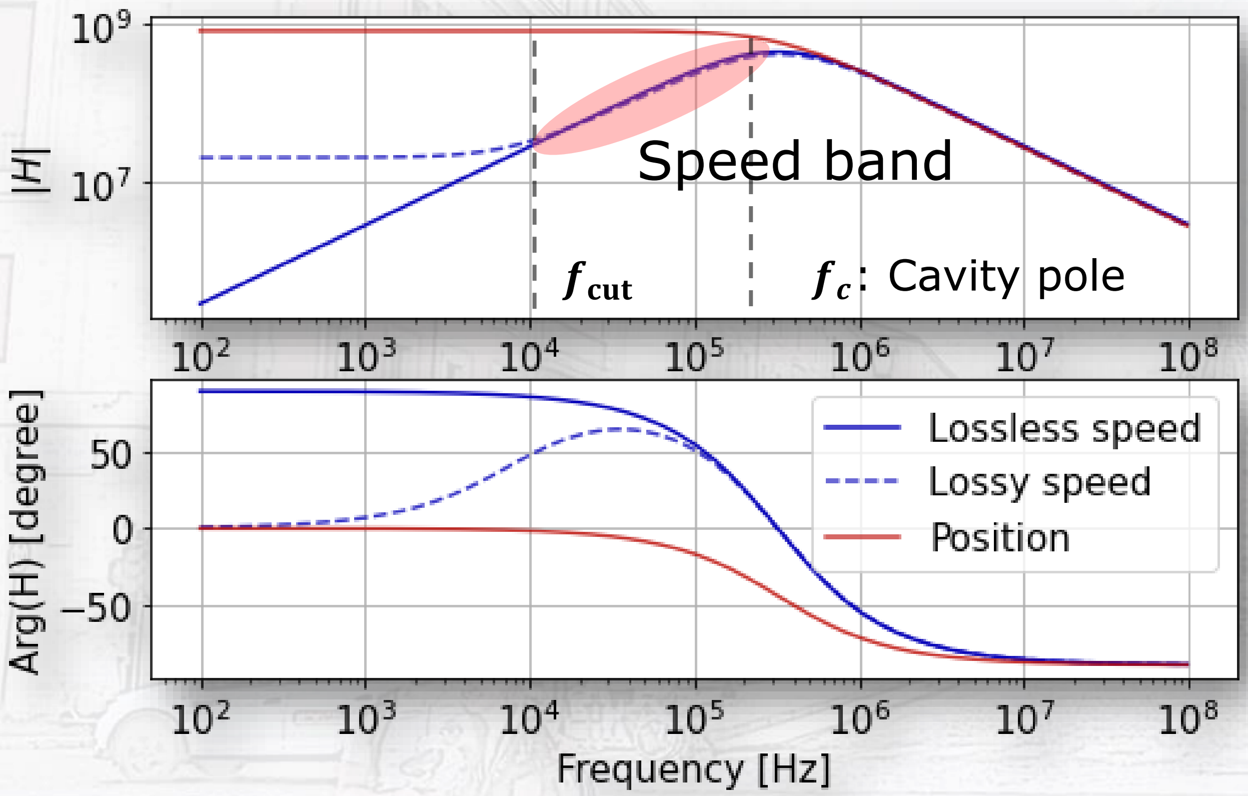

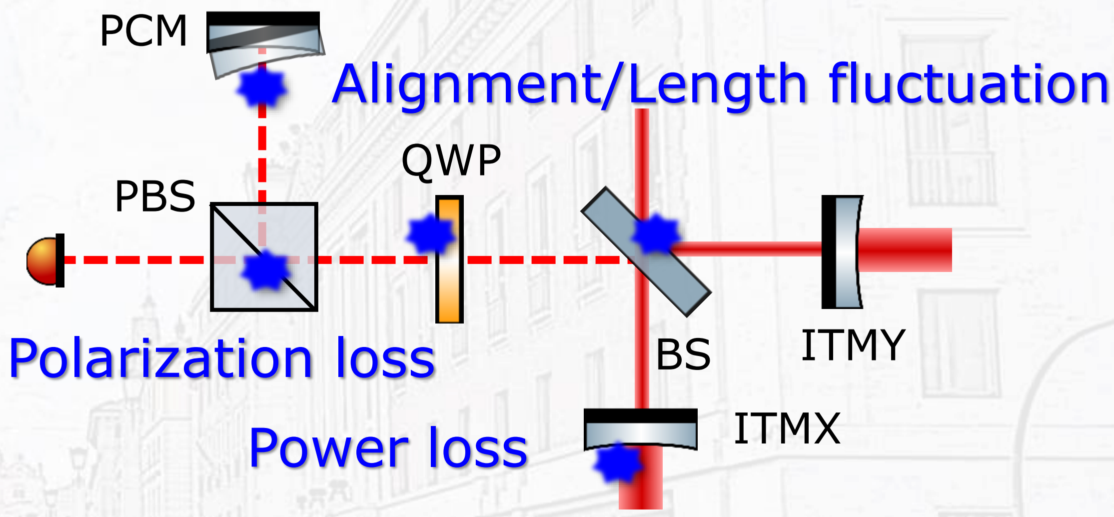

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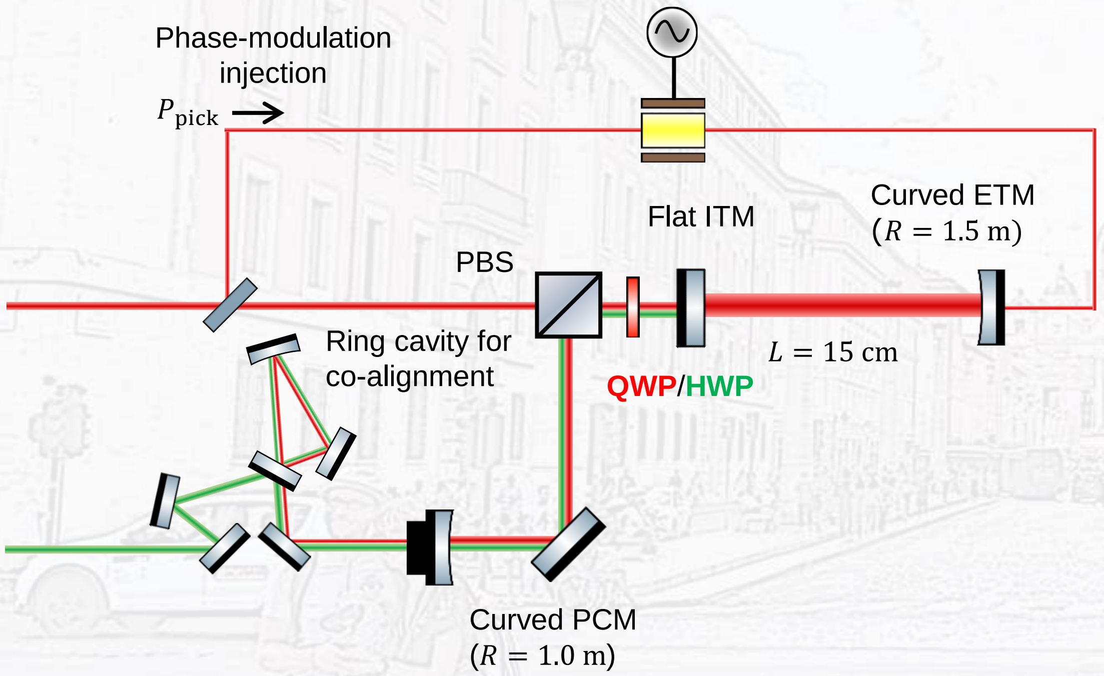
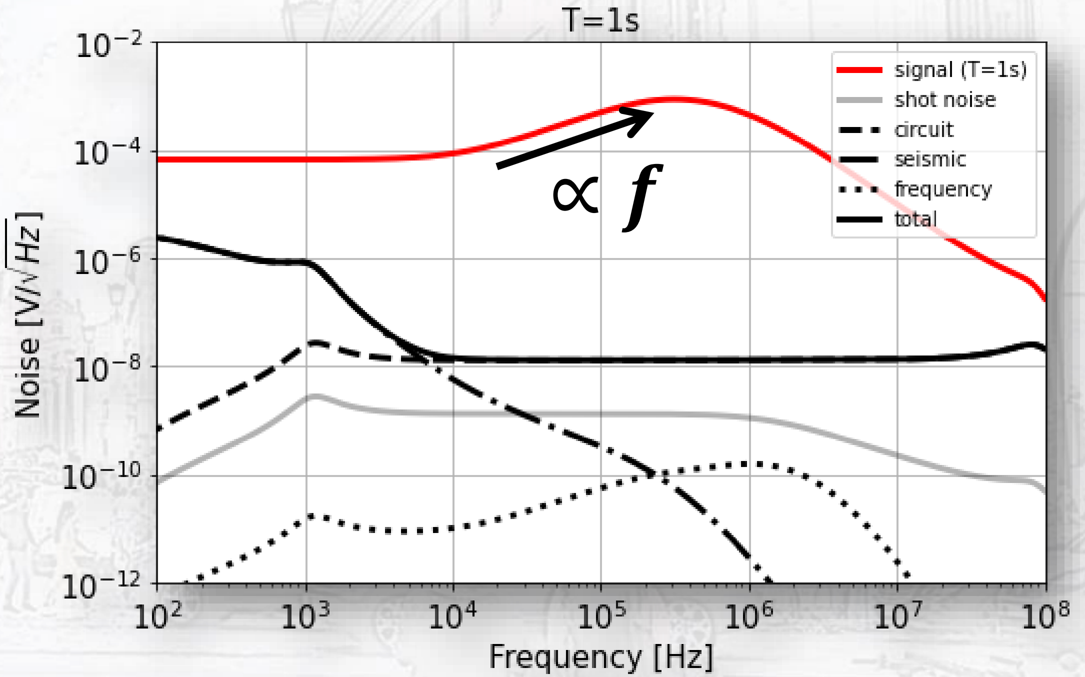
Proof of principle experiment in NAOJ

- NAOJ group has started a proof-of-principle experiment of the polarization circulation speed meter
- Our goal is to observe f-proportional region in its transfer function.
- We also try locking the polarization circulation cavity using an auxiliary green laser





Y. Nishino, *et al.*, Phys. Rev. D **107**, 084029 (2023).

Summary

- Speed meters are one of the solutions to reduce quantum radiation pressure noise
- Polarization circulation speed meter is the most possible candidate for future detectors
- We need to control the length of the polarization circulation cavity
- Proof of principle experiment is ongoing in NAOJ

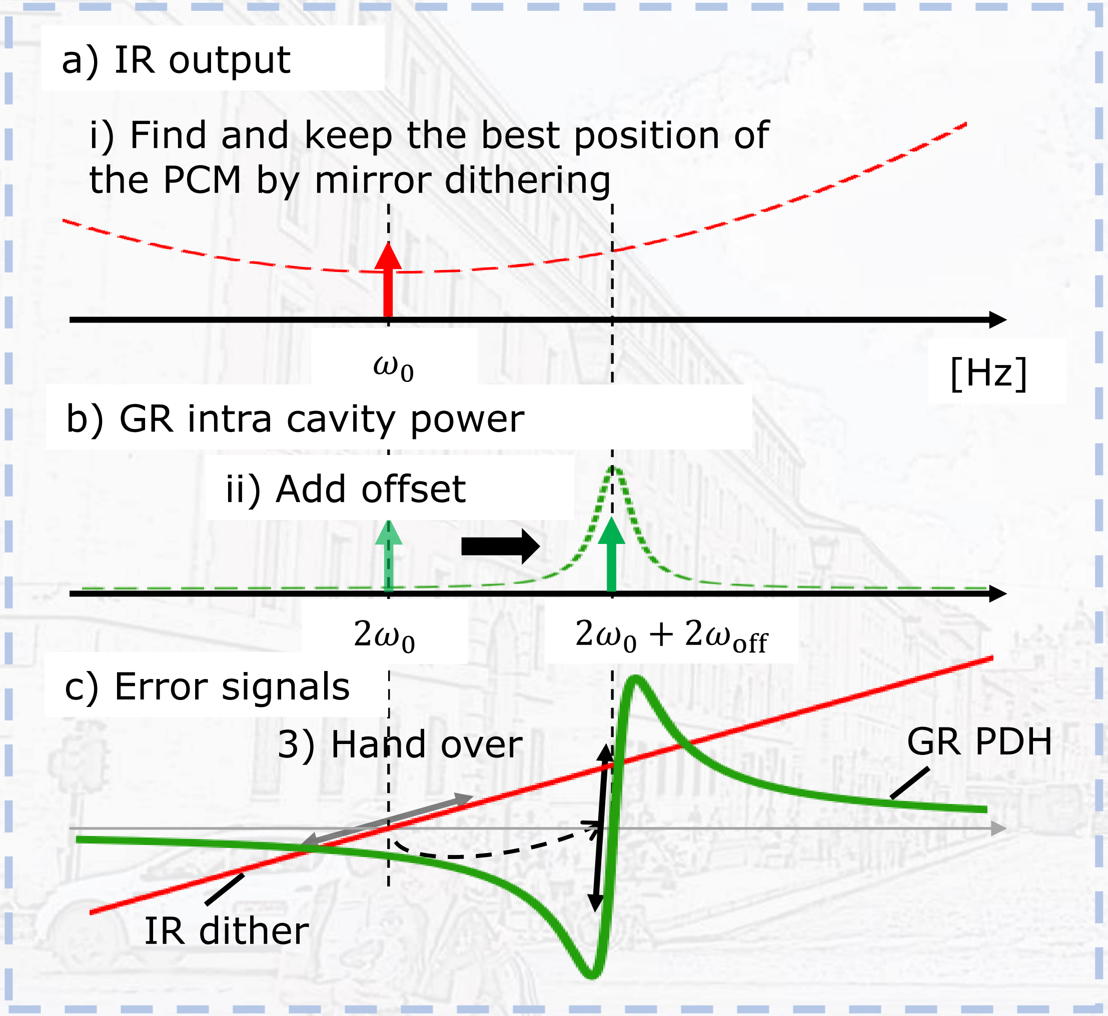
Reference:

Danilishin, S.L., Khalili, F.Y. Quantum Measurement Theory in Gravitational-Wave Detectors. *Living Rev. Relativ.* **15**, 5 (2012). https://doi.org/10.12942/lrr-2012-5

Danilishin, S.L., Knyazev, E., Voronchev, N.V. *et al.* A new quantum speed-meter interferometer: measuring speed to search for intermediate mass black holes. *Light Sci Appl* **7**, 11 (2018). https://doi.org/10.1038/s41377-018-0004-2

Yohei Nishino, Tomotada Akutsu, Yoichi Aso, and Takayuki Tomaru, Phys. Rev. D **107**, 084029 (2023) https://journals.aps.org/prd/abstract/10.1103/PhysRevD.107.084029

Lock acquisition



One should follow some steps to lock the PCC

Lock acquisition:

i. The best PCM position is where the output of the PBS transmission becomes minimum by dithering
ii. Adding the frequency offset, the GR can resonate in the PCC
iii. One can hand over the control signal to the GR PDH, which is steeper than the IR dithering

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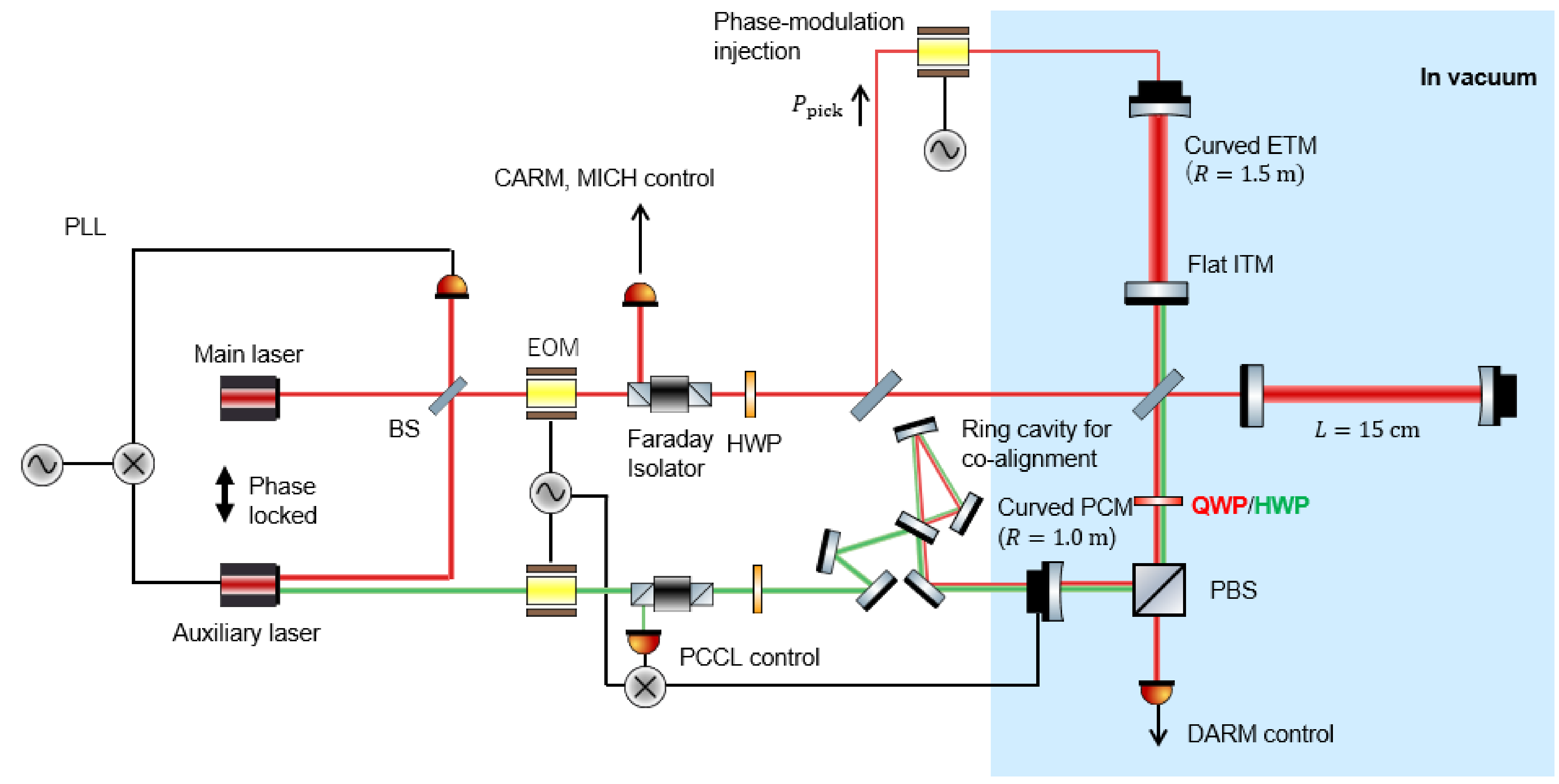
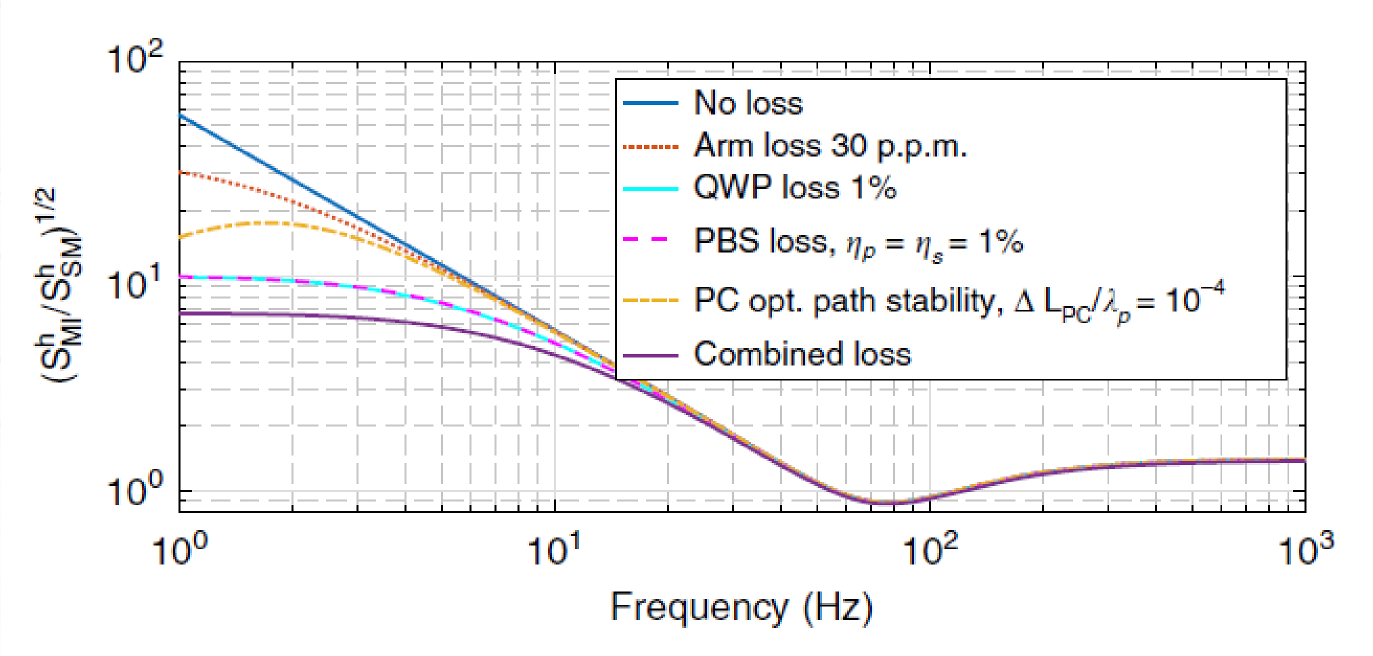
Future

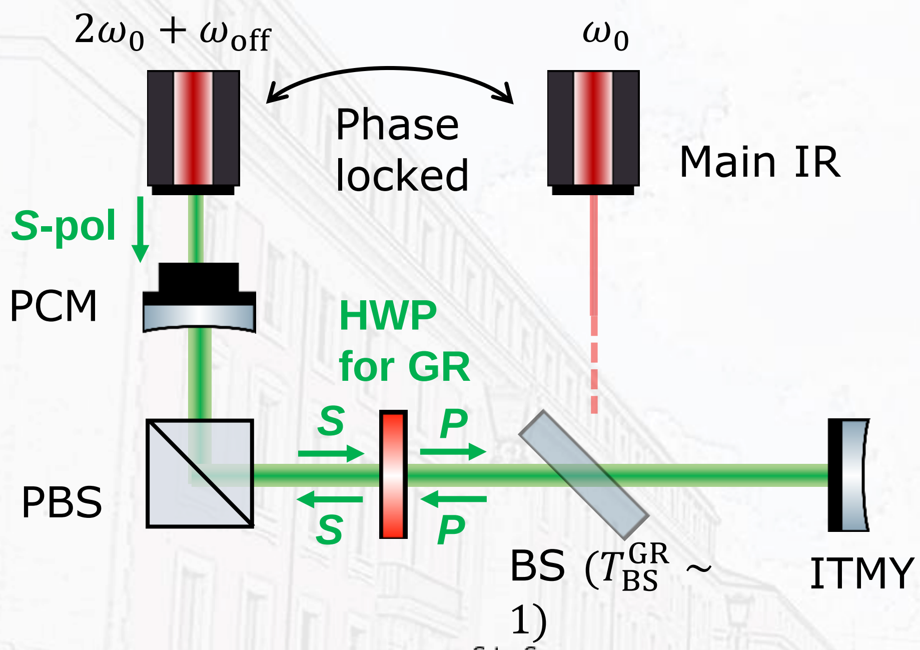


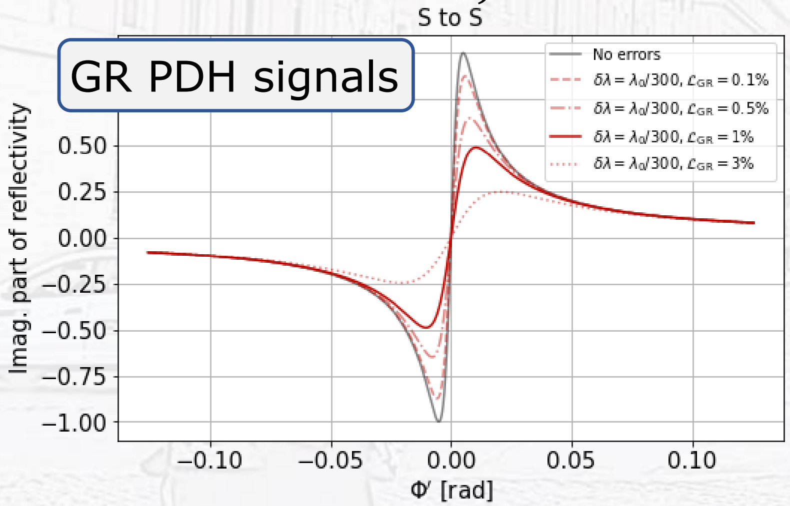
Phase-modulation injection
P_{pick}
In vacuum
Curved ETM
$(R = 1.5\ \text{m})$
CARM, MICH control
PLL
Flat ITM
Main laser
EOM
BS
Faraday Isolator
HWP
Ring cavity for co-alignment
$L = 15\ \text{cm}$
Phase locked
Curved PCM
$(R = 1.0\ \text{m})$
QWP/HWP
PBS
Auxiliary laser
PCCL control
DARM control



Danilishin, S.L., *et al.*, Light Sci Appl 7, 11 (2018).

Dual-Retardance Control



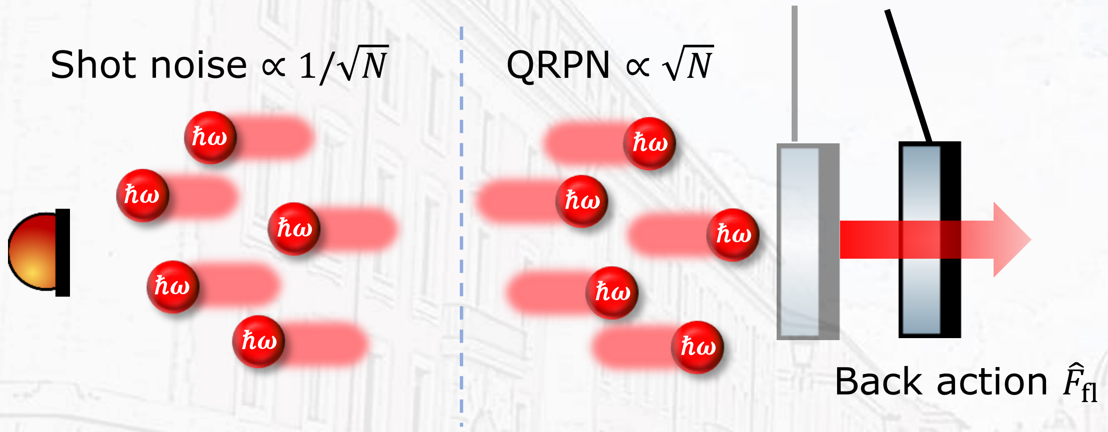


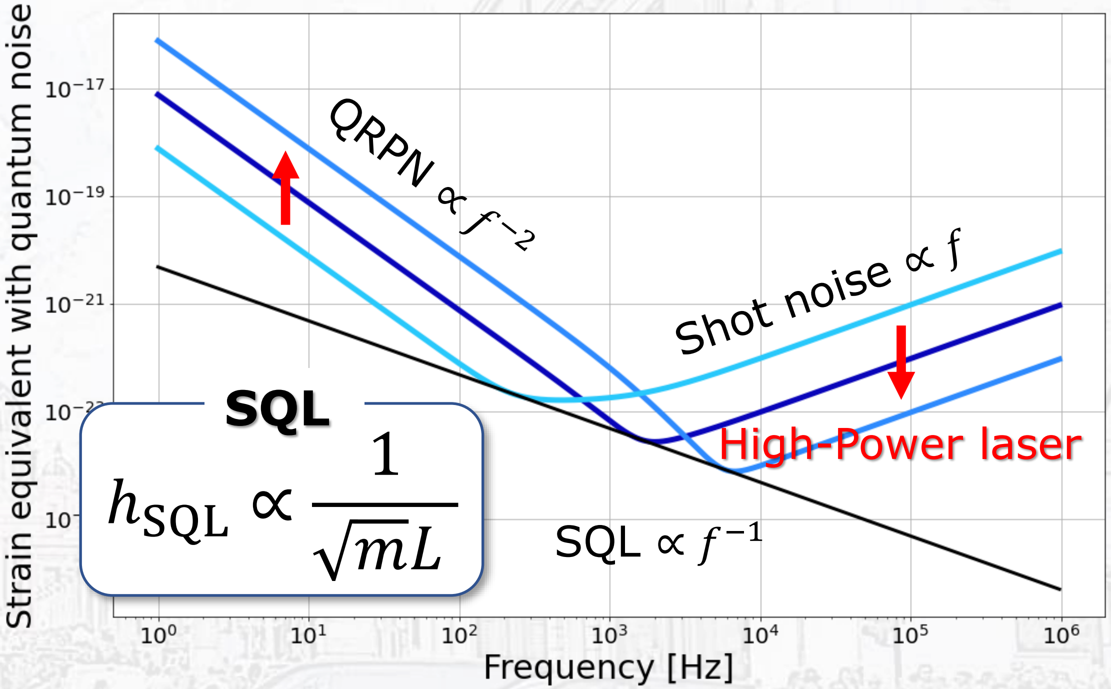
Implementation and benefits

- Implementation:
  - ✓ Use a dual-retardation waveplate and 532 nm auxiliary laser
  - ✓ The auxiliary laser is phase locked with the main 1064 nm laser and injected behind the PCM
  - ✓ 532 nm will resonate in the PCC and one can obtain the PDH signal in 532 nm
- Benefits:
  - ✓ The error signal has a high signal-to-noise ratio
  - ✓ Wave-front sensing for the alignment control can be used

Quantum noise

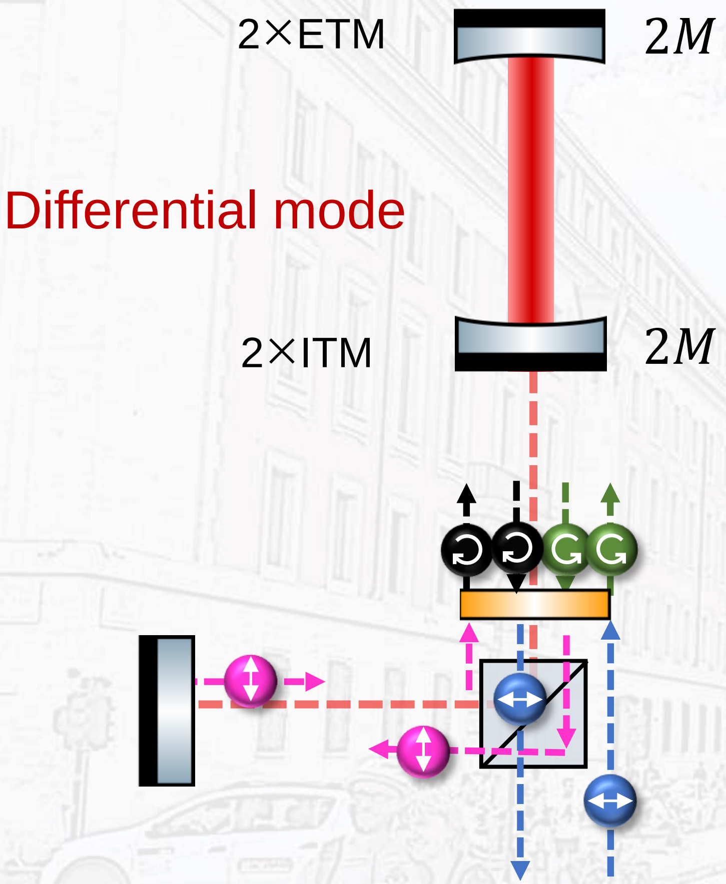
Vacuum fluctuation is a source of quantum noise, which fundamentally limits the sensitivity





- ✓ Statistical photon-number fluctuation = **Shot noise**
- ✓ Random kick by the photon-number fluctuation = **Quantum Radiation Pressure Noise (QRPN)**
- ✓ Increasing the laser power, the shot noise will be improved, but the QRPN will be worsen.
- ✓ Trade off between these noises: **S**tandard **Q**uantum **L**imit (**SQL**)

Back action evasion



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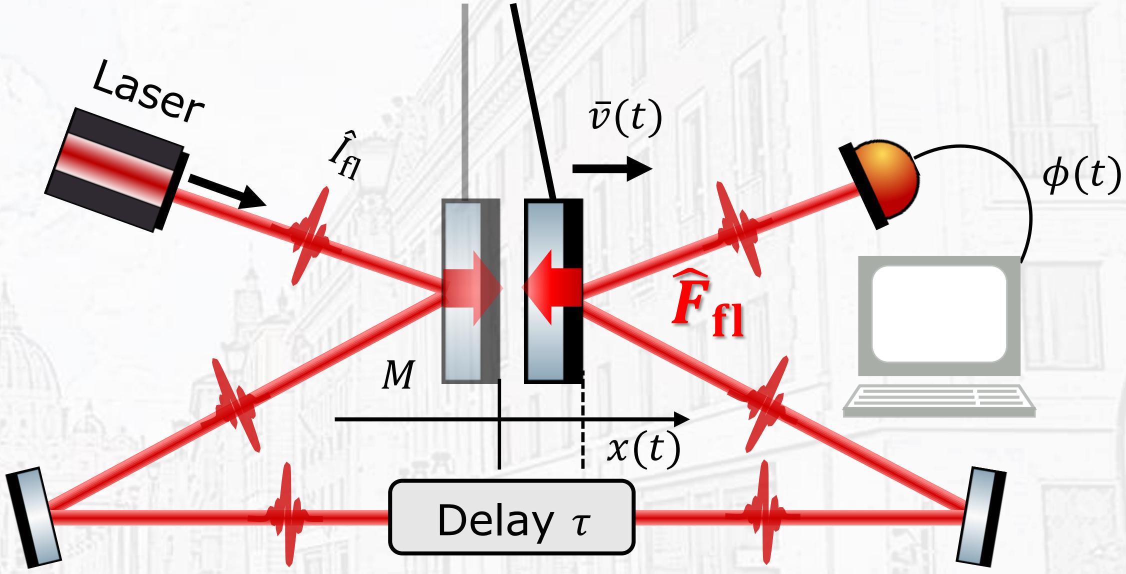

$p \to l \to s \to r \to p$