A one more extravagant way to build a speed meter (and not only that...) ☺!

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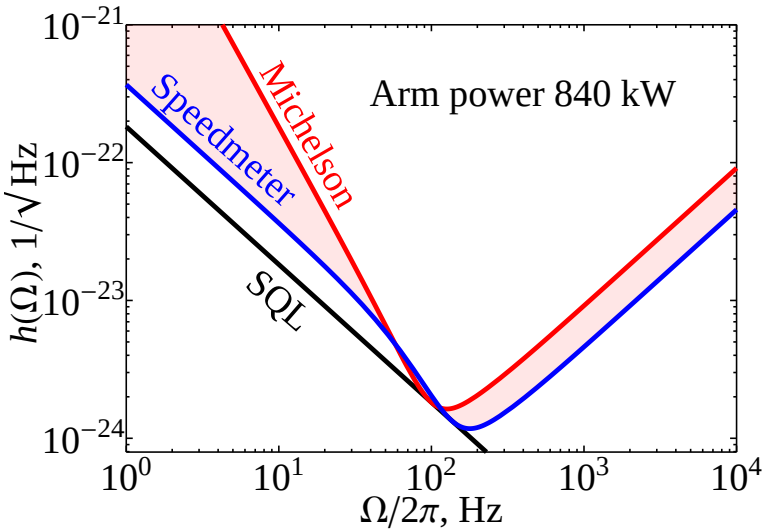
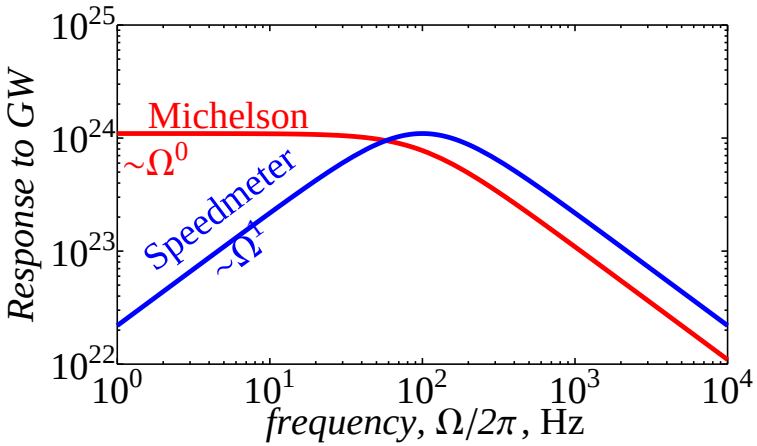
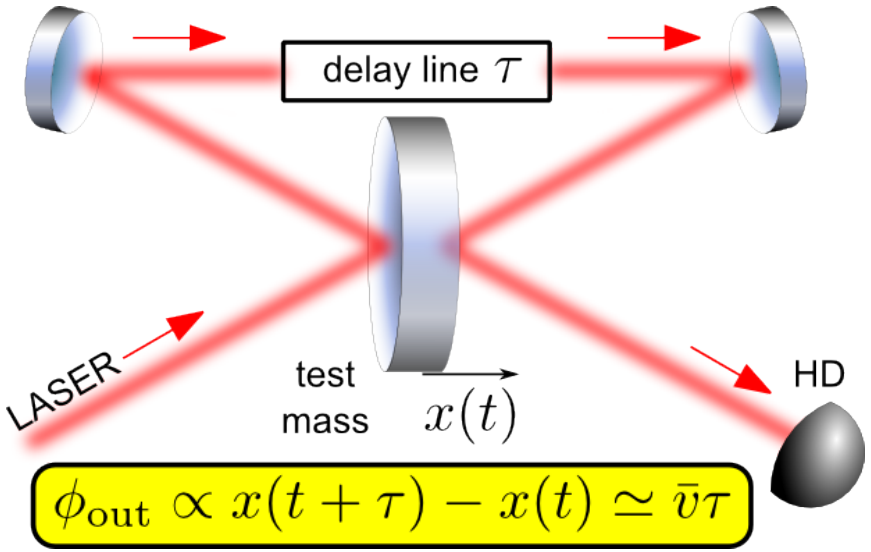
[2]Faculty of Physics, M.V. Lomonosov Moscow State University

LIGO-G1601220
GWADW meeting on Elba, 27 May, 2016

Why speed meter is better than position meter?







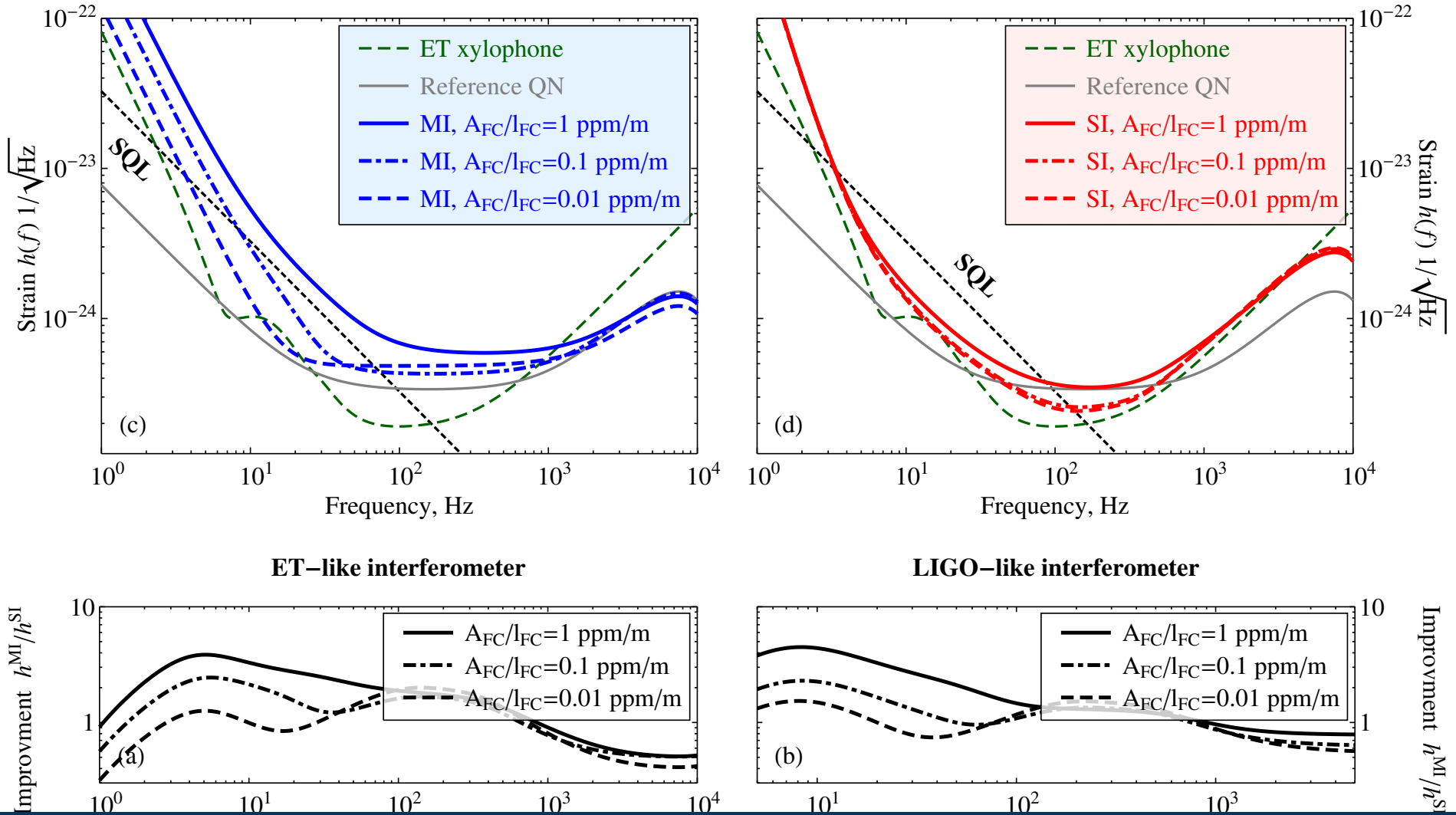
- Back- action reduction: RP force of two reflections cancel each other, but with delay τ:

$$\hat{F}_{\rm b.a.}(\Omega) \simeq -i\Omega\tau \frac{2\bar{P}_{\rm pulse}}{c},$$

- The benefit: Much better QN sensitivity at low frequencies than Michelson;
- The price to pay: Response of speed meter wanes linearly with frequency as it goes to DC.

Carthago delenda est!

SMs relax loss requirements to filters for FD squeezing by an order of magnitude vs. MI!



Main concerns about speed meters as the next GW detectors

If speed meters are so great, why are we not building one yet?

1. Lack of experience and detailed knowledge (additional noise/imperfections/asymmetries specific for SM) ⇒ prototyping@Glasgow is under way:
   - 1-metre Proof-of-Principle Sagnac speed meter (well underway);
   - 10-metre polarisation Sagnac speed meter (single arm cavity under construction. Aim for full 10m prototype by 2019)
2. Original proposals required radical changes to the core infrastructure/layout/optics ⇒ new SM configurations seem to be simpler!
3. High interest to SMs led to multiple topologies being proposed, each with its own strengths/open questions.

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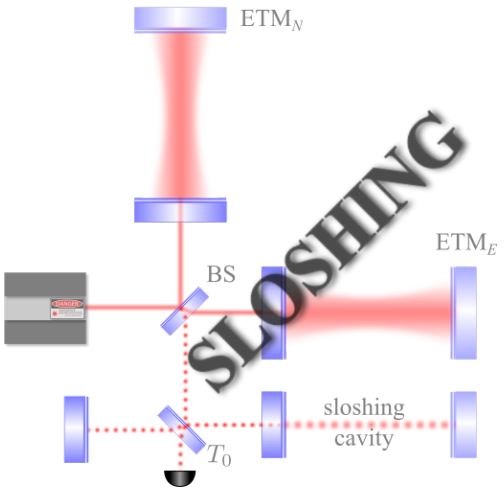
There are 2 distinct speed meters drawn below. How many do you see ☺?



Braginsky *et al.* Phys. Rev. D **61**, 4002 (2000)
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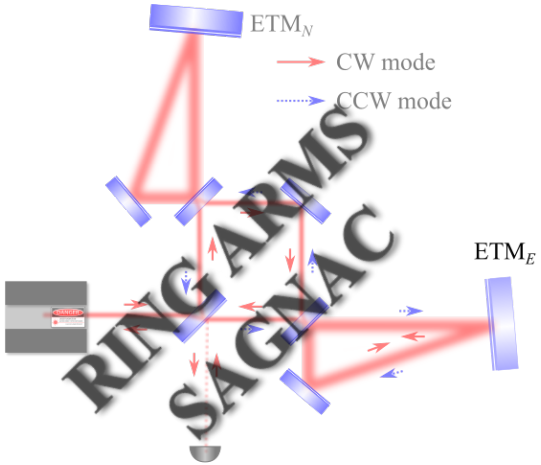

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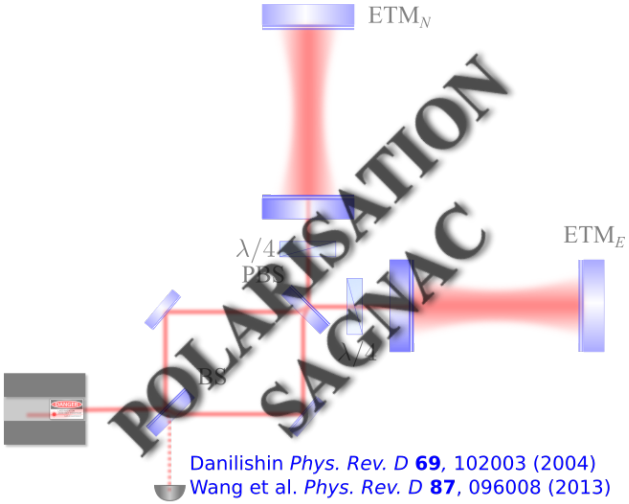

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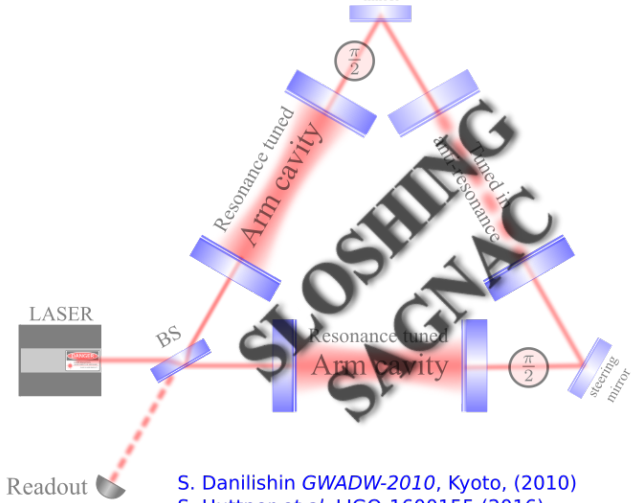
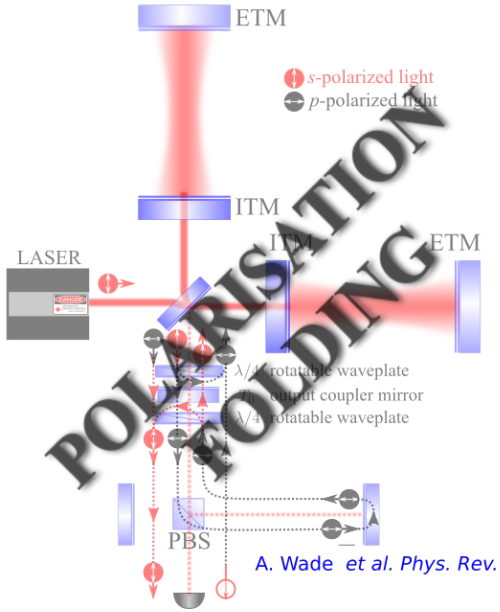


S. Danilishin *GWADW-2010*, Kyoto, (2010)
S. Huttner *et al.* LIGO-1600155 (2016)



A. Wade *et al. Phys. Rev. D* **86**, 062001 (2012)

Time to tidy up and systematise

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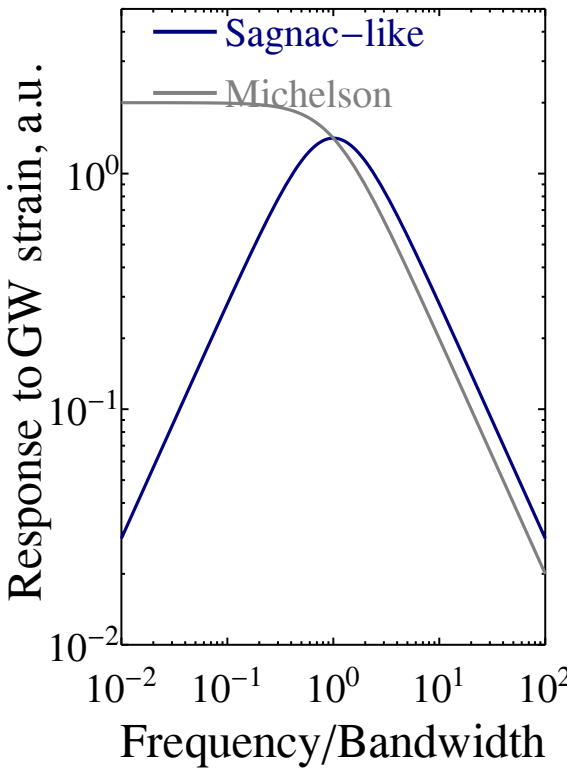
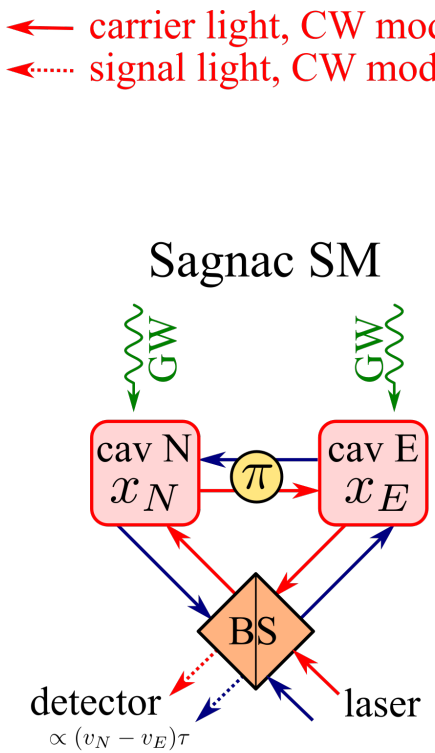
Taxonomy of speed meters

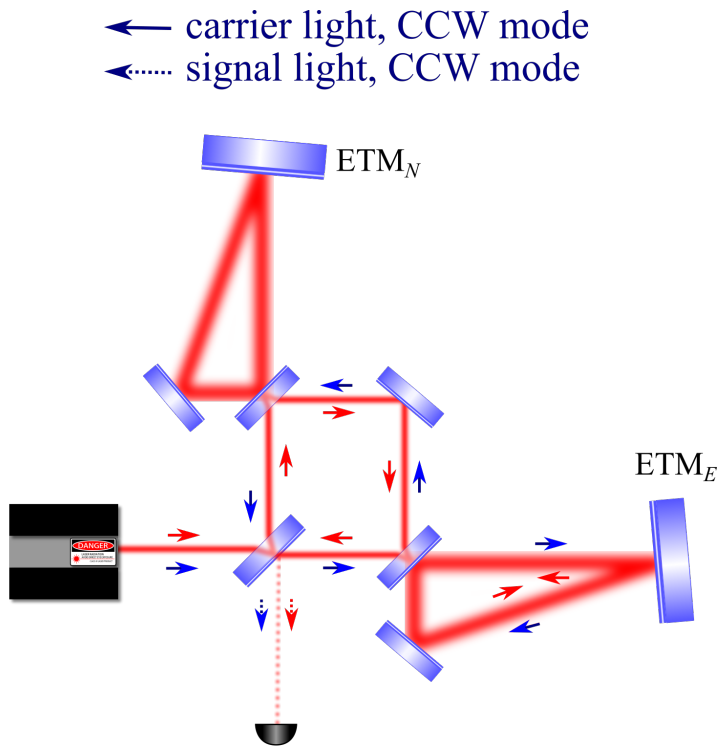
There are only 2 distinct species of speed meter:

No matter how different they look, response/QN of all speed meters has 2 distinct shapes:

1. Sagnac-like: carrier and signal sidebands share the same optical path;
2. Sloshing SM-like: signal sidebands' path deviates from the carrier's one;







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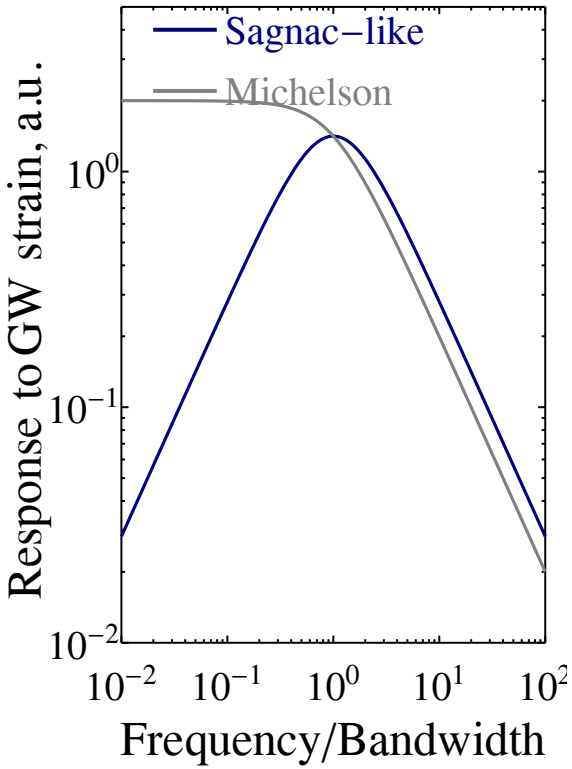

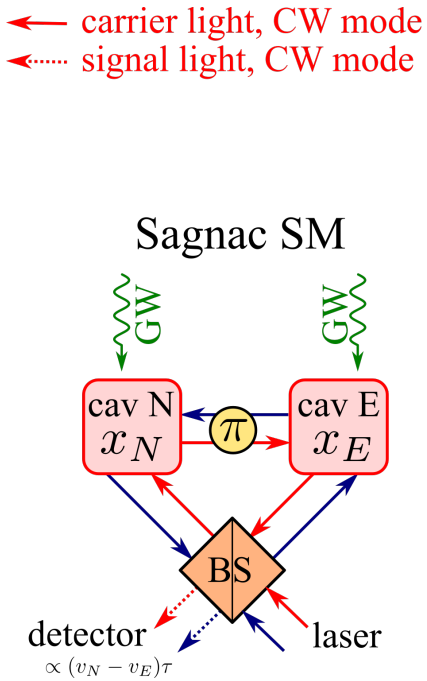

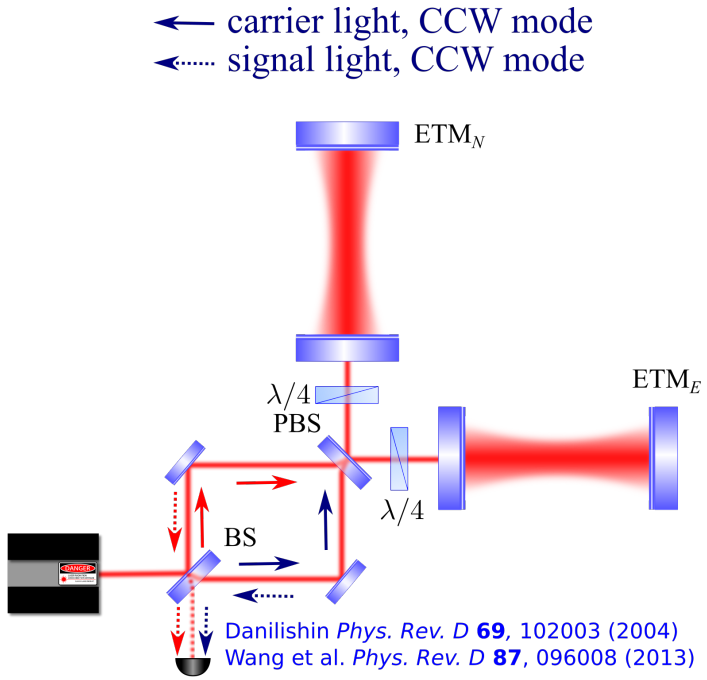

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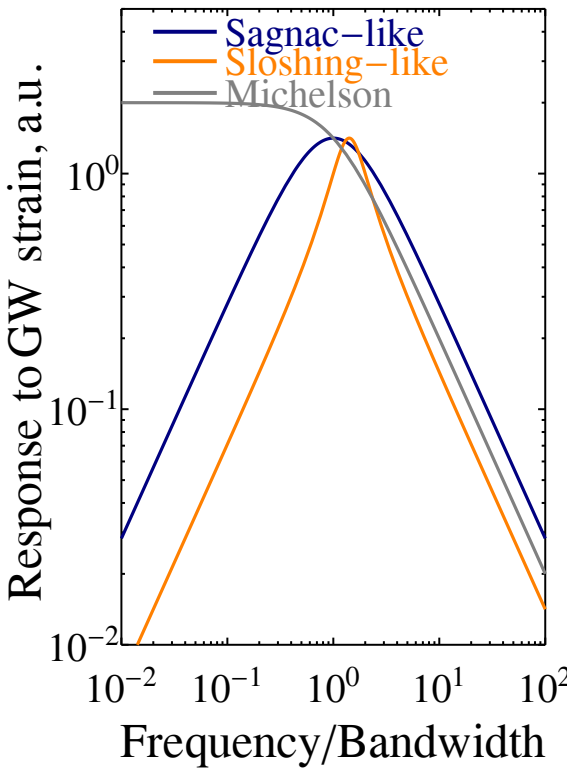

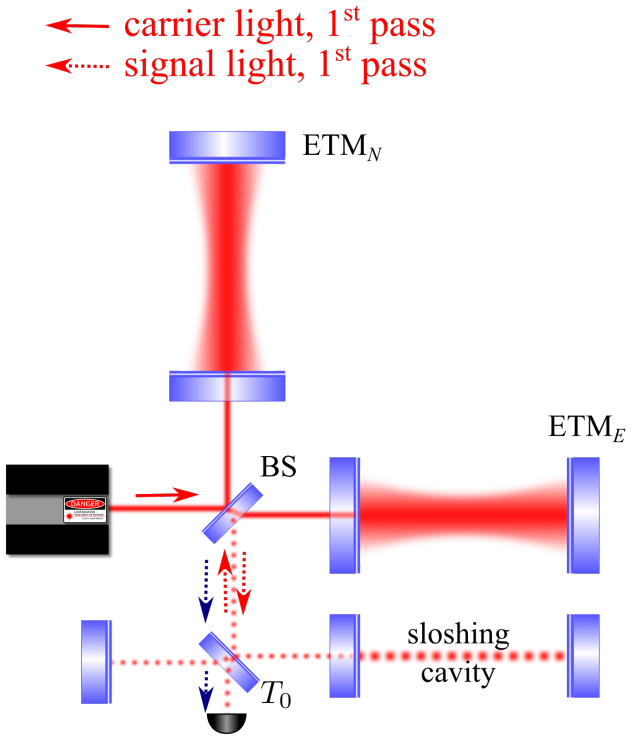

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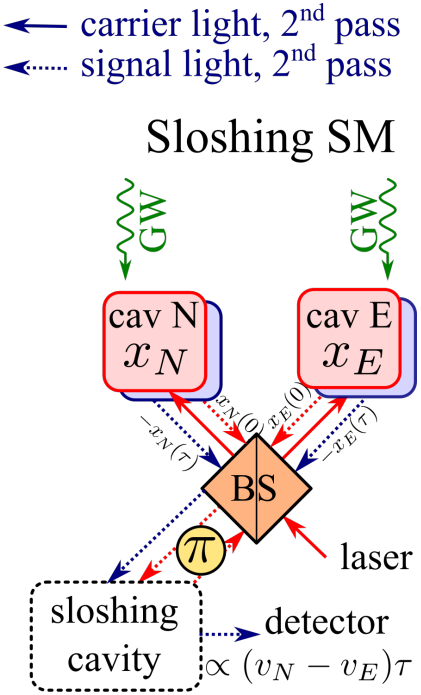
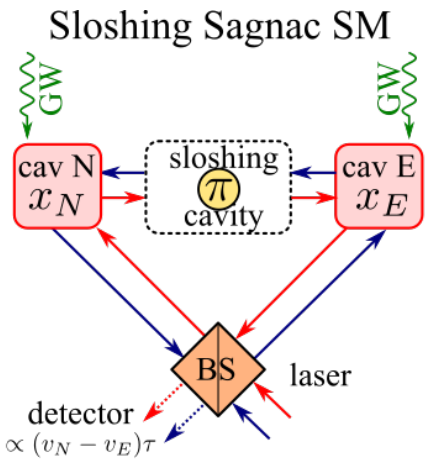
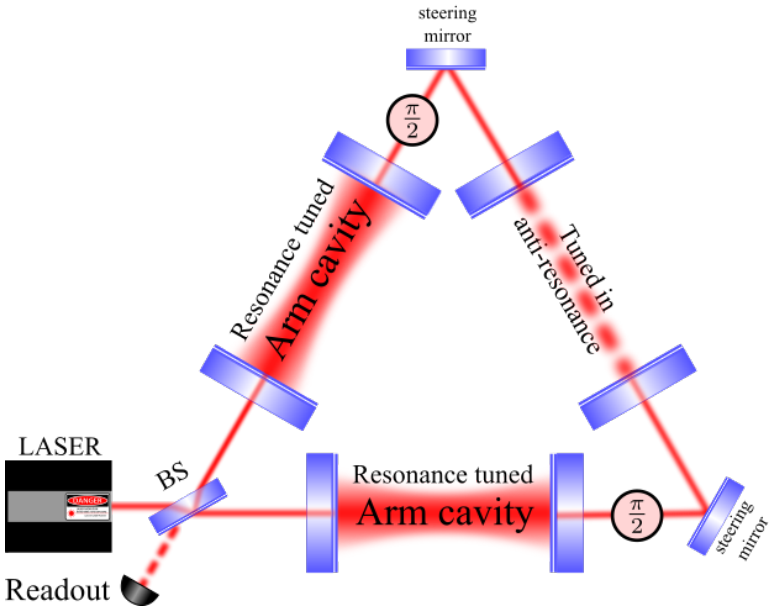


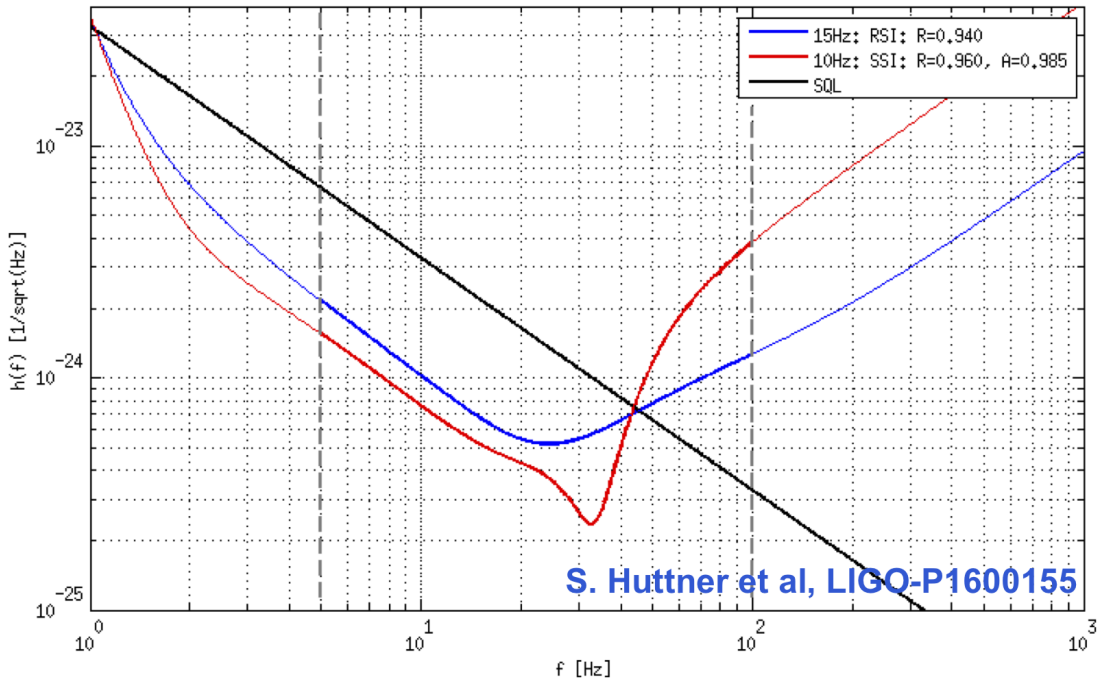
Sloshing Sagnac Speed Meter





Sloshing Sagnac ≡ Sloshing Speed Meter

1. Sloshing cavity (AR-tuned) between the arms;
2. Linear cavities & fits the ET layout;
3. Reduced ETM reflectivity ⇒ 2.2 times lower coating TN.



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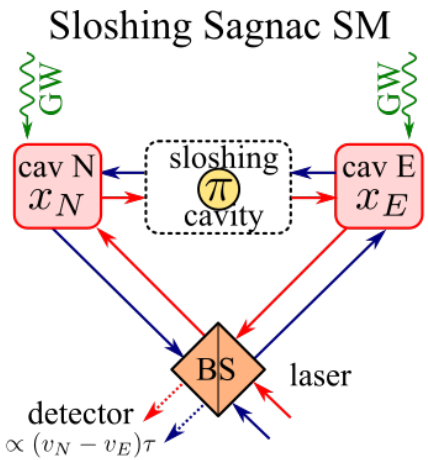

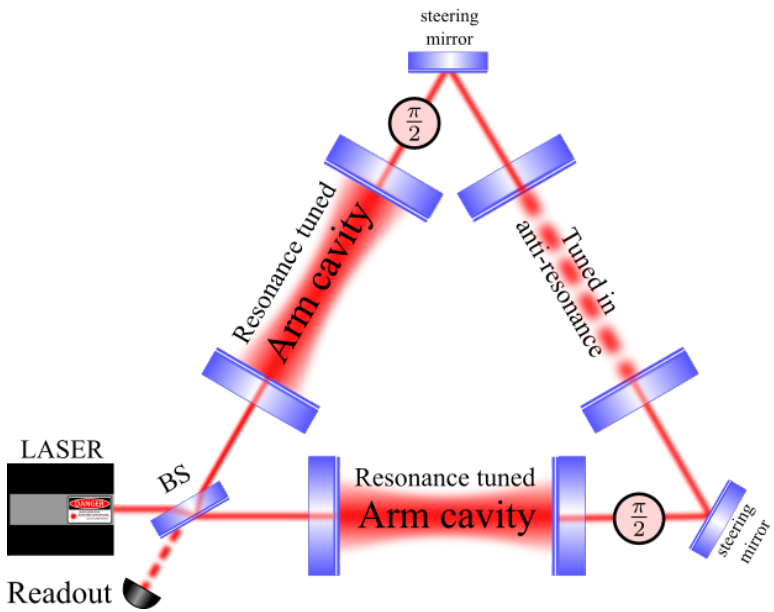

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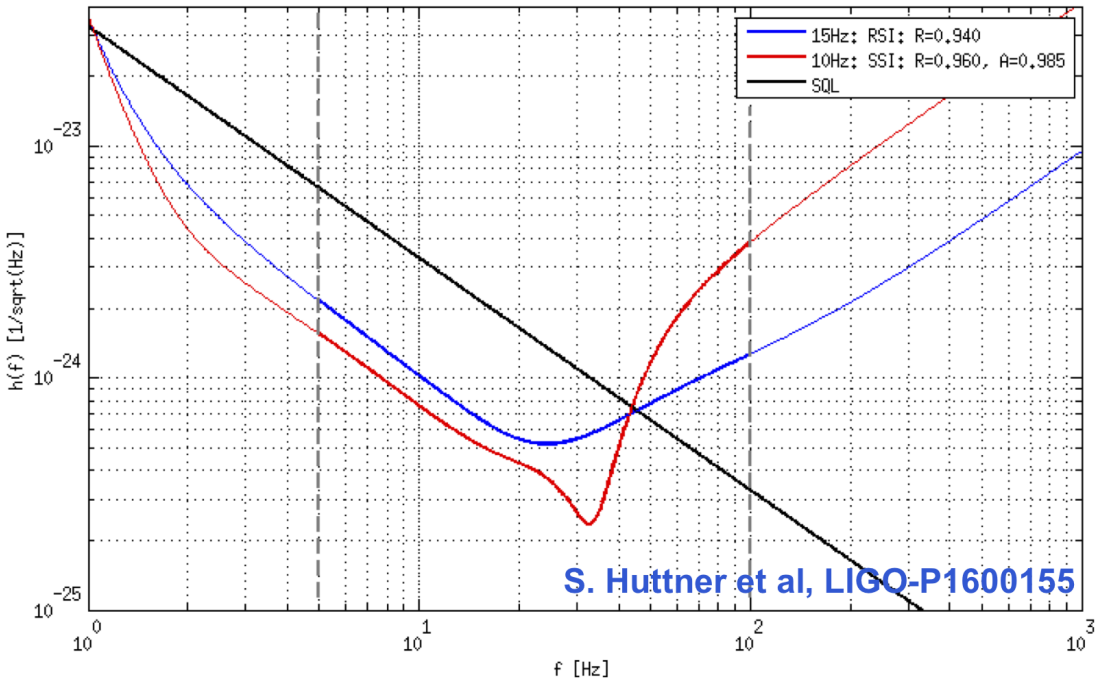

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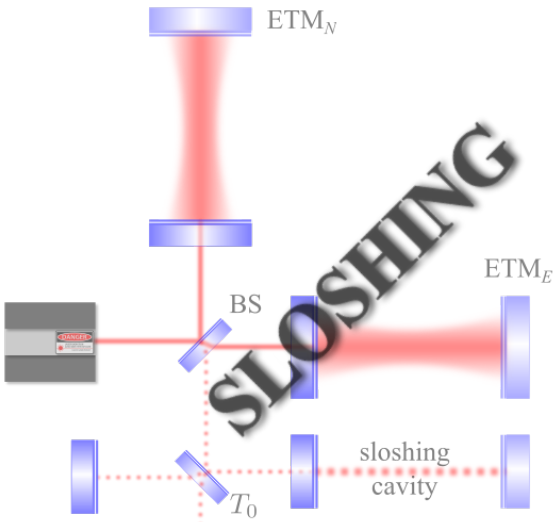

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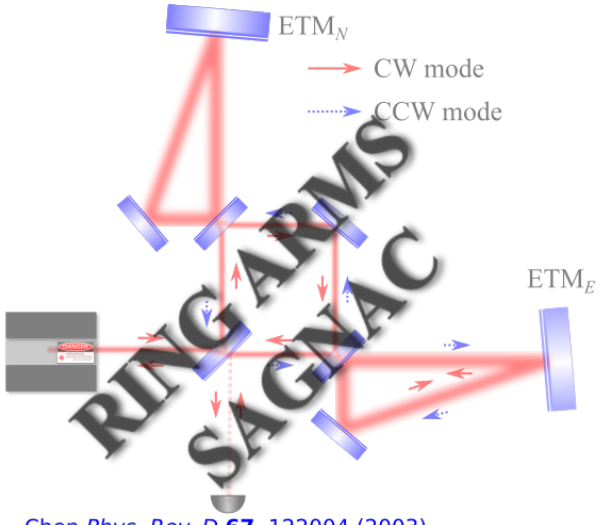

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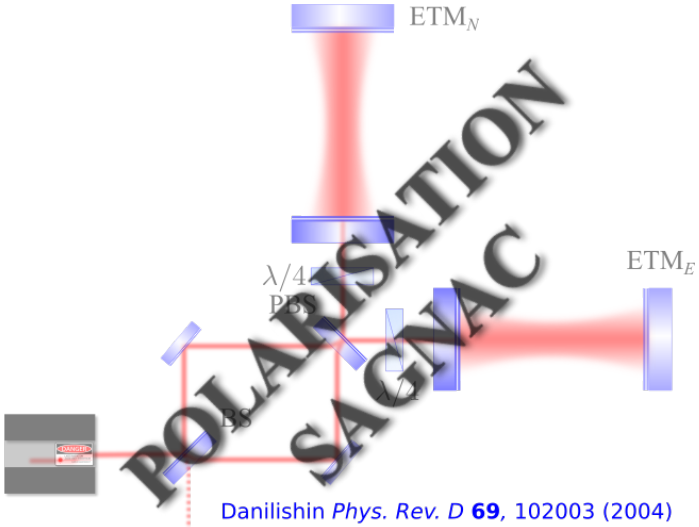

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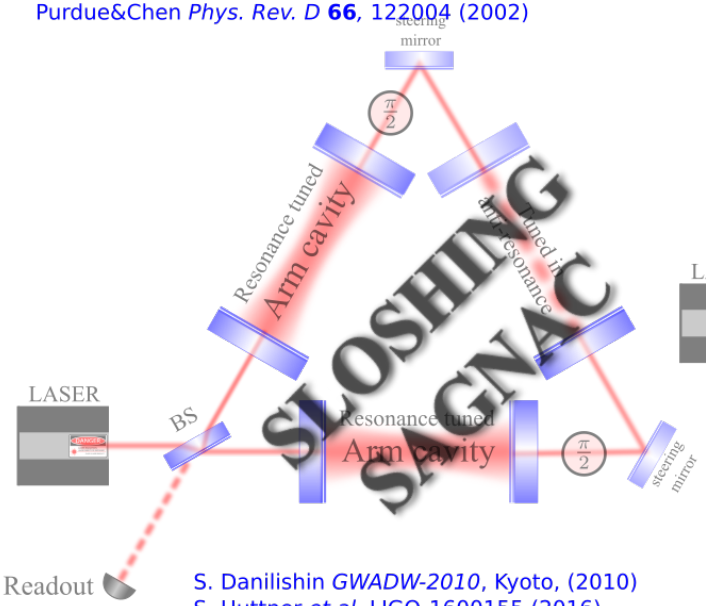

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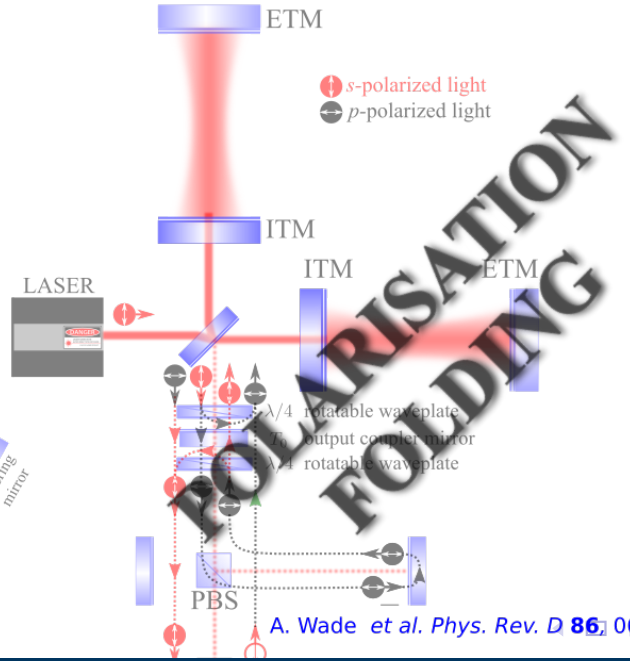

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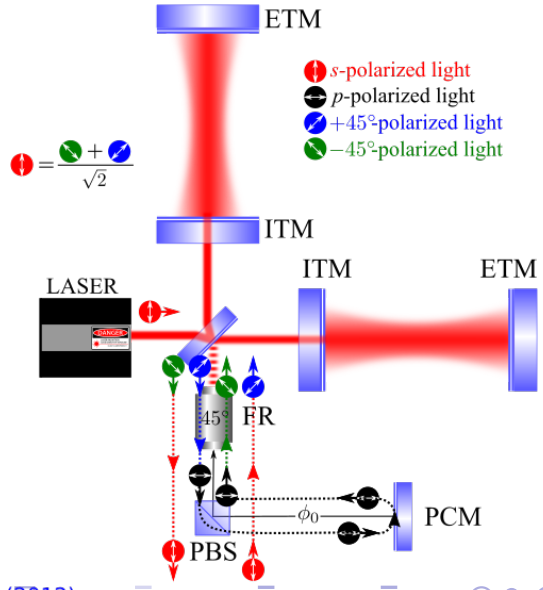
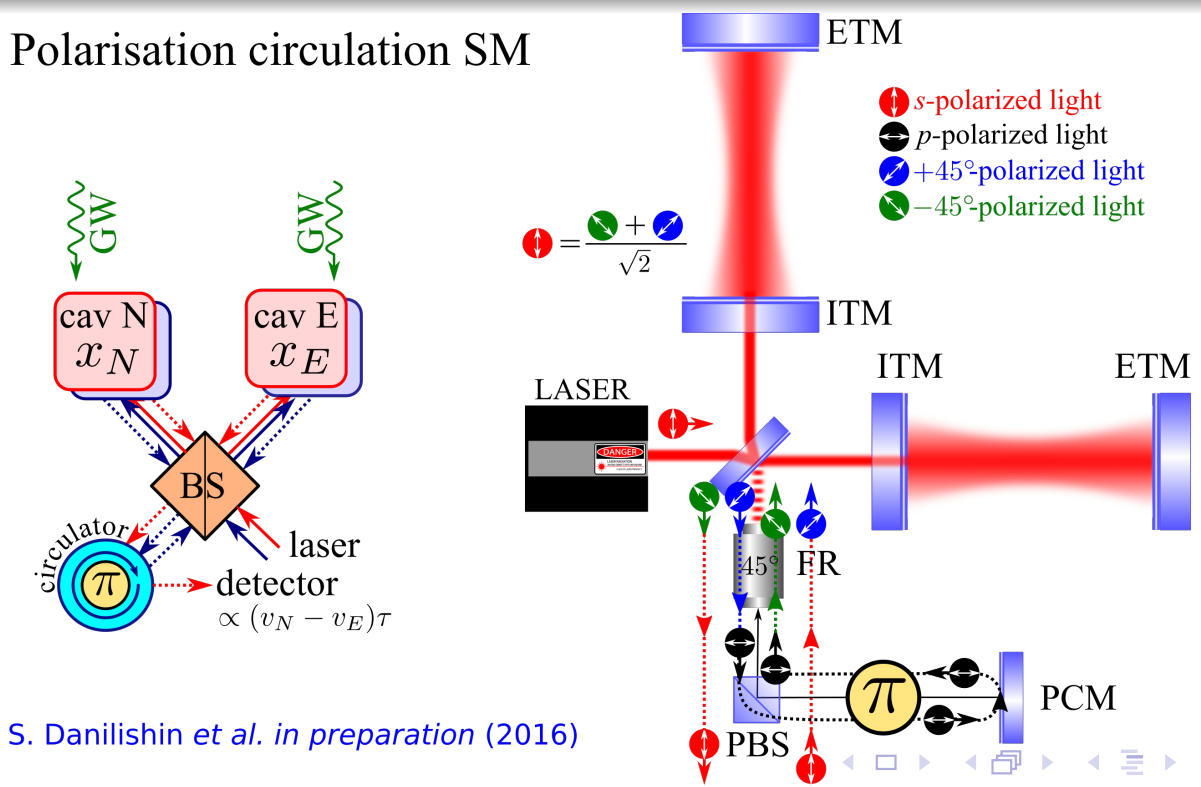


S. Danilishin *et al. in preparation* (2016)

Polarisation Circulation Speed Meter

How it works?

- Separates light, visiting IFO for the 1st time from that, visiting for the 2nd one;
- Use FR, PBS and HR-mirror to make a Polarisation Modes Circulator (PMC);
- PMC rotates signal polarisation by 90°, adds π phase shift and resends it back to IFO;
- Effectively, it is a Sagnac speed meter $\Rightarrow$ $\pm 45°$ polarisation modes are akin to CW and CCW propagating beams in the conventional Sagnac;



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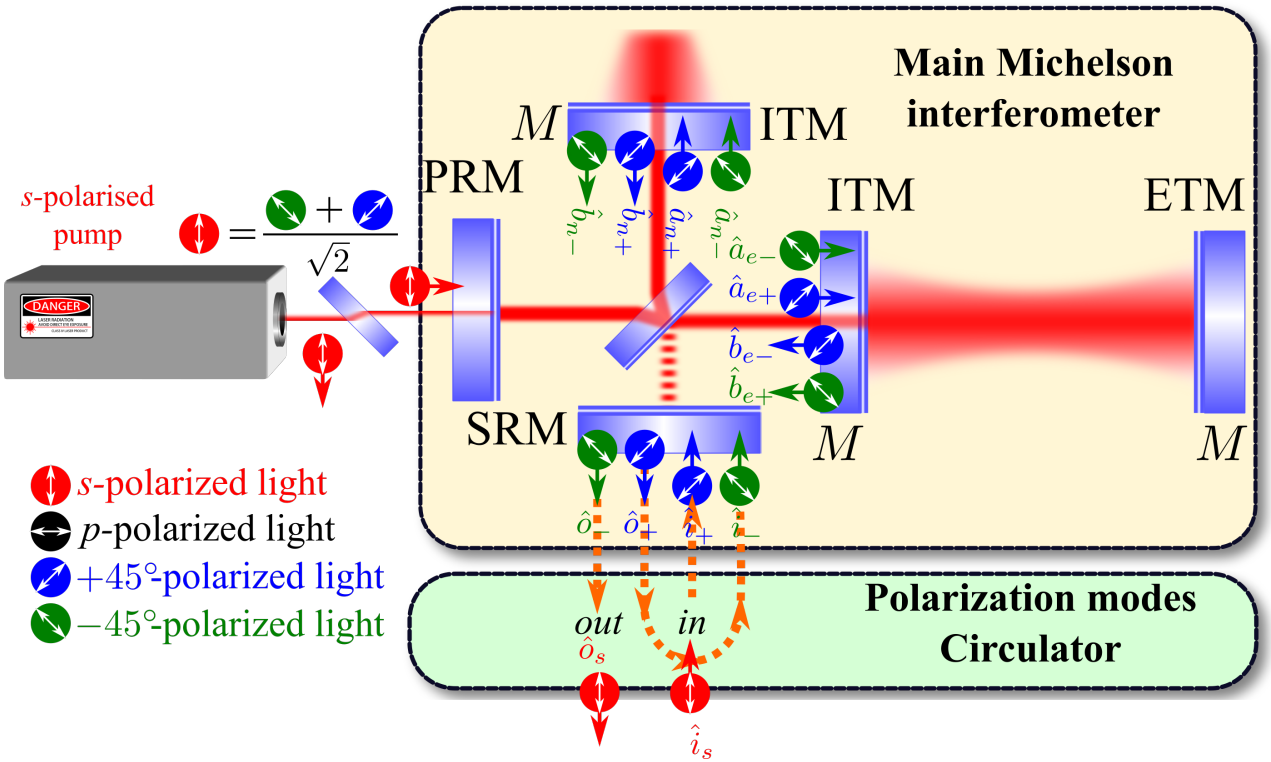
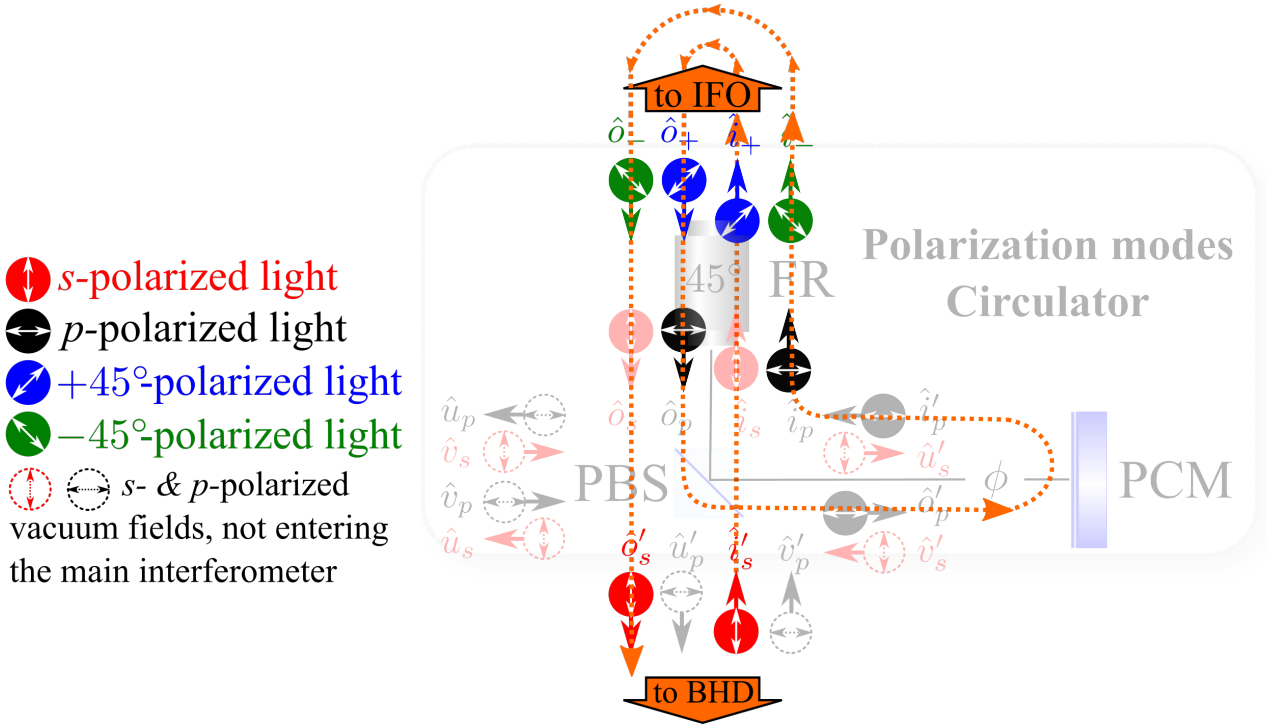


Propagation and interaction of polarisation modes with the IFO:

1. Signal is now contained in 2 orthogonal polarisation differential modes, ±45°, and each is coupled to ist own part of carrier field from the common mode;
2. Readout is performed for the *s*-polarised light, that contains velocity information (after two consecutive interactions with the main IFO).

Polarisation Circulation Speed Meter (lossless)



Polarisation Modes Circulator

- Circulator design is based on Faraday rotator, Polarisation Beam Splitter and a high-reflectivity mirror. As simple as that!
- Polarisation optics has imperfections ⇒ a variety of loss-associated vacuum fields & cross-talk between polarisation modes has to be taken into account.

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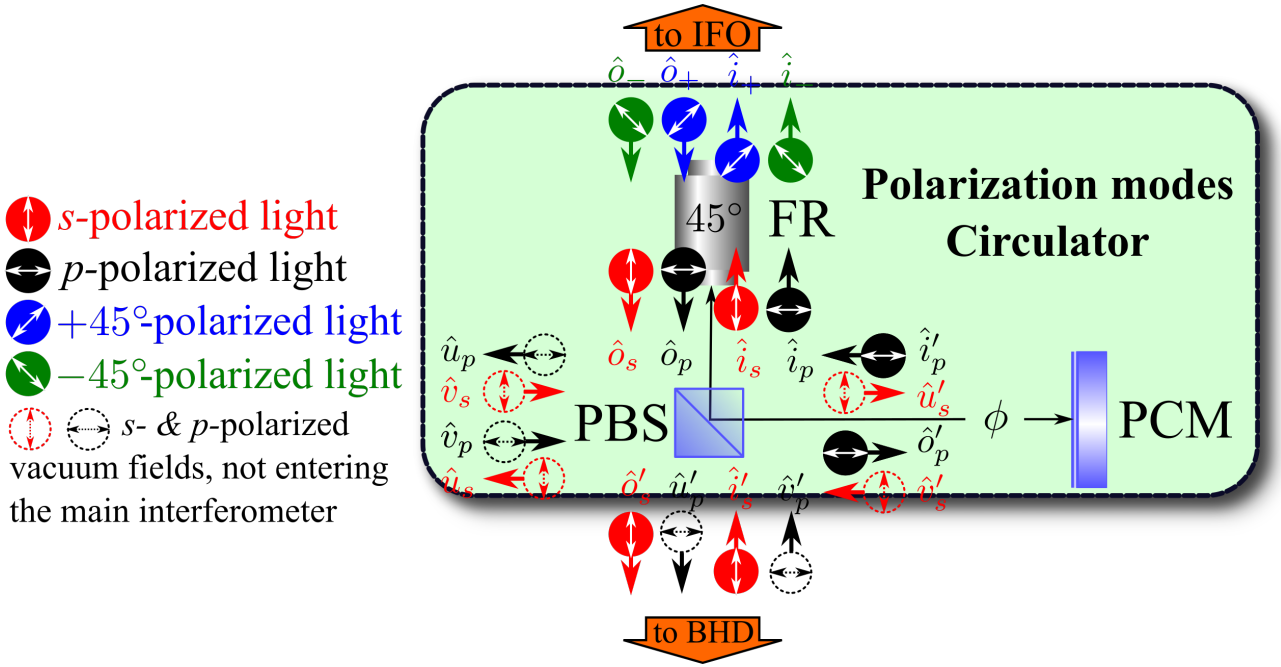

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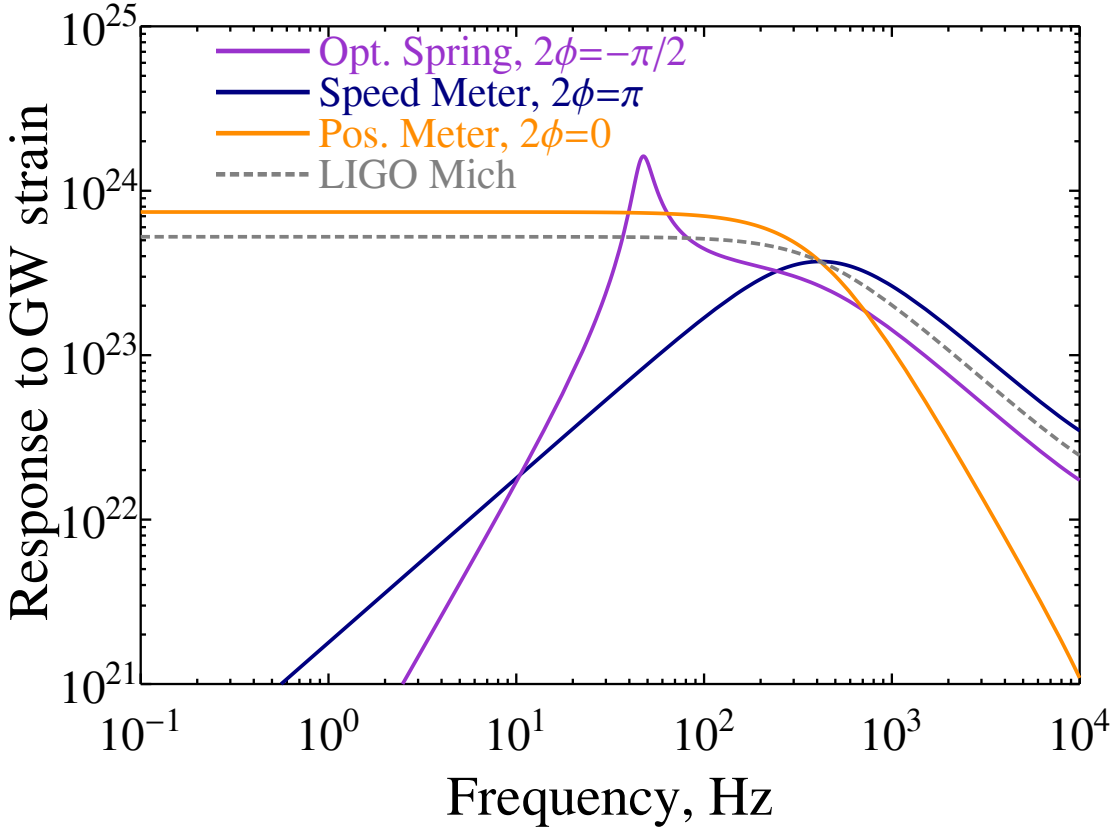
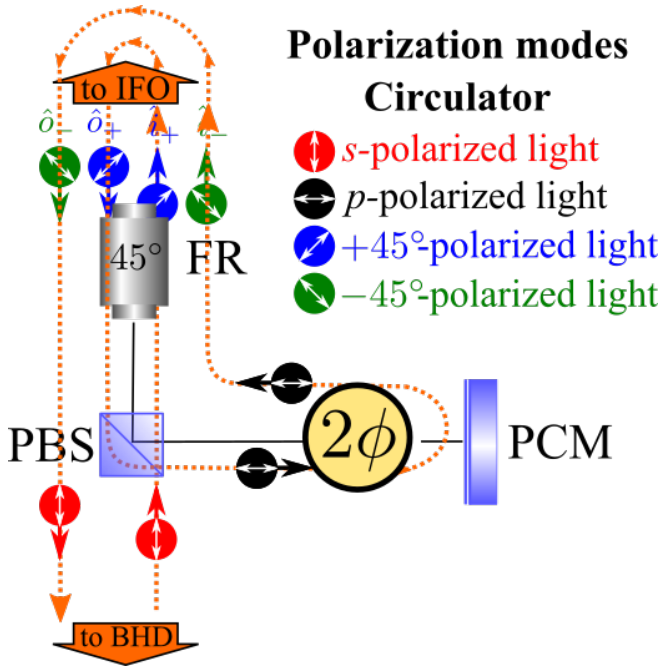
More than a speed meter.

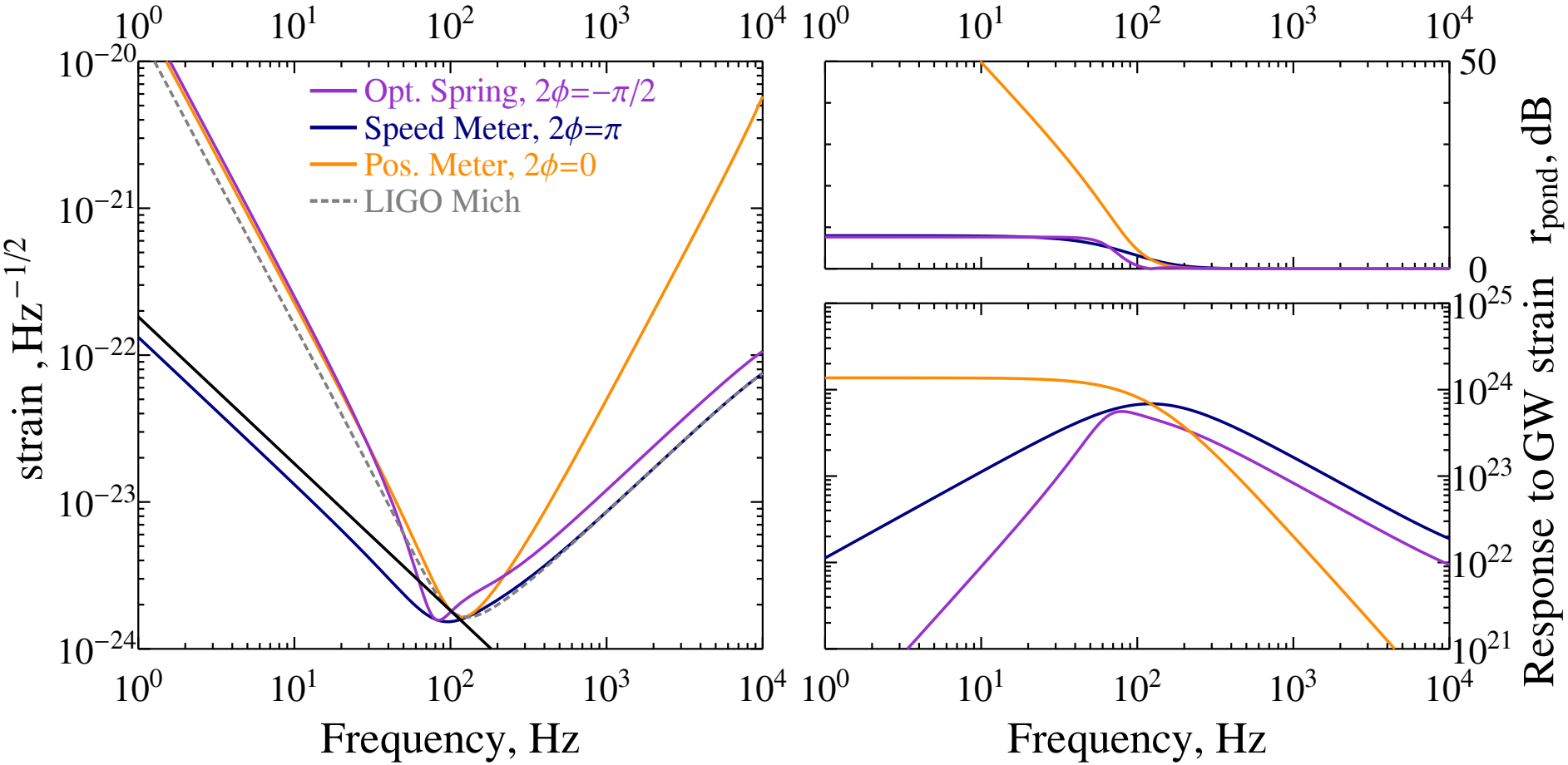




It is more than a speed meter!

Varying round-trip phase shift, 2ϕ, between the polarisation modes one sweeps continuously from Position Meter@$2\phi = 0$ to Speed Meter@$2\phi = \pi$) through detuned configurations with optical spring (Work in progress by E. Knyazev from MSU)

Quantum noise of the new beast in the zoo



Parameters (non-optimal): $P_{circ} = 0.8$ MW, $T_{\mathrm{ITM}}^{eff} = 0.04$, no squeezing, no loss, aLIGO parameters.

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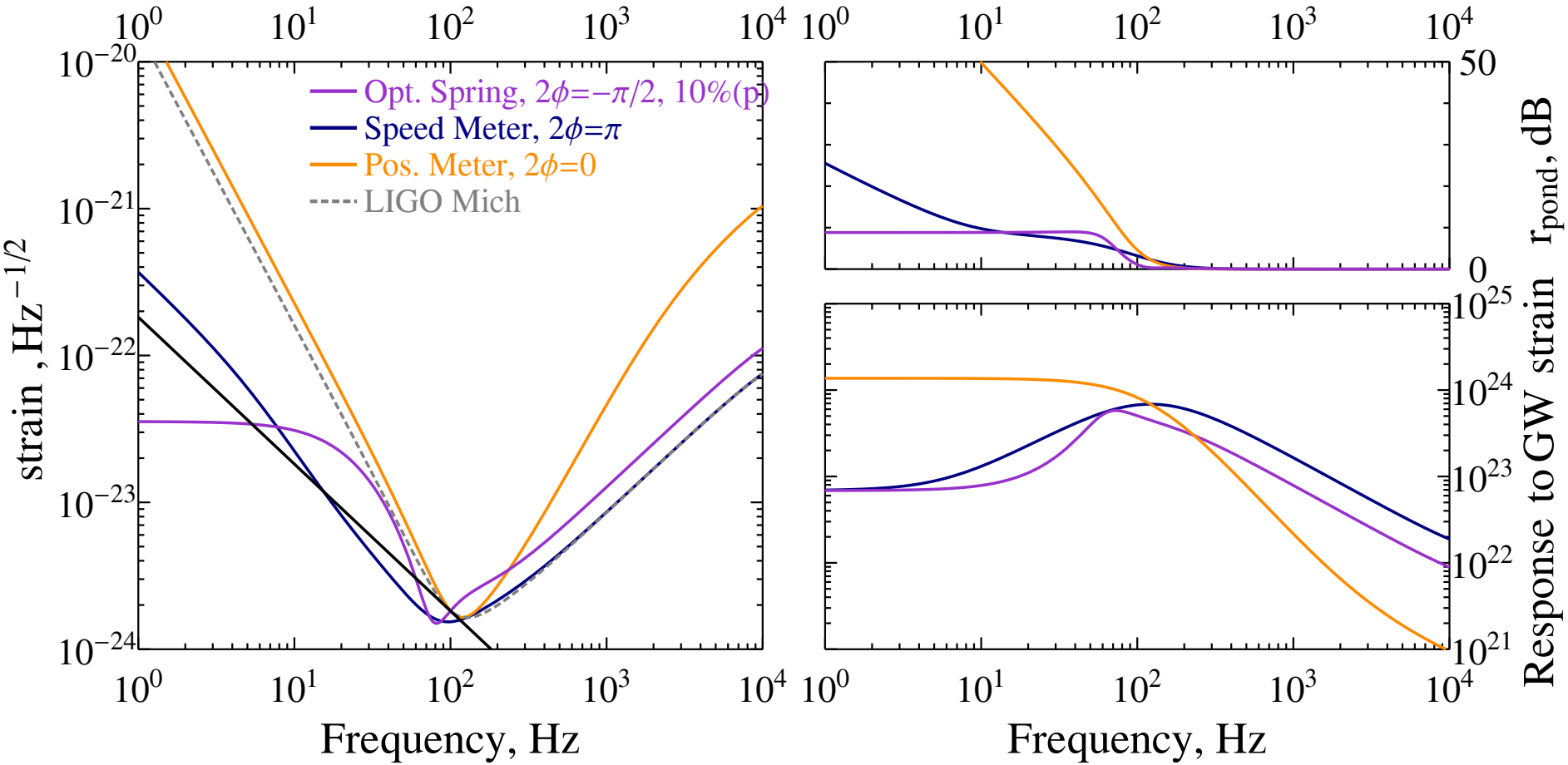
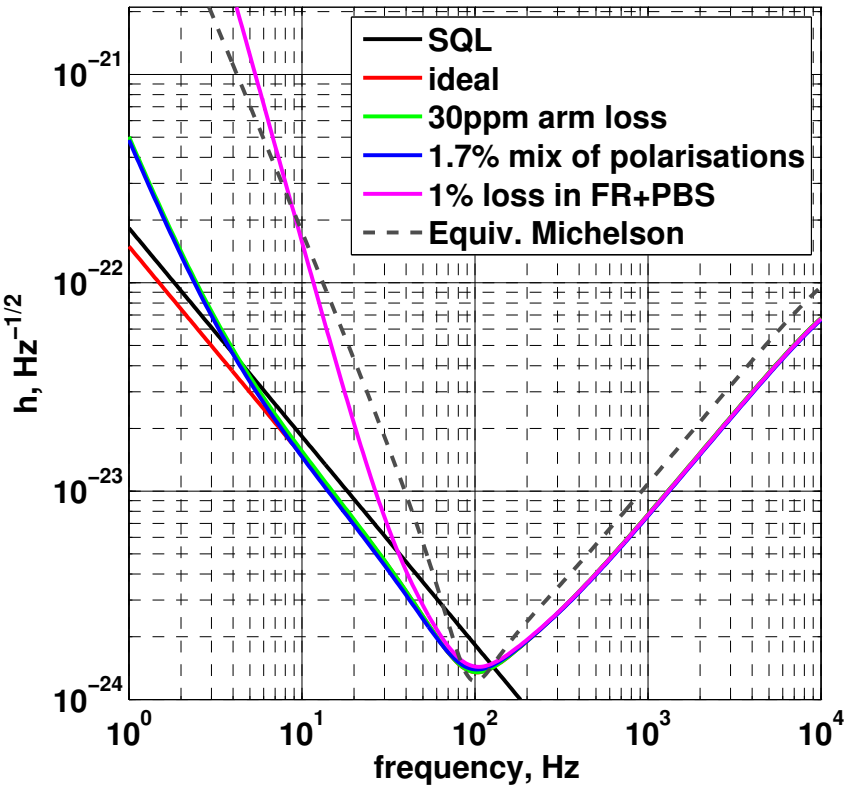
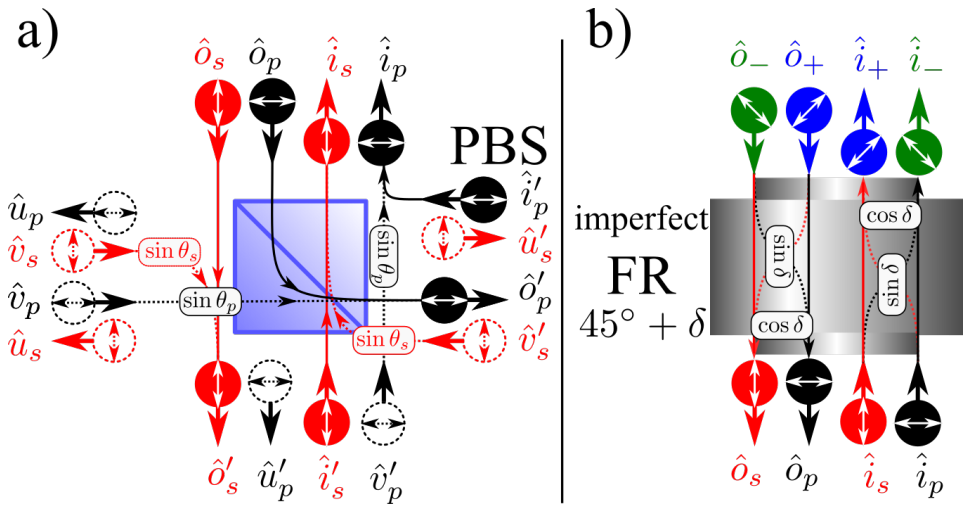


Mix of PM response at LF and SM response at medium frequencies + Optical Spring eliminate RPN at LF completely.

Polarisation Circulation Speed Meter (unabridged)





Partial cure to PBS leak:

Measure the orthogonal polarisation, $\hat{o}_p$, with an independent BHD ⇒ should improve LF sensitivity (work in progress)

Possible caveats/imperfections

1. Both, *s*- and *p*-polarisations must be @ dark fringe;
2. Cross-coupling of polarisations ⇒ minor;
3. Losses in the arms ⇒ minor;
4. FR loss + Imperfect PBS ⇒ SERIOUS!
5. Stability of PMC path ϕ ⇒ not a problem;

Summary

Theory conjectures

1. Multitude of breeds of speed meters boils down to only two distinct species: Sloshing-like and Sagnac-like;
2. Position meter and speed meter are but the two limiting points in the continuous, single-parameter family of intermediate interferometer configurations;

Summary

Practical conclusions

1. Speed meters lower quantum radiation pressure noise not only frees LF-band from QN, but significantly relaxes loss requirements to filter cavities;
2. Using linear cavities (2 arms + 1 sloshing) in ring arrangement one gets a speed meter + reduction of coating thermal noise 2.2 times (see S. Huttner et al. LIGO-P1600155);
3. Using 2 polarisation DoFs of light one can design a speed meter (and not only!) without any serious changes to the Michelson infrastructure;
4. We propose a new design of a tuneable short-scale polarisation circulator, turning a Michelson into a speed meter;
5. More to that, by the choice of the phase shift between the two polarisation modes, one can create an optical spring + speed meter response;
6. Main concerns: polarisation-sensitive BS ratio/phase, loss in the FR, PBS imperfections.

THANK YOU

FOR YOUR ATTENTION!!!