How ready is the speed meter interferometer technology for the future detectors of GWs?

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GWADW, Girdwood, Alaska, May 20, 2015
LIGO-G1500692

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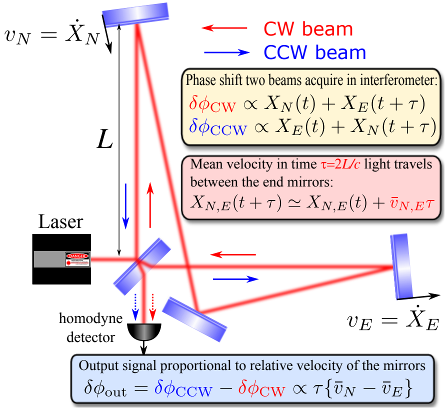
Questions to answer

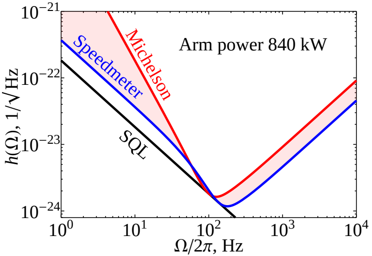
- How ready is Sagnac technology for being implemented in 10-20 years from now?
- How is it beneficial for long-base (>4 km) interferometers?

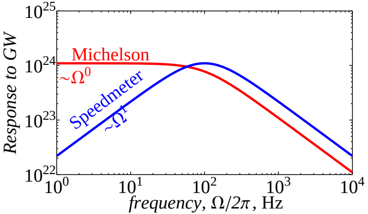
Why speed meter is better than position meter?

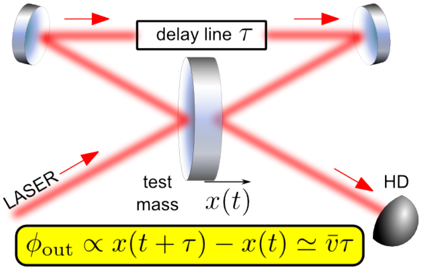


- Michelson interferometers are sensitive to displacement of the mirrors.
- Displacement operator does not commute with itself at different times, $[\hat{x}(t), \hat{x}(t')] \neq 0 \Rightarrow$ it cannot be measured with arbitrary precision$\Rightarrow$ SQL ;
- Zero-area Sagnac interferometer senses velocity, $\hat{v}(t)$, which is proportional to the momentum of the mirrors, $\hat{p}(t) = m\hat{v}(t)$, which is a QND observable $\Rightarrow$ no back action (ideally);

Why speed meter is better than position meter?







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

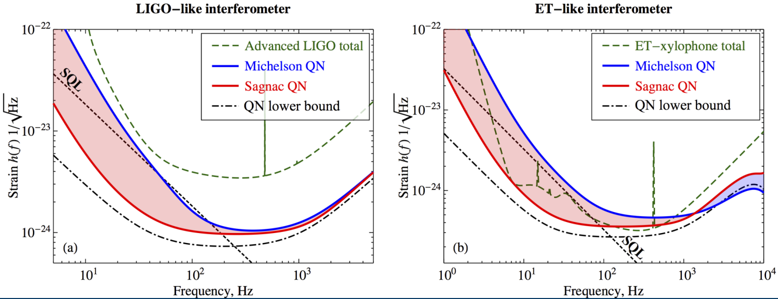
$$\hat{F}_{\text{b.a.}}(\Omega) \simeq -i\Omega\tau \frac{2\bar{P}_{\text{pulse}}}{c},$$

- 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.

What is our starting point?

tum noise suppression goes via the change of interferometer configuration. We show that Sagnac interferometer has superior potential for broadband sensitivity gain compared to Michelson interferometer for any given set of advanced interferometric techniques, *i.e.* signal recycling [21–23], squeezed vacuum injection [46, 47], frequency-dependent phase rotation of squeezed vacuum phase [24] *etc.* We also demonstrate that better broadband performance is exhibited by Sagnac interferometer with significantly relaxed requirements to auxiliary optics and thereby at much lower cost.

http://arxiv.org/abs/1503.01062



It can't be. It's not possible. It's not right!

Well, such a bold statement requires a justification at least, and, expectedly, raised a torrent of incredulous remarks from the referees ☺

1. How about losses in the readout train and in the squeezing injection train?

   Tuesday morning session of "Topologies and Squeezing" was all about it.

2. How about asymmetries and imperfections? Is speed meter really up for this job, if we take all of this into account?

   Recent paper by UGlasgow speed meter prototype team
   S. Danilishin et al., New J. Phys. 17 (2015) 043031

3. How are you going to control this beast, if you don't know what it is doing at DC?

   There are ways, I will talk of it later.
   Work in progress by S. Leavey and A. Gläfke and the UGlasgow speed meter prototype team

What is our starting point?

1. Squeezing injection becomes a conventional technique for GW interferometers (Recall this statement of mine and your reaction on it at GWADW 2010 in Kyoto ☺);

   Emil's and Katherine's talk yesterday and Nergis's and Lisa's talks on Monday

2. Frequency dependent squeezing is a "must have" for any broadband sub-SQL detector, relying on back-action noise cancellation;

   Lisa's talk on Monday and Tomoka's talk yesterday

3. Signal recycling mirror is an integral part of the majority of proposed advanced topologies, so why not assume the arbitrary detuning thereof as well?

Having said that, we:

- Hope thermal and seismic noise are reduced, within 10-15 years, by the heroic efforts of our colleagues from the other workshops and concentrate on purely QN limitations

  recall Haixing's talk yesterday

- Take Michelson and Sagnac. Assume FD squeezing and detuned SRC in both. For each, find the optimal set of parameters to get best broadband QN noise curve
- Make a fair comparison of the two and make a conclusion.

How and what do we optimise

- Non-quantum noise levels is being constantly pushed down due to the efforts of the whole collaboration ⇒ QN should be compared against QN of different configurations;
- Any "universal" benchmark QN curve?
  1. Lower frequencies: Losses create uncompensated RPN in any quantum filtering scheme:

$$S^h_{\mathrm{RP\ loss}}(\Omega) \simeq h^2_{\mathrm{SQL}}(\Omega)\varepsilon^{1/2}_{\mathrm{loss}}e^{-r_{\mathrm{eff}}}\,, \tag{1}$$

  2. Upper frequencies: Shot noise of a Michelson with phase squeezing, given power and given bandwidth is our limit

perhaps, close to the EQL, Haixing talked yesterday.

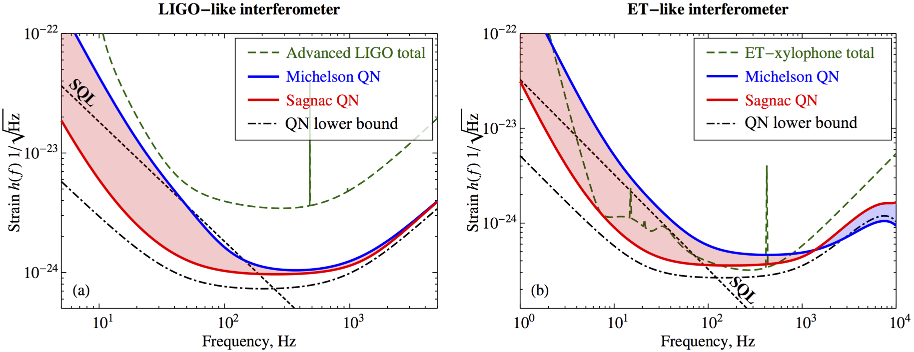
$$S^h_{\mathrm{SN}}(\Omega) = \frac{h^2_{\mathrm{SQL}}(\Omega)}{2}\,\frac{e^{-2r_{\mathrm{eff}}}+\varepsilon_{\mathrm{loss}}}{\mathscr{K}_{\mathrm{eff}}(\Omega)}\,, \tag{2}$$

where

$$h_{\mathrm{SQL}}(\Omega) = \sqrt{\frac{8\hbar}{ML^2\Omega^2}}\,,\quad \text{and}\quad \mathscr{K}_{\mathrm{eff}}(\Omega) = \frac{\Theta\tau}{\Omega^2}\,\frac{2T_{\mathrm{eff}}}{1-2\sqrt{R_{\mathrm{eff}}}\cos 2\Omega\tau + R_{\mathrm{eff}}}\,,\quad \Theta = \frac{4\omega_0 P_c}{McL}\,.$$

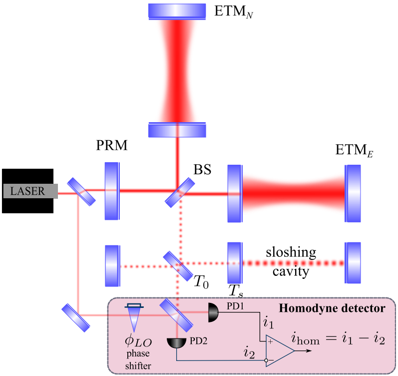
How and what do we optimise

- Non-quantum noise levels is being constantly pushed down due to the efforts of the whole collaboration ⇒ QN should be compared against QN of different configurations;
- Any "universal" benchmark QN curve?
- Figure of merit for optimisation: We try to minimise the area between the benchmark curve and the sensitivity curve of the configuration under study in logarithmic scale!



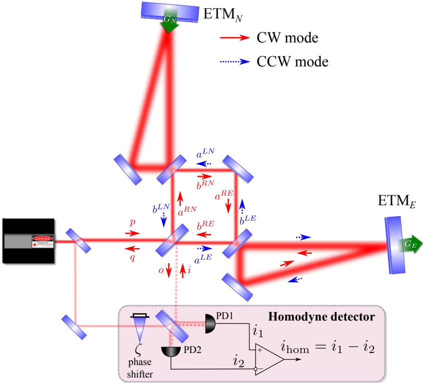
Speedmeter interferometers

Sloshing speedmeter



- P. Purdue, Phys. Rev. D 66, 022001 (2002).
- P. Purdue, Y. Chen, Phys. Rev. D 66, 122004 (2002).
- A.R. Wade et al., Phys. Rev. D 86, 062001 (2012).

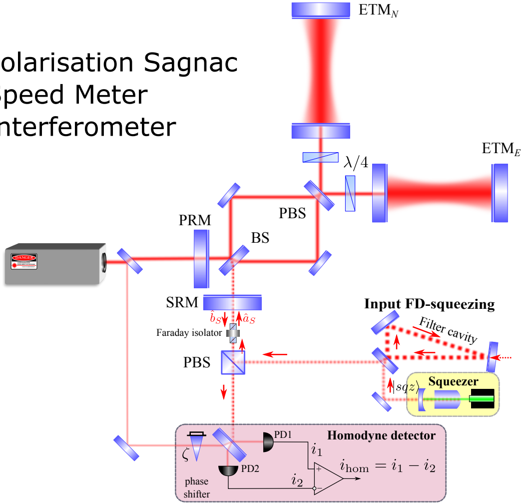
Ring arm cavities Sagnac speedmeter



- P.T. Beyersdorf et al., Opt. Lett. 24, 1112 (1999).
- F.Ya. Khalili, arXiv:gr-qc/0211088,(2002).
- Y. Chen, Phys. Rev. D 67, 122004 (2003).

The strawman design for this study

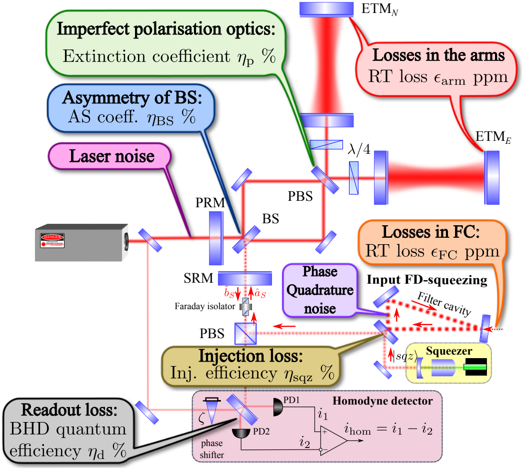
Polarisation Sagnac Speed Meter Interferometer



1. Polarisation Sagnac;
2. Balanced Homodyne Readout;
3. PR and SR (SR detuned);
4. FD Squeezing (1 filter cavity);

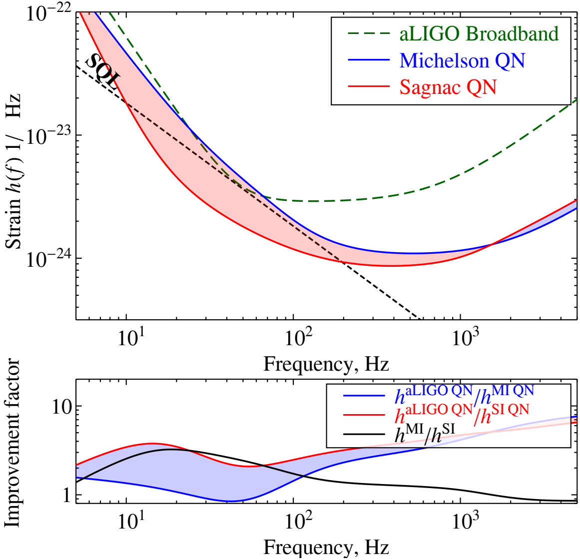
- S.L. Danilishin, Phys. Rev. D 69, 102003 (2004).
- M. Wang et al., Phys. Rev. D 87, 096008 (2013)
- N.Voronchev et al., arXiv:1503.01062 (2015)
- P. Fritchel et al., Opt. Express 22, 004224 (2014)
- M. Stefszky et al., Clas. Quant. Grav. 29, 145015 (2012)
- J. Miller et al., LIGO-P1500062 (2015)

Potential problems?



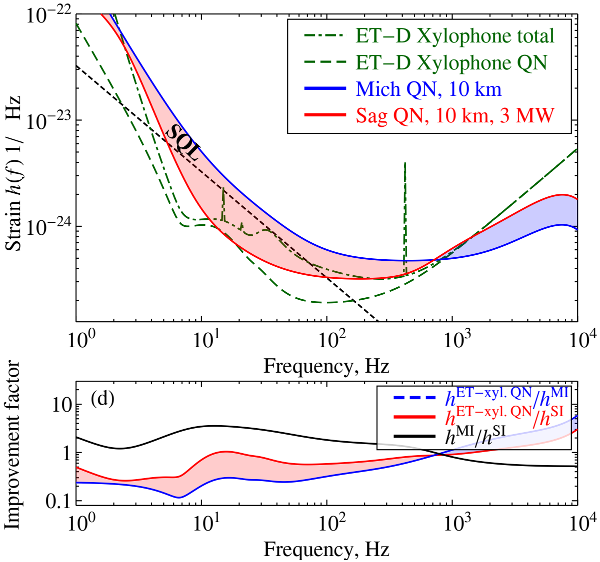
Parameter	Not.	Value
Interferometer		
Arms loss, ppm	ϵ_{arm}	40
BS imbalance, %	η_{BS}	0.1
Laser noise, ×SN	L	10
Readout loss		
BHD readout loss, %	$1-\eta_d$	1.0
Filter cavities		
FC rt-loss, ppm/m	ϵ_{FC}	1.0
SQZ inj. loss, %	$1-\eta_{sqz}$	5.0
FC ph. jitter, mrad	σ_{PQN}	10
Add. anti-SQZ, dB	$\Delta r_{a.s.}$	5

LIGO infrastructure: $L = 4$ km, $P_c = 1$ MW, $m = 40$ kg



Parameter	Mich	Sag
m, kg	40	40
L, km	4	4
P_c, MW	1.0	1.0
T_{ITM}, %	14.8	7.5
r, dB (w/5% inj. loss)	12.6 (6.9)	17.8 (9.2)
ϕ_{sqz}, deg	$-7°$	$-17°$
ζ, deg	83°	74°
SRC parameters		
T_{ITM}, %	80	90
ϕ_{SRC}, deg	90°	102°
FC parameters		
T_{FC}, %	0.11	2.5
A_{FC}/L, ppm/m	1	1
δ_{FC}, Hz	210	1600
σ_{PQN}, mrad	10	10

Long arms IFO: $L = 10$ km, $P_c = 3$ MW, $m = 200$ kg



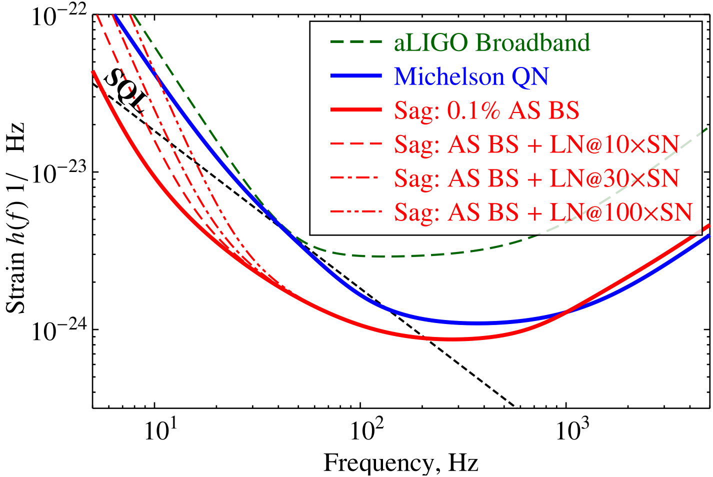
Parameter	Mich	Sag
m, kg	200	200
L, km	10	10
P_c, MW	3.0	3.0
$T_{\rm ITM}$, %	5.2	11.4
r, dB (w/5% inj. loss)	13.2 (7.2)	18.9 (9.5)
$\phi_{\rm sqz}$, deg	-4°	-12°
ζ, deg	86°	78°
SRC parameters		
$T_{\rm SRC}$, %	11	90
$\phi_{\rm SRC}$, deg	90°	100°
FC parameters		
$T_{\rm FC}$, %	0.06	1.6
$A_{\rm FC}/L$, ppm/m	1	1
$\delta_{\rm FC}$, Hz	79	921
$\sigma_{\rm PQN}$, mrad	10	10

What lessons did we learn from optimisation?

To summarise the optimisation results:

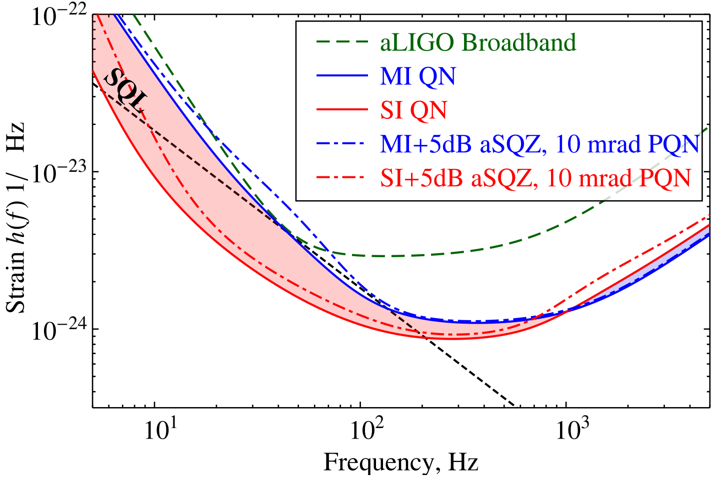
- SQZ injection: Symmetric Sagnac benefits from all squeezing you give it, while Michelson has an upper limit for it. Asymmetry sets the limit on Sagnac as well.
- Signal recycling: Michelson is better off with RSE tuned case, while Sagnac requires a bit of detuning;
- Filter cavities: frequency dependent squeezing is good for both schemes, but for Sagnac FC finesse need to be 10-15 times lower $\Rightarrow$ less impact of losses.

How bad is it with laser noise and asymmetric BS?



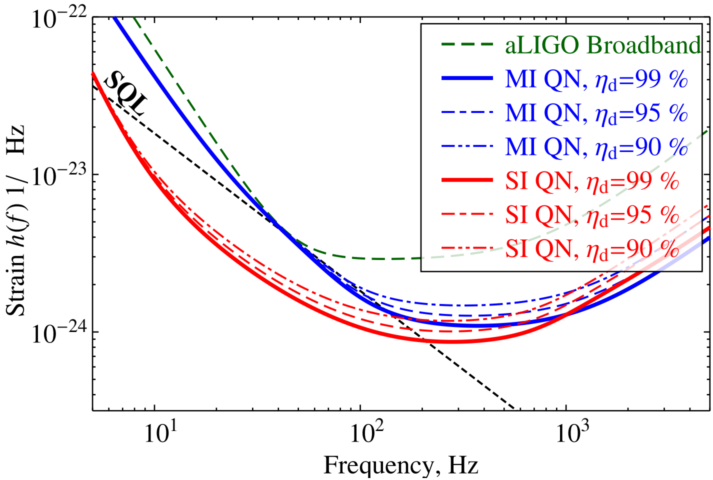
Laser noise with asymmetry in BS is a problem, but not a show stopper ⇒ still better than Michelson

How bad is it with 5 dB additional anti-squeezing?



SQZ angle jitter + anti-squeezing is a problem as well, but as well as for Michelson.
Can be fixed by reoptimizing FC parameters to get squeezing angles right again.

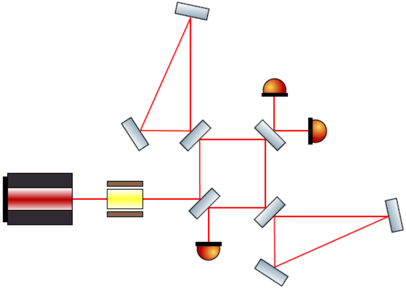
How bad will it be if 1 % of readout loss is a too optimistic value?

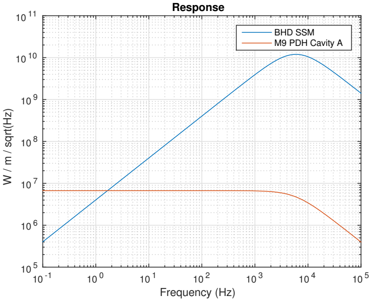


Readout loss is a problem, but equally so for Michelson.

How do we control speed meter if it has zero response at DC?

Instead of controlling dARM DoF, in Sagnac one can individually control the arms.





- Pick off light for control between the arms;
- PDH signals for each arm are measured independently;
- Will there be any problems with vacuum, entering through this port?
  In general, no, unless the pick off transmittance is below 0.1%
- In polarisation speed meter, PBS leakage can be used for deriving the control signal

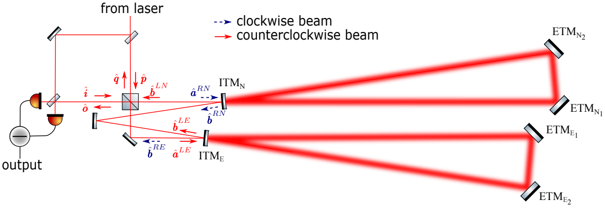
How do we know it all works?

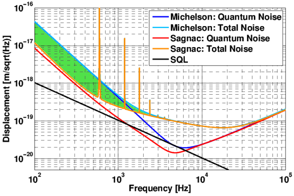
To gain credibility within the community, experimental test is crucial.

To these ends, the IGR team lead by S. Hild is building a prototype speed meter experiment funded by ERC Starter Grant scheme.

Glasgow Speed Meter major goals:

1. Create an ultra-low noise speed meter testbed which is dominated by quantum RP noise;
2. Demonstrate the reduced back-action noise of the Sagnac topology;
3. Explore speed meter technology for future GW detectors, such as ET





Summary

Summary

1. Configurations must be compared against quantum limitation, rather than current technical noise budget;
2. The main problems: asymmetry of BS and laser noise ⇒ uncompensated radiation pressure noise ⇒ yet still better than equivalent Michelson!
3. For LIGO parameters, QN of Sagnac interferometer is consistently 2 to 7 times better then the QN of the aLIGO baseline configuration;
4. Due to much lower back-action at low frequencies, Sagnac interferometer:
   - Requires more than 10 times lower-finesse filter cavities ⇒ cheaper, reduced loss impact;
   - Allows to tailor FC rotation angle almost perfectly at ALL frequencies;
5. For longer arms (10 km), QN of a single Sagnac gives almost the same sensitivity as the xylophone configuration of 2 specialised Michelsons ⇒ more economical in all respects;

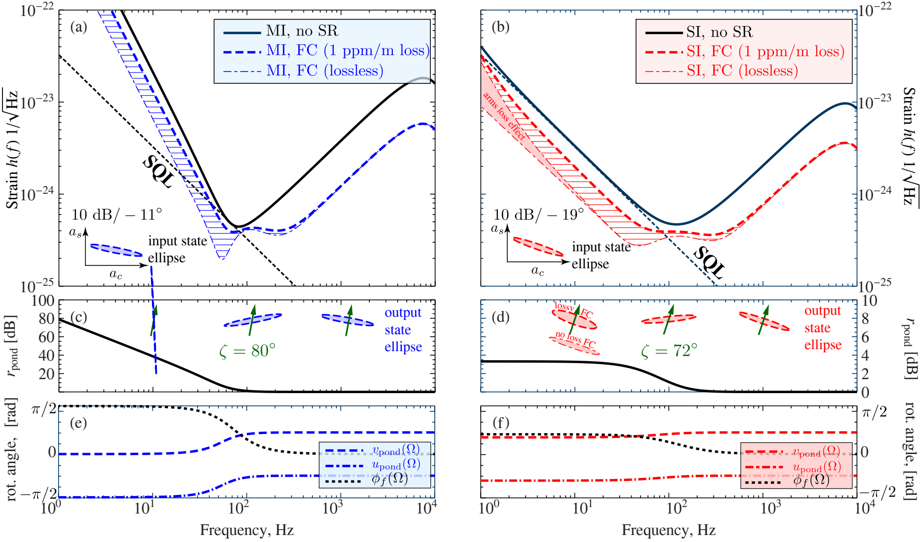
Workshop Questions

1. Is technology ready in 10-20 years from now?
   YES!
2. Is it particularly good for longer arms?
   It's good. Longer arms is always good!

THANK YOU

FOR YOUR ATTENTION!!!

Squeezed vacuum injection + Filter Cavity



Squeezed vacuum injection + Filter Cavity + Signal Recycling