Transmissive cavities as filters of squeezed states

Thomas Corbitt

Quantum Measurement Group

MIT: Keisuke Goda, Nergis Mavalvala, Eugeniy Mikhalov, David Ottaway

Caltech: Stan Whitcomb

Outline

- Squeezed states
- Application to interferometers
- Squeezed state filters
- Astrophysical sources
- Experimental demonstration

Squeezed states

- Reduce the noise at one quadrature, but increase noise at a different quadrature.
- Any linear combination of the quadratures a1 and a2, such as $b = a_1 \cos\theta + a_2 \sin\theta$ may be squeezed. We use the term “squeeze angle” for θ.
- Squeezed sources generally produce a frequency independent squeeze angle.

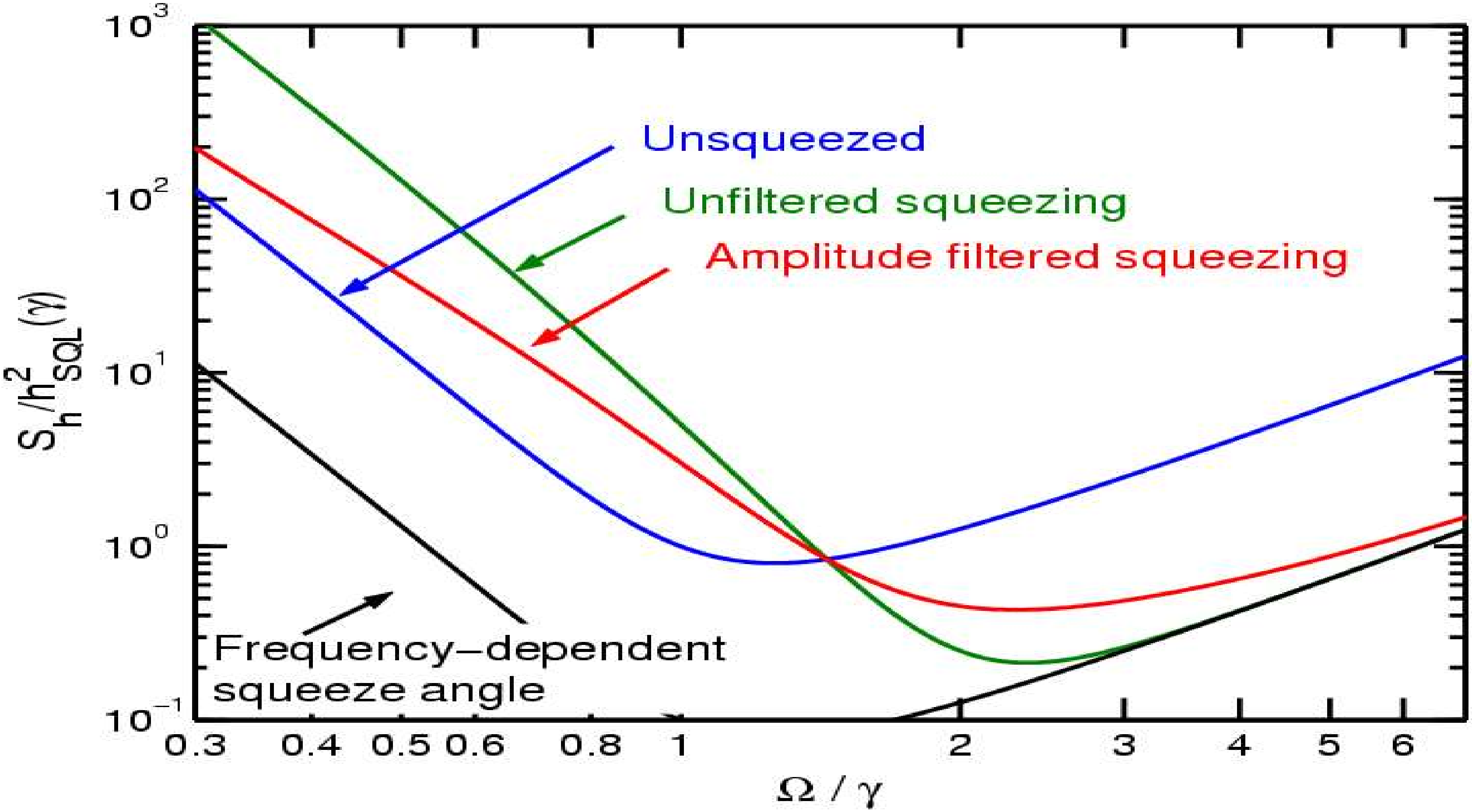
Application to interferometers

- In general, the detected field at the output of an interferometer may depend on an arbitrary linear combination of the quadratures of the input field, which may be a function of frequency. We also describe this linear combination with an angle, which determines the optimal squeeze angle.
- For LIGO type interferometers (neglecting other noise sources), shot noise dominates at high frequencies, and radiation pressure dominates at low frequencies. These two noise sources depend on orthogonal quadratures. Other configurations may be more complicated.

Effects of squeezed state on an interferometer

- With a frequency independent squeeze angle, the noise at high or low frequencies may be reduced, at the expense of increasing the noise in the other band.
- We can imagine three solutions to this problem:
  1. Do nothing. When looking for a high/low frequency source, optimize for high/low frequencies. This is bad because you lose sensitivity out of band.
  2. Modify the squeezed source so that its squeeze angle matches the interferometer. See Roman's presentation. Squeeze angle filtering.
  3. Destroy the squeezing in the frequency band where it is harmful, while leaving it alone where it is beneficial. Squeeze magnitude filtering.

Noise curves



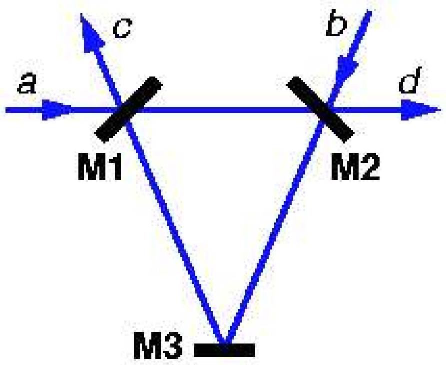
Cavities as squeeze filters

Filtered squeezed state. Goes to IFO.

Unsqueezed vacuum

Frequency independent squeezed vacuum

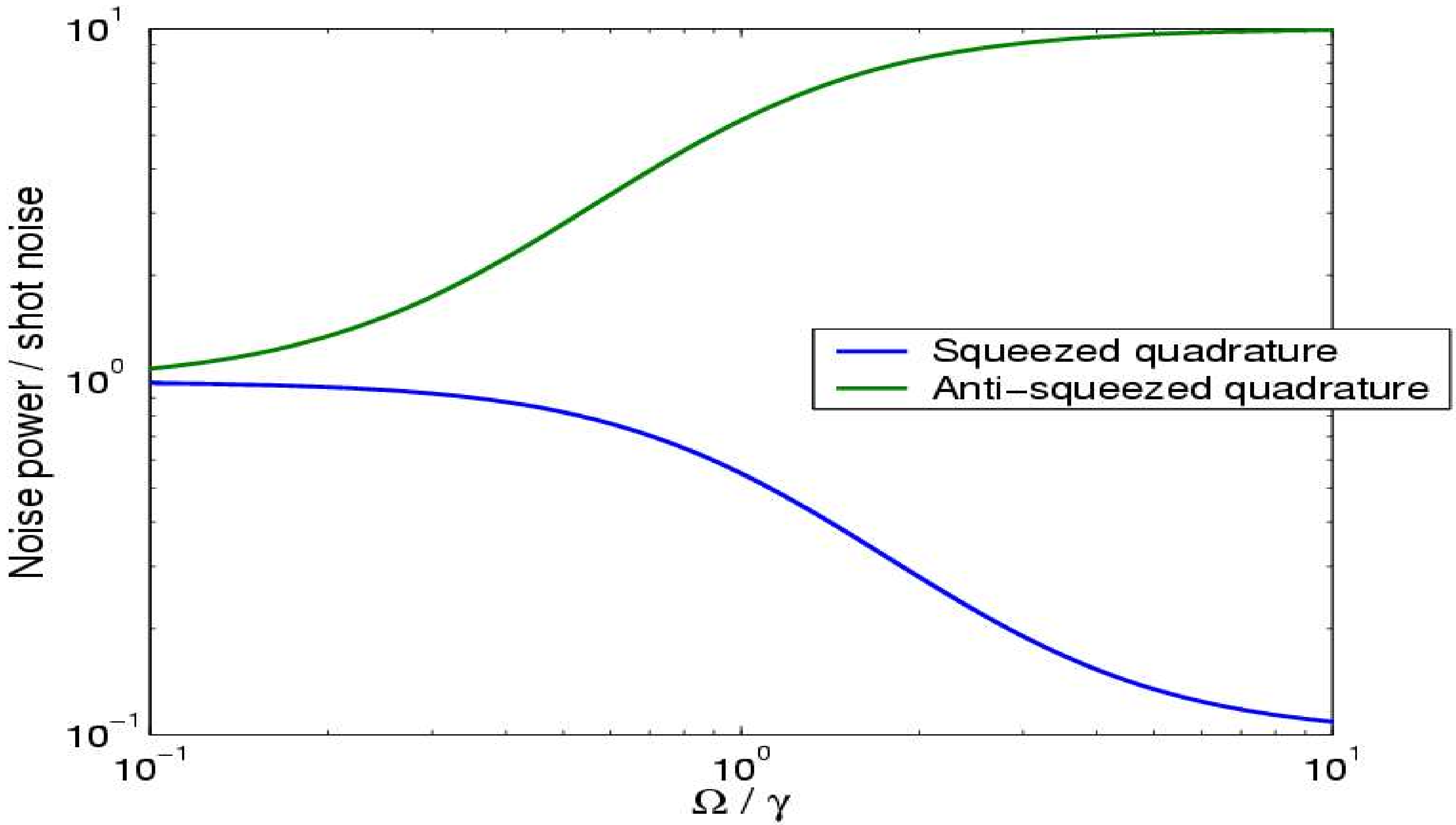
Filtered squeezed state.



Operation of squeeze filter

- Cavity is locked on resonance to the carrier frequency.
- Fields at frequencies within the linewidth of the cavity propagate inside the cavity and are transmitted. Fields with other frequencies are reflected. Cavity mirrors should be matched to provide a high transmission.
- For the frequencies which are transmitted, unsqueezed vacuum fields replace what is lost to transmission in the cavity.
- If we use the reflected fields, then losses in the cavity don't matter, because the squeezed fields at high frequency do not sample them.

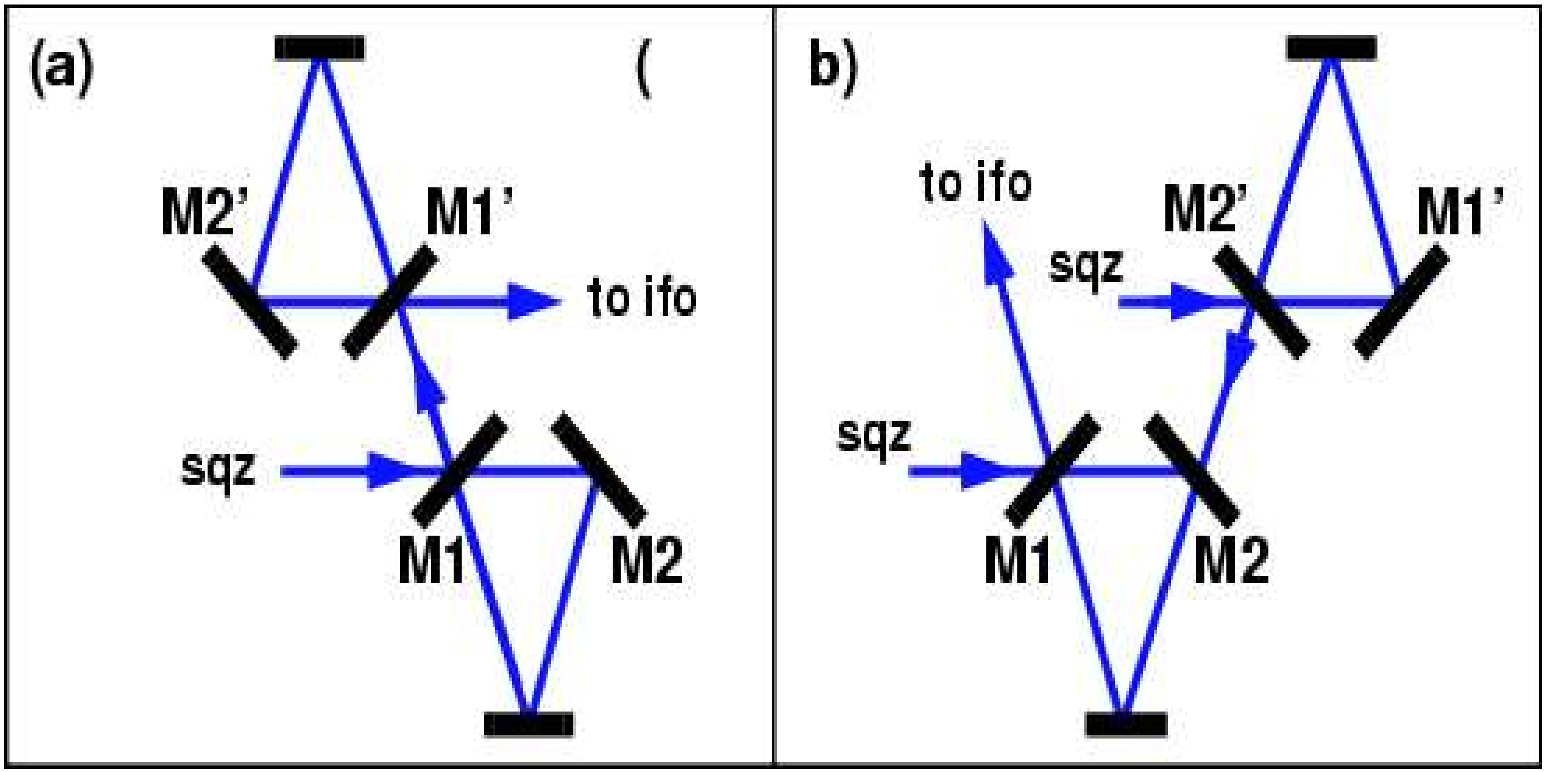
Performance of filter



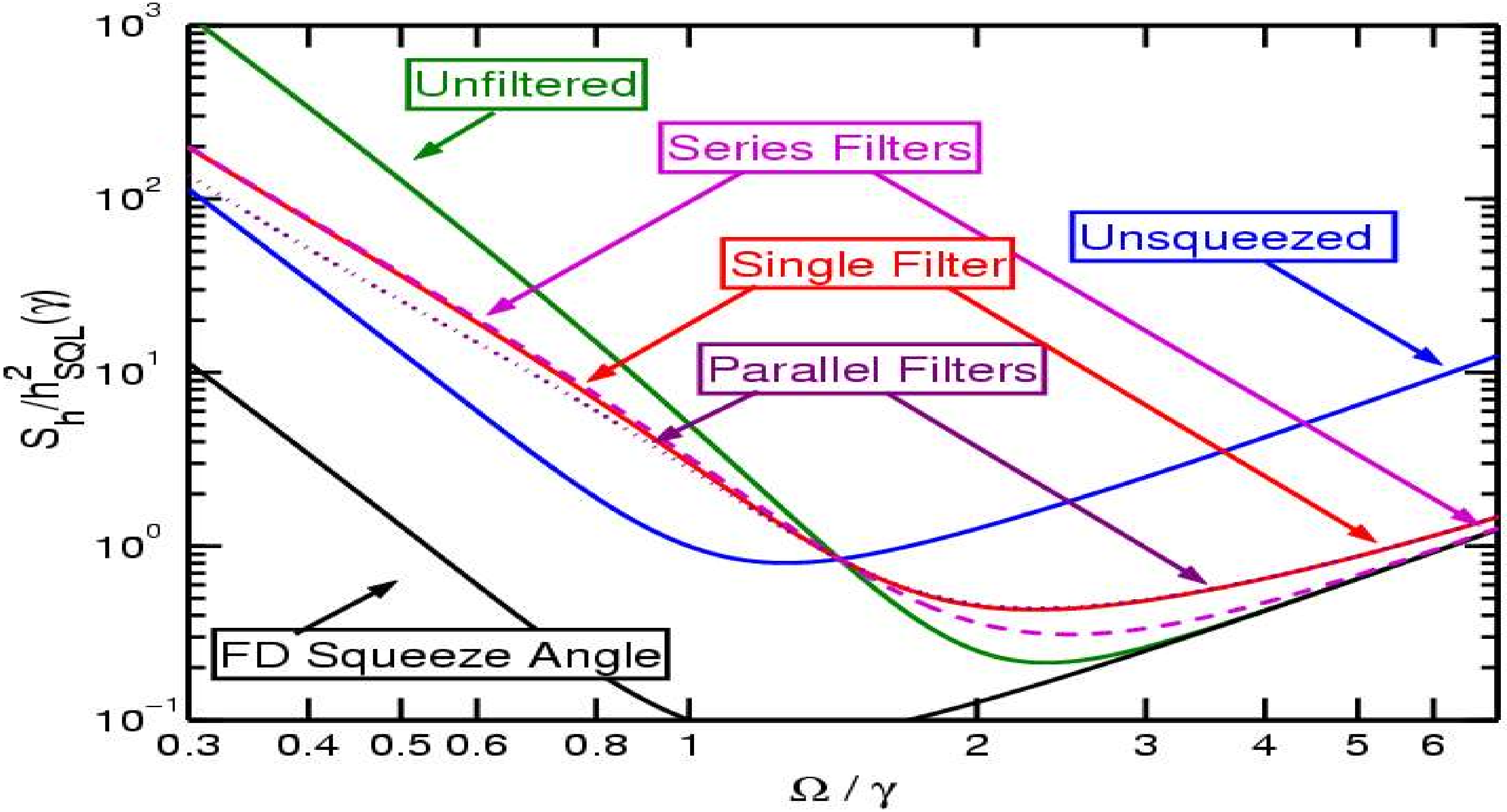
Multiple filters

Series

Parallel



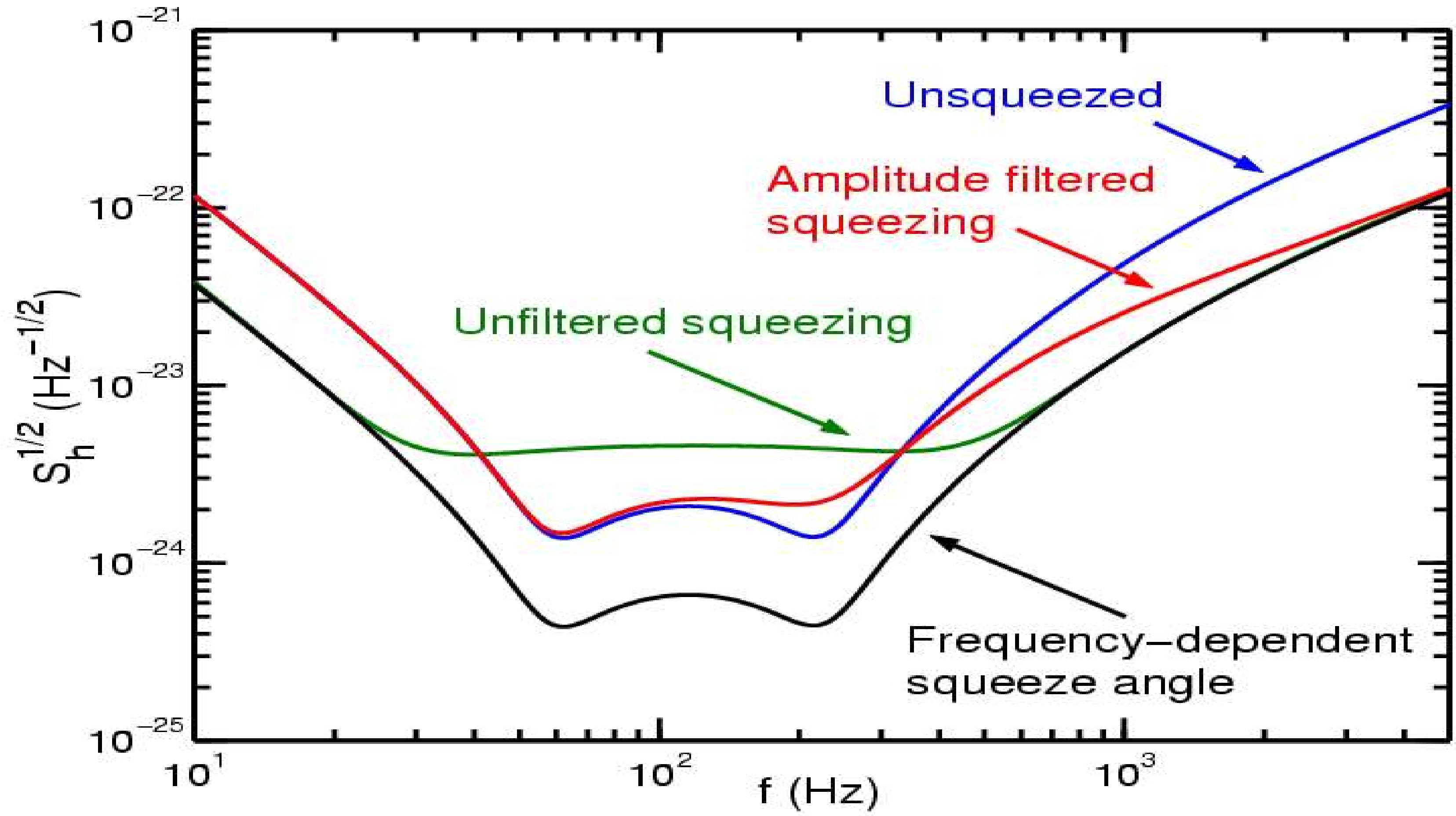
Multiple filter performance



Astrophysical sources

Configuration	$\frac{\gamma_f}{\gamma}$	Stochastic	NS Inspiral	Periodic
Conventional interferometer	–	1.00	1.00	1.00
Unfiltered fixed-angle squeeze	–	0.32	1.16	3.16
Single filter	1	0.89	1.00	3.03
Single filter	5	0.99	0.98	1.89
Series filter	$1/\sqrt{2}$	0.98	1.02	3.03
Series filter	$5/\sqrt{2}$	1.00	1.01	1.86
Parallel filter	$\sqrt{2}$	0.89	1.09	1.12
Parallel filter	$5\sqrt{2}$	0.99	0.98	2.24
FD squeeze	–	3.16	3.16	3.16

Advanced LIGO



Advanced LIGO performance

Configuration	$\frac{\gamma_f}{100\text{ Hz}}$	NS Inspiral	$\frac{1}{\sqrt{S_h}}\left(\frac{\Omega}{2\pi}=1\text{ kHz}\right)$	$\frac{1}{\sqrt{S_h}}\left(\frac{\Omega}{2\pi}=10\text{ kHz}\right)$
SR interferometer	–	1.00	1.00	1.00
Unfiltered fixed-angle squeeze	–	0.654	3.16	3.08
Single filter	3	0.854	2.39	3.07
Single filter	5	0.924	1.89	3.05
Single filter	10	0.974	1.35	2.96
FD squeeze	–	3.16	3.16	3.16

Other uses for transmissive cavity

- The transmitted beam could be used for other purposes – monitoring the output of the squeezer.
- Instead of locking the cavity on resonance, lock it midway between resonances. Low frequencies will then be reflected, and the frequencies around one half FSR will be transmitted. This allows for you to use the low frequency portion for the IFO (it could then be filtered to produce the required squeeze angle), while the transmitted portion could be used for monitoring.

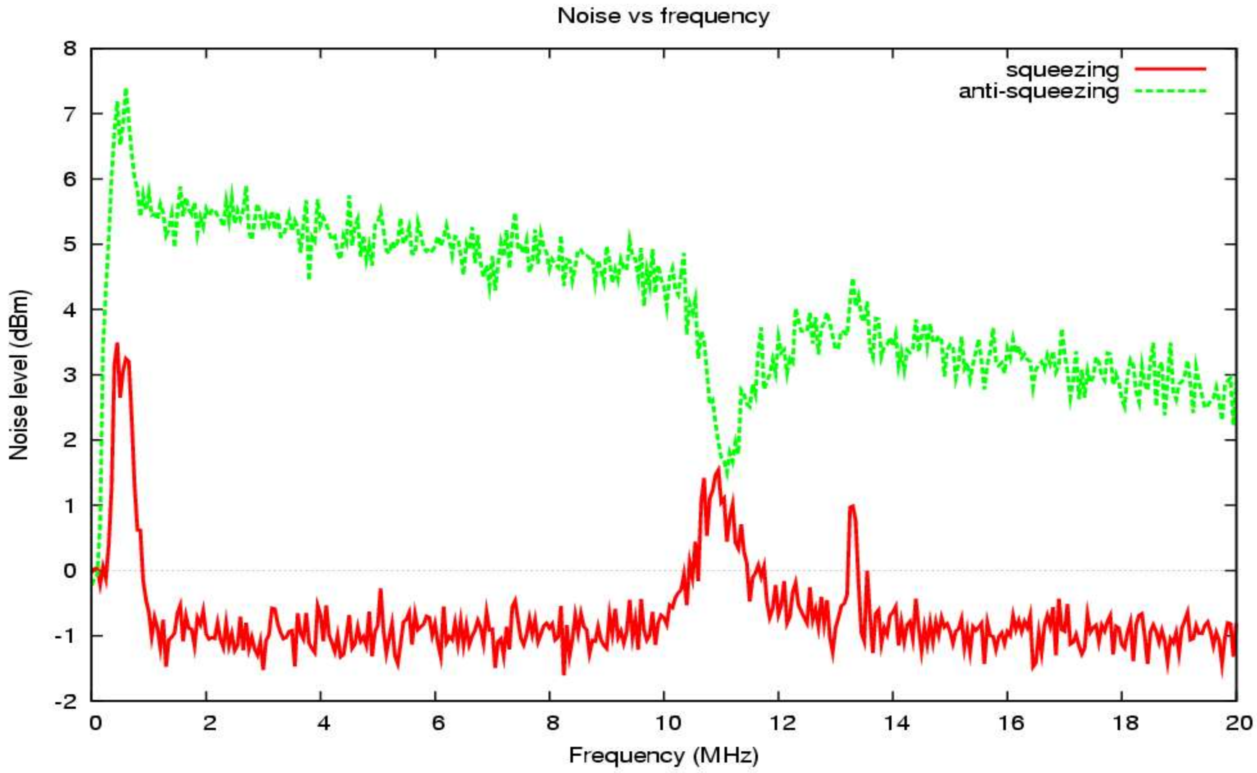
Experimental test

- Performed using MIT squeezer. Squeezed vacuum was injected to a cavity and the reflected beam was measured.
- There was a problem with operating the cavity on resonance due to a large amount of noise at low frequencies that masks the filtering effect.
- The cavity was instead detuned so that the cavity filters at the detuned frequency, rather than around zero frequency.

Detuned filter performance

- One sideband is transmitted, but the other is absorbed, so the correlation (squeezing) is destroyed. But since one sideband is reflected, the resulting noise is not at shot noise, but is a factor of 2 below the anti-squeezed noise at all quadratures.

Experimental data



Conclusions

- Squeeze amplitude filters may provide improvements to the SNR of various sources, depending on the particular configuration, in a squeezed input interferometer.
- Squeeze amplitude filters do not nearly provide the benefit of squeeze angle filters, but they may be easier to build and just as good in some cases (when other noise sources prevent lowering the quantum noise at some frequencies) and may also other uses.
- Amplitude filters are not a solution, but they are a tool which may be useful as we begin using squeezed states in interferometers.