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Quantum noise in the NextG of GW detectors and how to suppress it

S.L. Danilishin[1]

[1] ITP/IGP, Leibniz Universität Hannover / MPI für Gravitationsphysik (AEI)

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Max-Plank-Institut für Gravitationsphysik (Albert-Einstein-Institut)

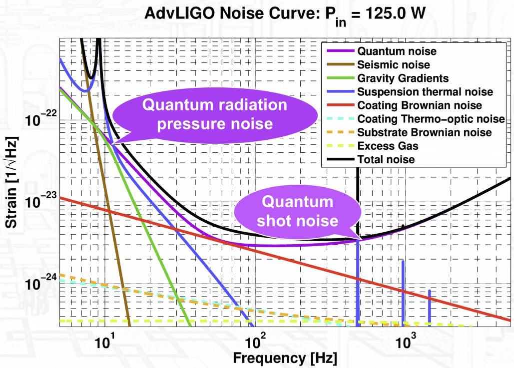
Outline

Motivation

Quantum noise will be **the dominant** source of noise in almost entire detection range of current detectors (> 10 Hz).

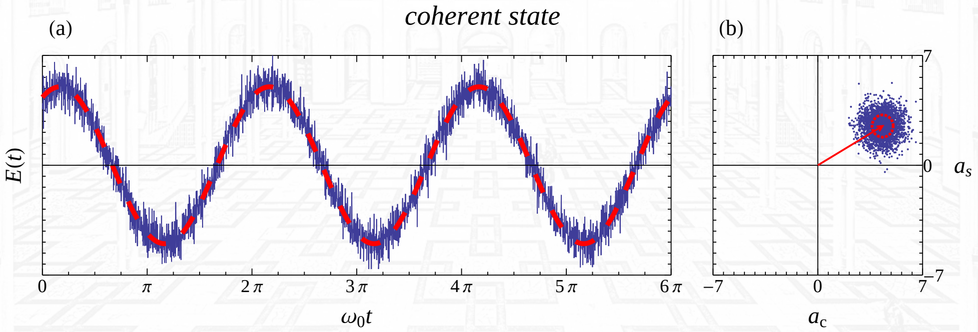
If we want GW detectors to become fully fledged astronomical tools

1. We need to push down **quantum back-action** noise, dominating LF:
   - To improve SNR for **early stages** of compact binary evolution
   - To see **more massive sources of GW** and reduce the gap with space detectors
   - To get longer **lead time** before the merger to issue timely warnings to our EM partners in **multi messenger** effort
2. We also need to improve on the **shot-noise**-dominated HF region:
   - To see details of **neutron star mergers** and **supernova explosions**
   - To measure the ringdown of **quasi-normal modes** of black holes after the merger of BBH.



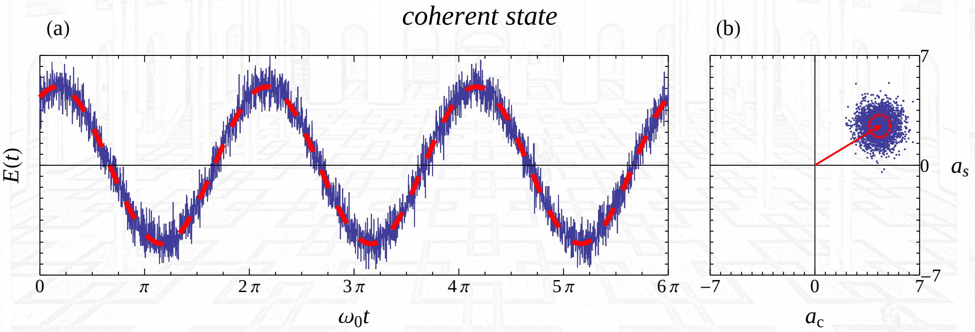
The next generation (NextG) of GW instruments is bound to use **QN Mitigation techniques** to get to projected > 10 better sensitivity as compared to Advanced LIGO and Advanced Virgo!

- Quantum Noise originates from inexorable quantum uncertainty of the laser light phase and amplitude, for light is quantum therefore is a wave and a flux of photons (light particles) at the same time;



1. Quantum Noise originates from inexorable quantum uncertainty of the laser light phase and amplitude, for light is quantum therefore is a wave and a flux of photons (light particles) at the same time;
2. Heisenberg Uncertainty Principle of QM dictates that precise values of phase, $\hat{X}_{\rm phase}$, and amplitude, $\hat{Y}_{\rm amp}$, of light cannot be known at the same time:

$$\Delta\hat{X}_{\rm phase}\Delta\hat{Y}_{\rm amp} \geqslant \hbar/2$$



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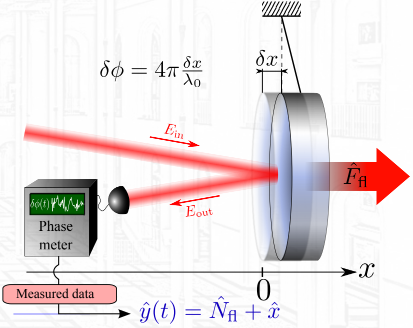
1. To monitor motion of the mirrors of the interferometer (*e.g.* induced by GW) we need to measure phase of the light beam reflected off the mirror very accurately;



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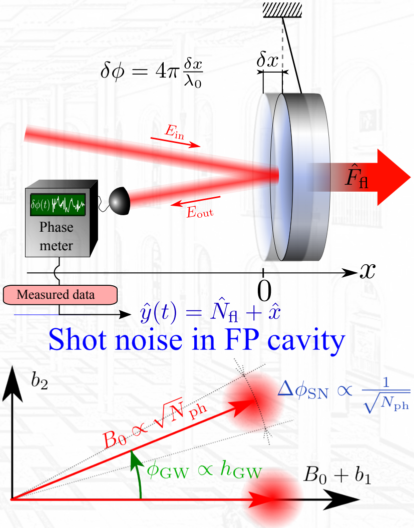
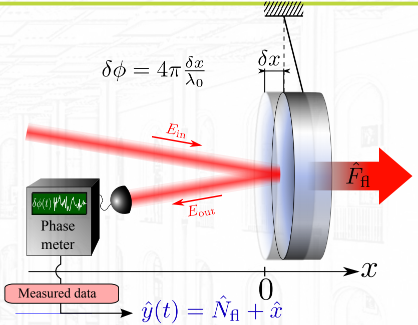
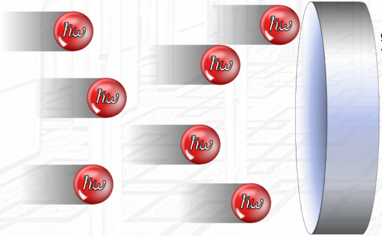
2. This is equivalent to distinguishing how much a fuzzy blob on the stick has moved by watching its centre shifting. The longer the sticks, the smaller angle (phase shift) we can discern;

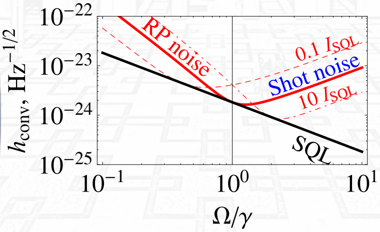


Quantum noise and quantum limits.

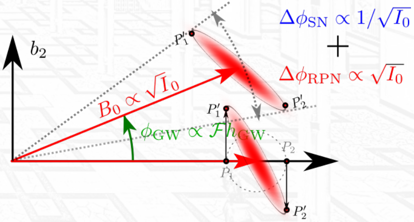
1. To monitor motion of the mirrors of the interferometer (*e.g.* induced by GW) we need to measure phase of the light beam reflected off the mirror very accurately;
2. This is equivalent to distinguishing how much a fuzzy blob on the stick has moved by watching its centre shifting. The longer the sticks, the smaller angle (phase shift) we can discern;
3. But it's not a full story! Longer stick ⇒ more photons ⇒ they randomly kick the mirror and make it move ⇒ more (*back-action*) noise mimicking GW



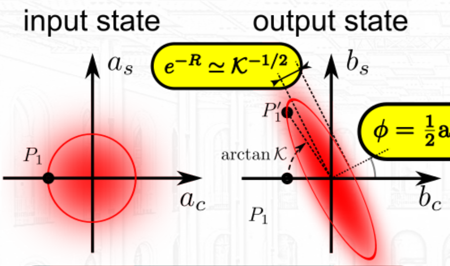




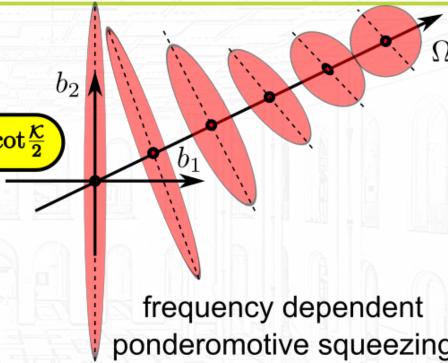
RP noise in FP cavity



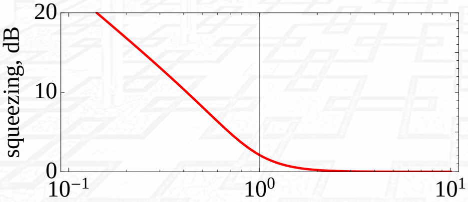
Quantum noise and quantum limits.

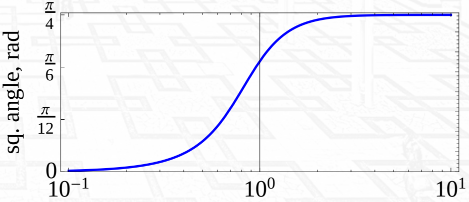


$$b_c = a_c e^{2i\beta(\Omega)}$$
$$b_s = (a_s - \mathcal{K}a_c)e^{2i\beta(\Omega)} + GW$$

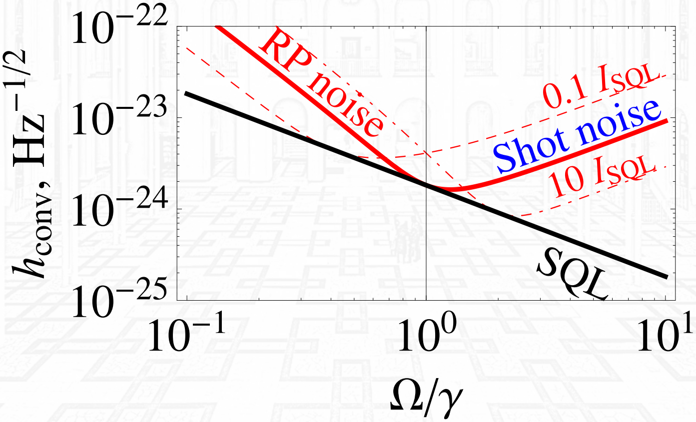


frequency dependent ponderomotive squeezing





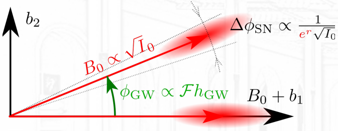
If we simply watch the phase of the reflected light, there will always be a limit of precision to which we can detect GW-induced motion of the mirror ⇒ Standard Quantum Limit.

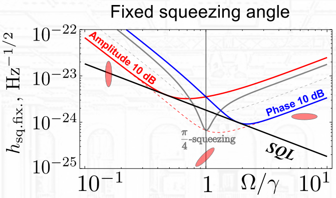


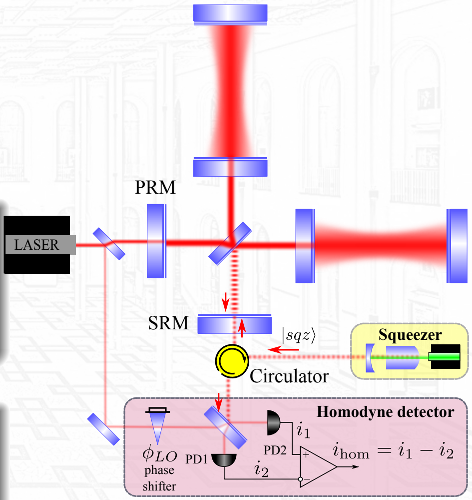
Different approaches to Quantum Noise mitigation

1. Change the **quantum state** of light that enters the interferometer $\Rightarrow$ **squeezing**, **FD squeezing**, **EPR-squeezing**;
2. Modify the **outgoing light** to evade back-action $\Rightarrow$ **variational readout**, **negative-mass spin-based filters**
3. Change the quantum state of light **inside** the interferometer $\Rightarrow$ **internal squeezing**, **unstable optomechanical filters**, **white-light-cavities**;
4. Tailor the **interaction between the light and the mirrors** to perform **quantum non-demolition** (QND) measurement $\Rightarrow$ **speed meters**
5. Modify the **dynamics** of the test masses using light $\Rightarrow$ **optical bars**, **negative inertia**, *etc.*

Squeezed vacuum injection







Idea behind squeezing injection

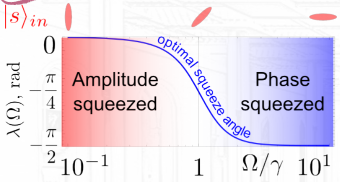
Replace *vacuum* that enters dark port of the IFO by *squeezed vacuum* with reduced phase quadrature fluctuations ⇒ enhanced resolution in phase quadrature that contains GW signal.

W. Unruh, PRD **19**, 2888 (1979)

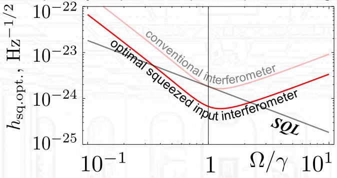
Fixed squeezing doesn't work at all frequencies:

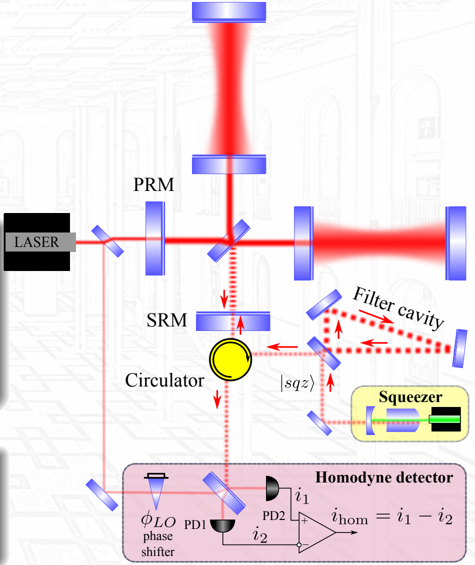
See-saw situation: LF and HF parts of QN are driven by orthogonal light quadratures ⇒ squeezing of one quadrature yields proportional increase of the noise in the other;

Frequency dependent squeezing



Frequency dependent phase pre-filtering





Idea behind FD squeezing injection

Why don't we inject *amplitude-squeezed* light at LF to suppress **QRPN**, *phase-squeezed* light at HF to suppress **QSN**, and intermediate-squeezed quadratures at mid-frequencies? $\Rightarrow$ Put an optical *filter cavity (FC)* between the squeezer and the IFO

J. Kimble *et al.*, PRD **65**, 022002 (2001)

Main challenges:

- Narrow bandwidth of FC (comparable to main IFO's) $\Rightarrow$ rather long ($>$ 100 m) and have high-finesse mirrors $\Rightarrow$ susceptible to optical loss;
- Injection loss (imperfect mode matching) $\Rightarrow$ less squeezing in the IFO.

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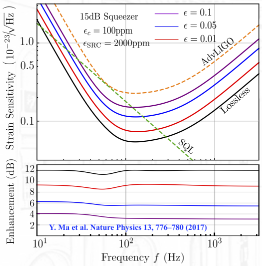
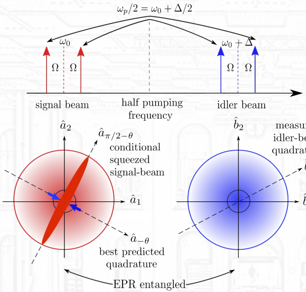
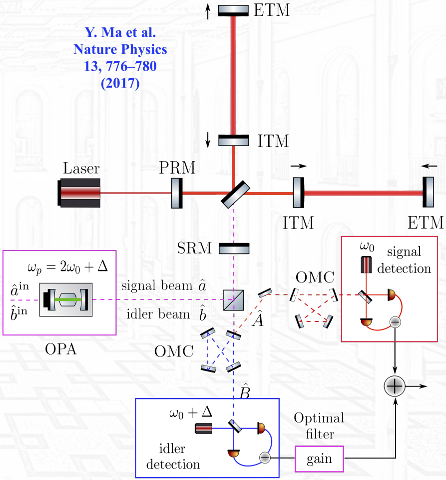




Y. Ma et al.
Nature Physics
13, 776–780
(2017)

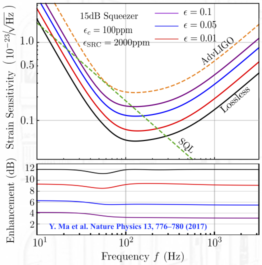


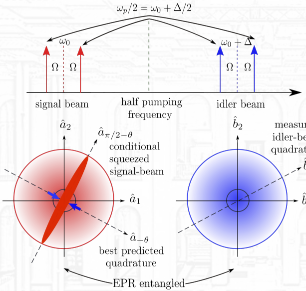
Idea behind EPR-squeezing

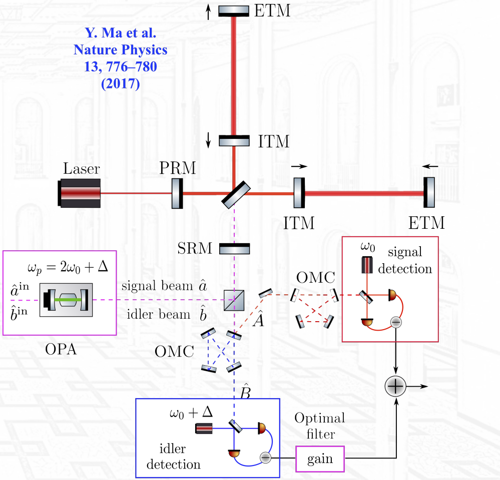
- Send 2 entangled squeezed vacuums (created in NOPA by PDC) with frequencies apart by several MHz to the dark port;
- *Signal* beam at ω_0 beats with carrier, *idler* beam at $\omega_0 + \Delta_{\rm MHz}$ uses IFO as filter cavity;
- Measurement of *idler* projects *signal* into FD-squeezed state.

Y. Ma *et al.* Nat. Phys. **13**, 776 (2016);

EPR-squeezing







Challenges:

- EPR entanglement taxes a *3dB* levy on achievable squeezing;
- Optical losses are doubled, for there are two beams;
- Very stringent requirement on the relative stability of the readout optical paths (OMCs, in particular).

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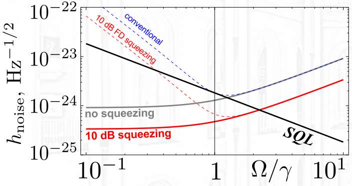
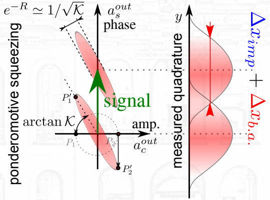
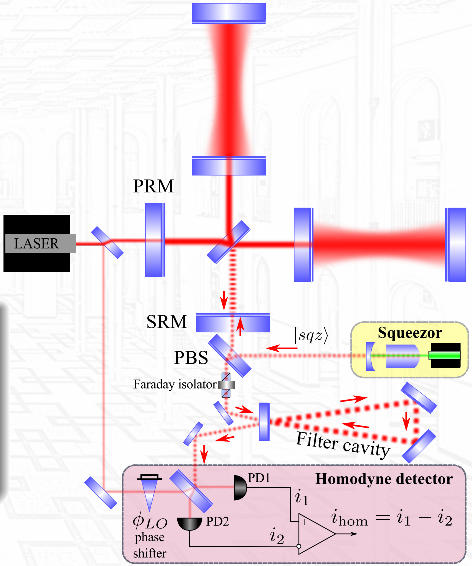
Frequency dependent phase post-filtering







Idea behind variational readout

- Why not align all the noise ellipses of FD ponderomotively squeezed outgoing light of the IFO by sending it through the dispersive FC?
- This means to measure the quadrature that has no BA noise in it $\Rightarrow$ *in ideal world*, it saturates the fundamental limit of sensitivity!

J. Kimble *et al.*, PRD **65**, 022002 (2001)

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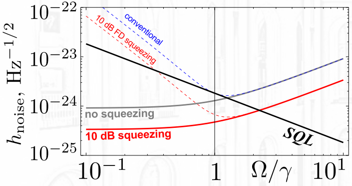
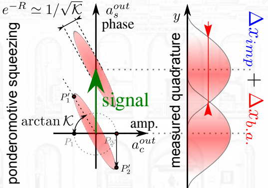
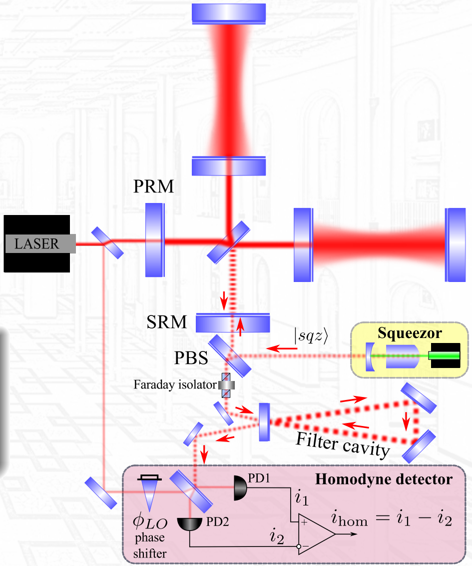
Frequency dependent phase post-filtering

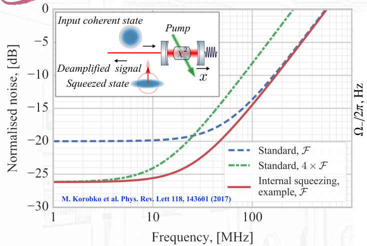


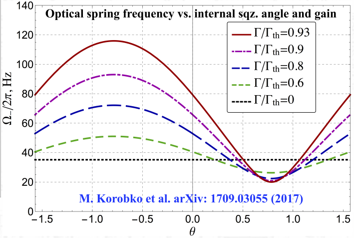


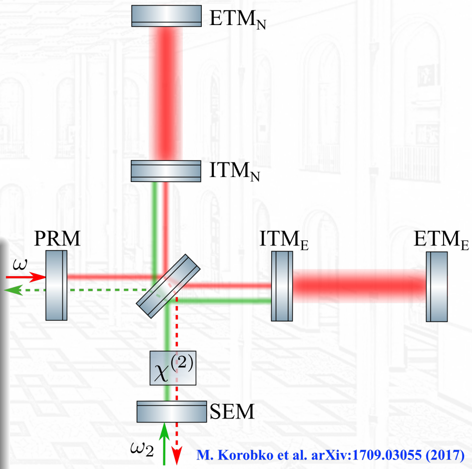


Challenges:

As always, **optical loss** in the FC and in the photodetectors kills the fragile quantum correlations.
The result is devastating: **Variational readout (postfiltering) has much worse sensitivity than FD squeezing for the same level of loss!**







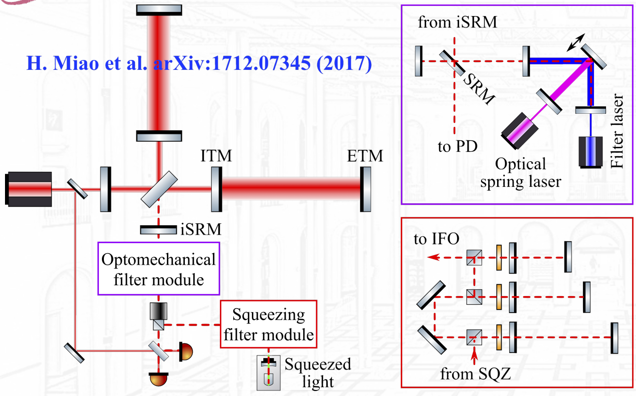
Idea behind internal squeezing & amplification

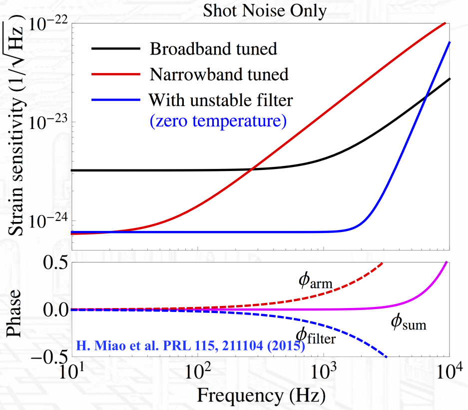
Avoid injection loss and put non-linear $\chi^{(2)}$-crystal right inside the SR cavity of the IFO $\Rightarrow$

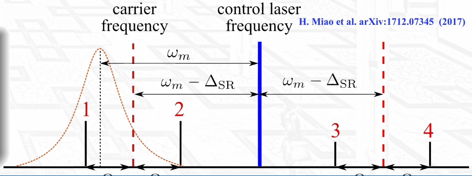
- Increase bandwidth of the IFO, keeping the same peak sensitivity;
- Amplify signal sidebands and also optical spring;

K. Somiya *et al.* PLA **380**, 521 (2016);
M. Korobko *et al.* PRL **118**, 143601 (2017);
M. Korobko *et al.* arXiv:1709.03055 (2017);

H. Miao et al. arXiv:1712.07345 (2017)





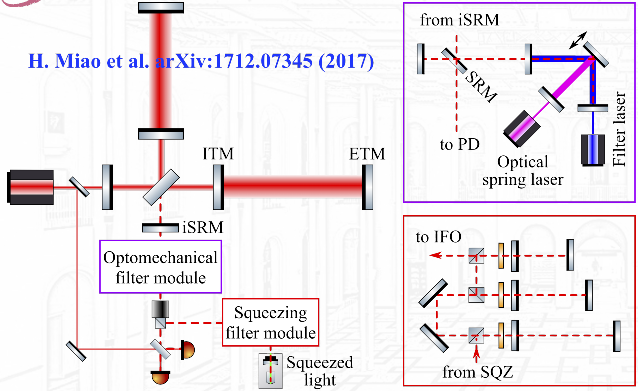


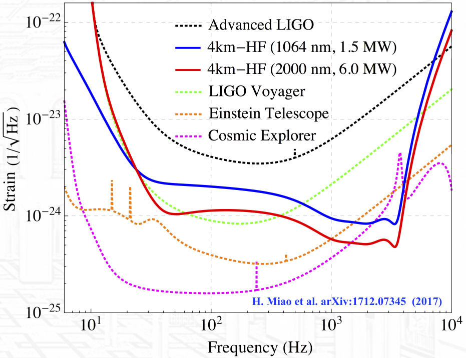
Idea behind unstable filtering

Use auxiliary OM system as filter cavity with negative dispersion to cancel the positive dispersion of the arm cavities of the main IFO

H. Miao *et al.* PRL **115**, 211104 (2017); H. Miao *et al.* arXiv:1712.07345 (2017);

Unstable opto-mechanical filters





Challenges

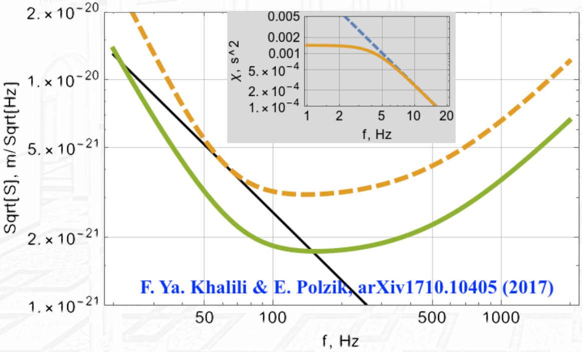
- Thermal noise of the mechanical resonator is directly down-converted to signal sidebands: $T/Q < 10^{-10}$!
- Introduces additional OM resonances thereby requiring 3 filter cavities for FD squeezing to work.

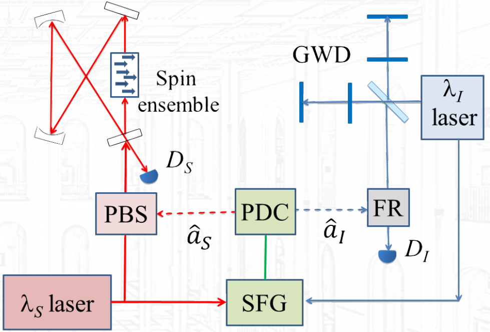
Back action evasion with negative-mass spin system

Idea behind negative-mass BA evasion

To undo ponderomotive squeezing due to BA, let injected squeezed light interact first with a system that has exactly the same OM response as the IFO, save to the sign of the "mass" $\Rightarrow$ cell with Cs vapours in magnetic field does that!

F. Ya. Khalili & E. Polzik, arXiv1710.10405 (2017);

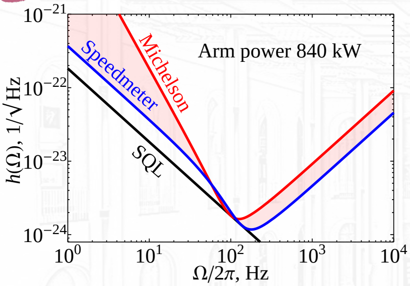


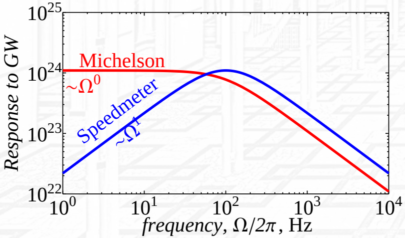


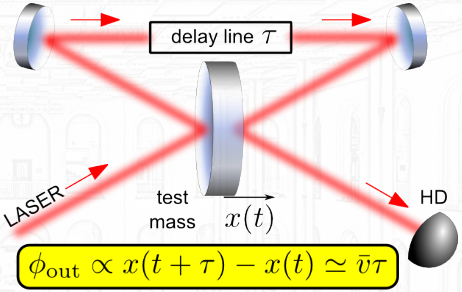
F. Ya. Khalili & E. Polzik, arXiv1710.10405 (2017)

Challenges:

- Spin system does not operate at $\lambda = 1064$ nm $\Rightarrow$ entangled light beams must be used $\Rightarrow$ similar to EPR-squeezing
- Hard to make effective frequency of spin system pendulum frequency of test masses.





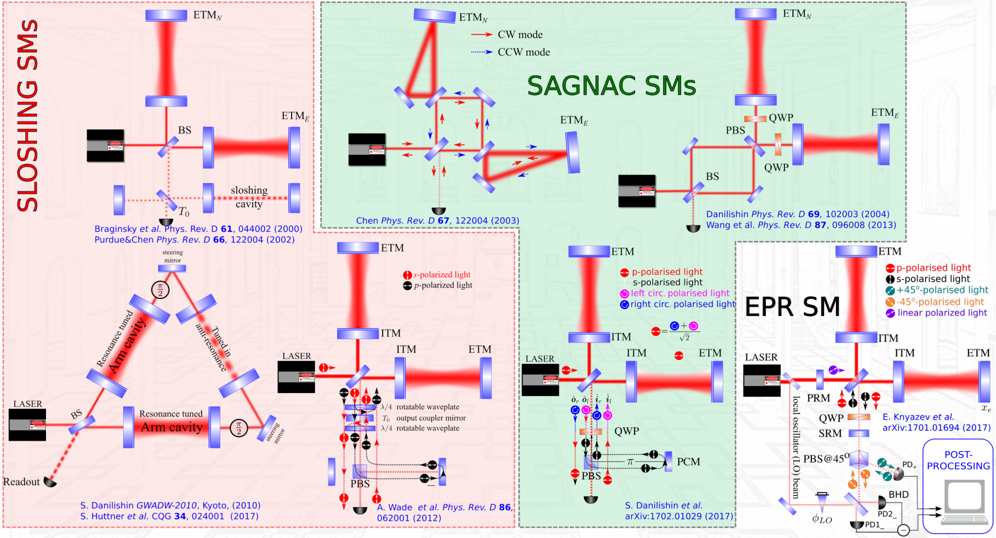


- **Back- action reduction:** RP force of two reflections cancel each other, but with delay τ:

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

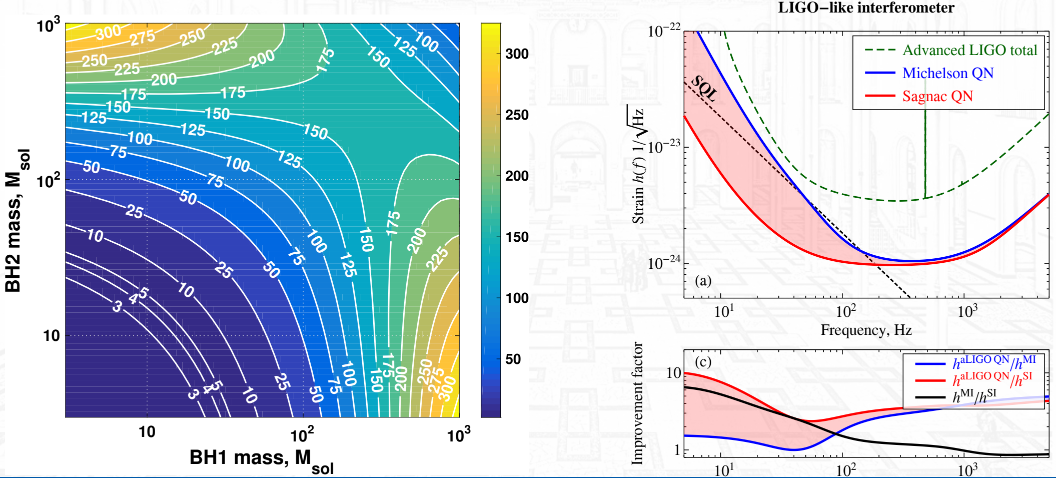
- **The benefit**: Much better QN sensitivity at low frequencies than Michelson;
- **The price to pay**: Response of speed meter wanes linearly with frequency as it goes to DC.

Zoo of speed meters



Speed meters offer dramatic increase of event rate for IMBH binaries

3 to 300 times improvement in event rate compared to equivalent Michelson!



Implementation of speed meters in GWD

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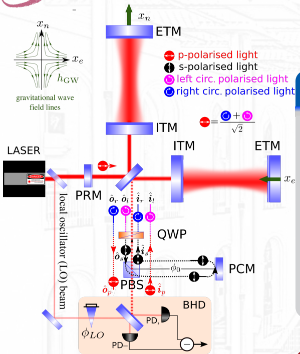
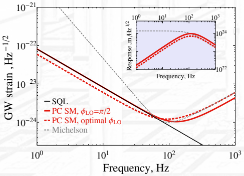


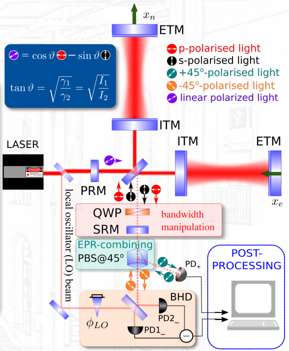


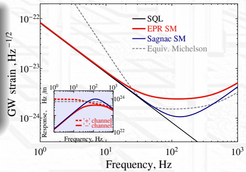
Novel polarisation-based schemes of SM

- Orthogonal polarisations are used to separate the light beams **inside** the IFO and make them interact with the mirrors twice, **without losing coherence!**;
- **Minimal changes** to the main IFO infrastructure or optics!;
- The left one has 3 magic letters **"EPR"** in the name that open many doors in funding agencies ☺

Challenges:

- Studies on all-polarisation optical coatings needed;
- Prototyping of speed meters, and polarisation -based one is necessary.





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Summary

1. Quantum noise, along with coating thermal and Newtonian gradient noise sources, is the main hindrance towards sensitivity goals of the NextG detectors;
2. **Squeezing** is the **most elaborate** and **ready-to-implement** technique for QN mitigation, including FD squeezing. And best of all, it is *compatible with other methods of QN mitigation*;
3. The main problem, when it goes about QN mitigation is **optical loss!** $\Rightarrow$ reduce the number of **interfaces** between the generator of non-classical states of light and the test masses of the detector;
4. **EPR-squeezing** partly solves the problem of optical loss in the FC by using the IFO itself as a filter, but at a price of **3 dB less squeezing** and the **loss in the readout** optical train is an issue;
5. The new **intracavity squeezing and amplification** techniques might be another solution to the loss-at-interface problem $\Rightarrow$ needs a lot of R&D and prototyping;
6. Unstable OM filters allows to improve HF sensitivity without compromising peak sensitivity $\Rightarrow$ has thermal noise issue and makes FD squeezing more challenging (3 FCs needed);
7. Back-action evasion with negative-mass spin systems allows table-top solution for LF problems $\Rightarrow$ needs atoms with transitions at 1064 nm, needs to reach ~ 1 Hz oscillation frequencies;
8. Speed meters offer BA suppression *in situ*, thus less susceptible to loss. Well studied theoretically (7 different configurations). Polarisation-based SMs require all-polarisation coating for the BS (IFO must be resonant for both polarisations). Needs prototyping (underway in Glasgow).

THANK YOU

FOR YOUR ATTENTION!!!