Frequency Dependent Squeezing Roadmap toward 10dB

Tomoki Isogai

LIGO MIT

In collaboration with:

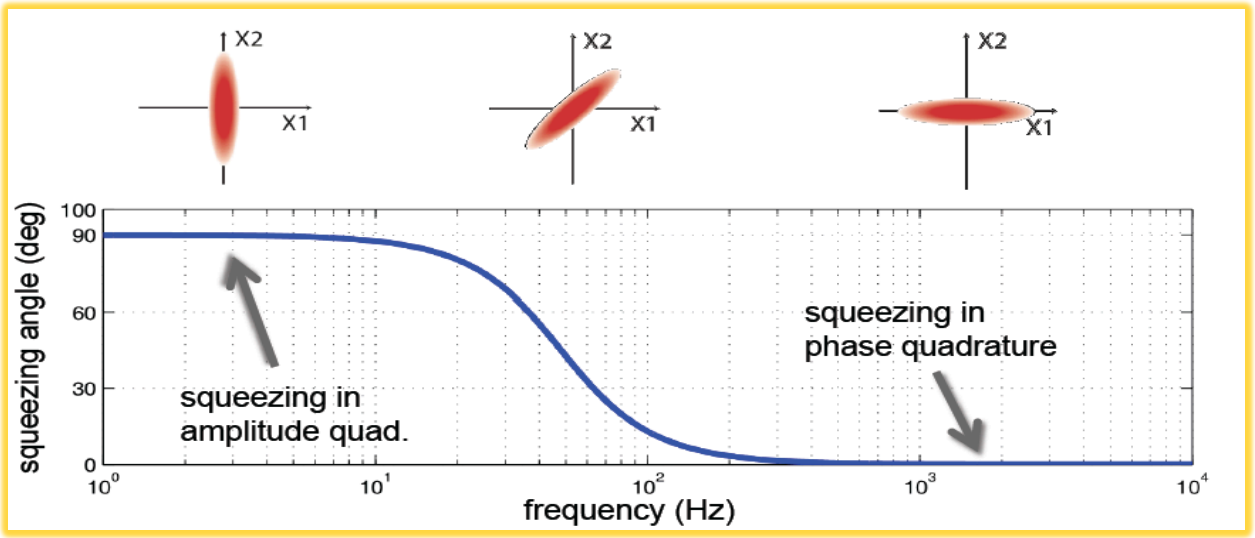
Eric Oelker, John Miller, Patrick Kwee, Maggie Tse,

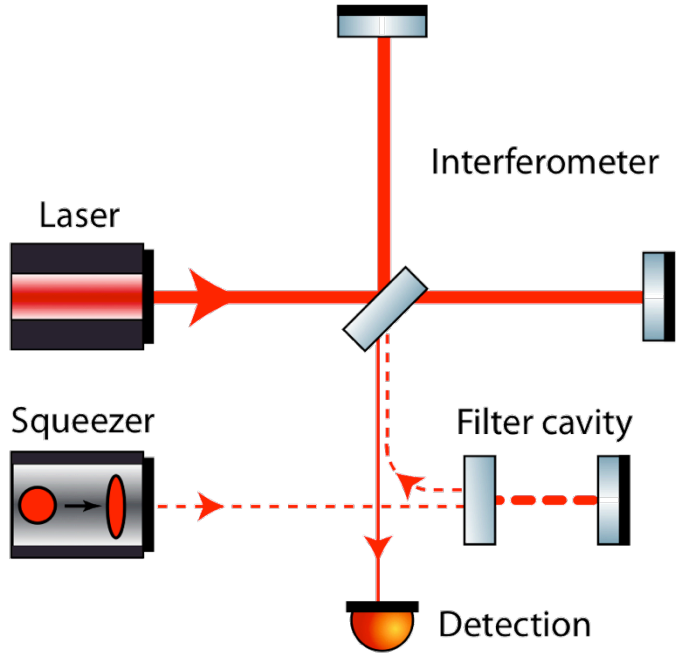
Lisa Barsotti, Mattew Evans, Nergis Mavalvala

G1500727

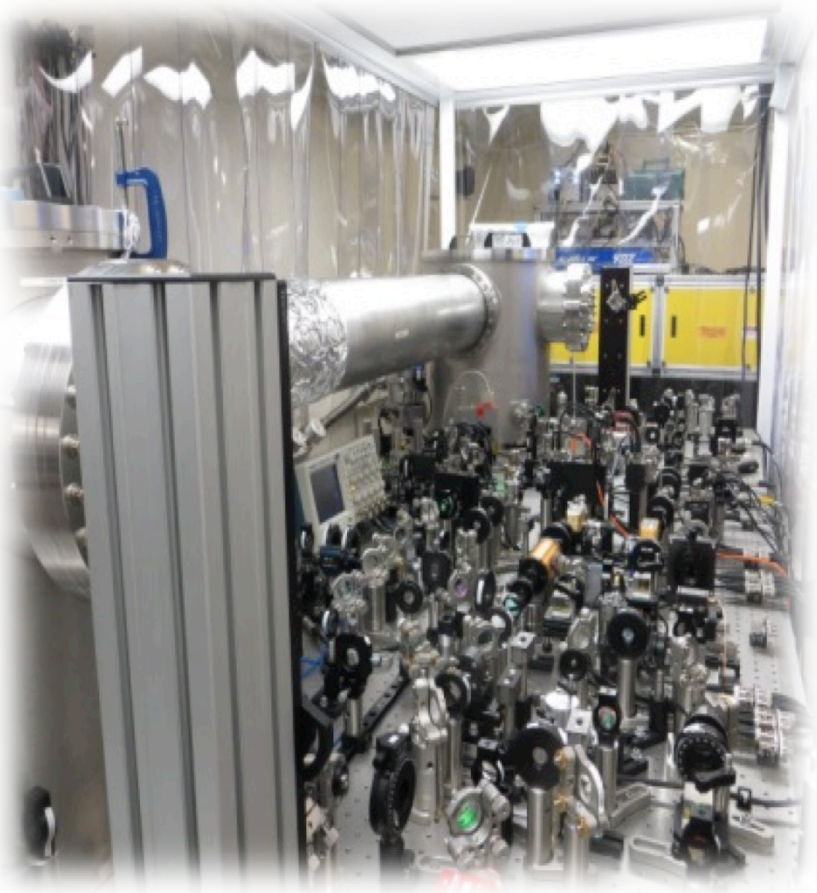
Audio-band frequency dependent squeezing is now real.

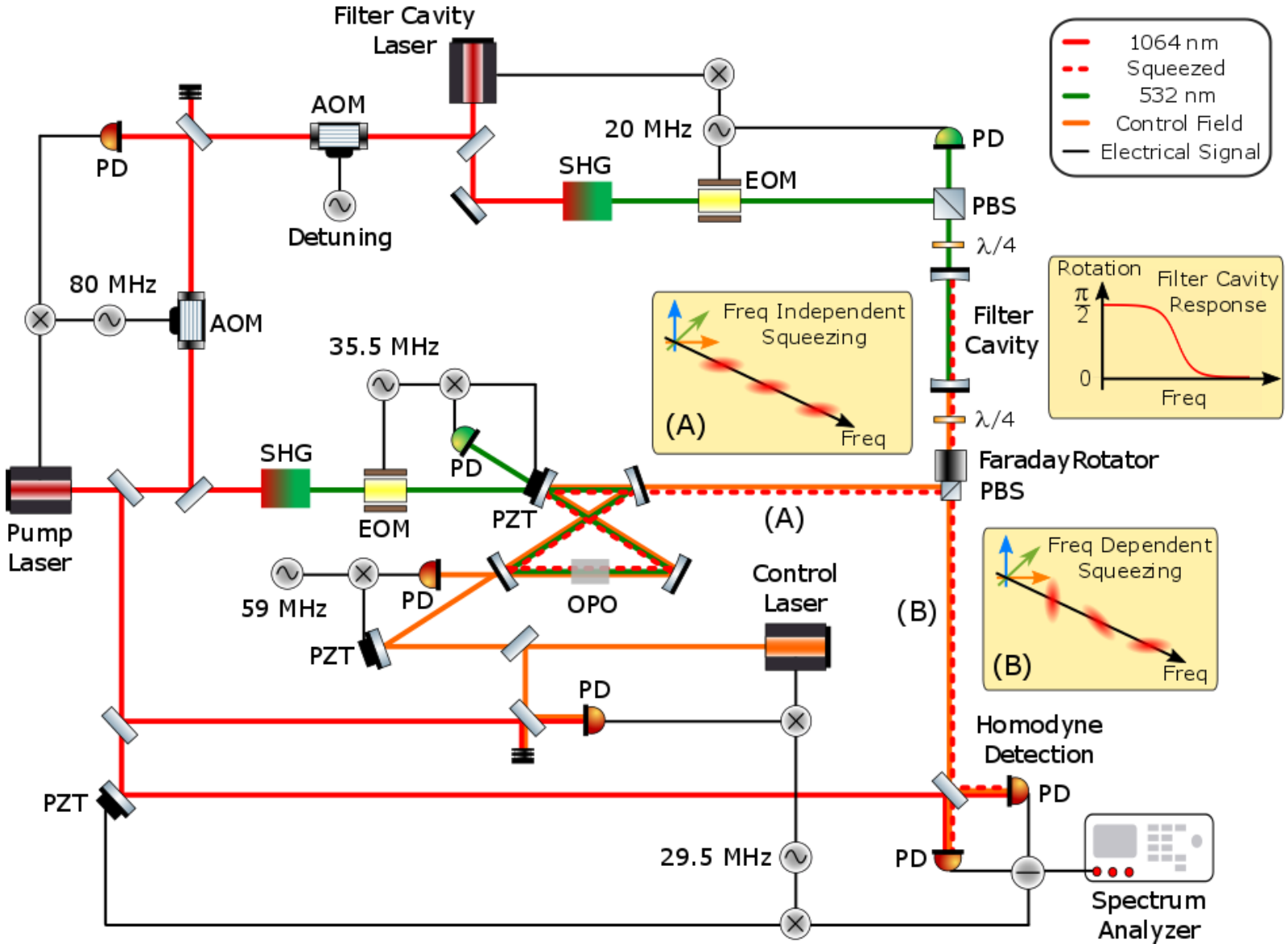
- For aLIGO and beyond, almost all the detection band will be limited by the quantum noise, and we need frequency dependent squeezing
- Audio-band frequency dependent squeezing using a filter cavity was demonstrated at MIT





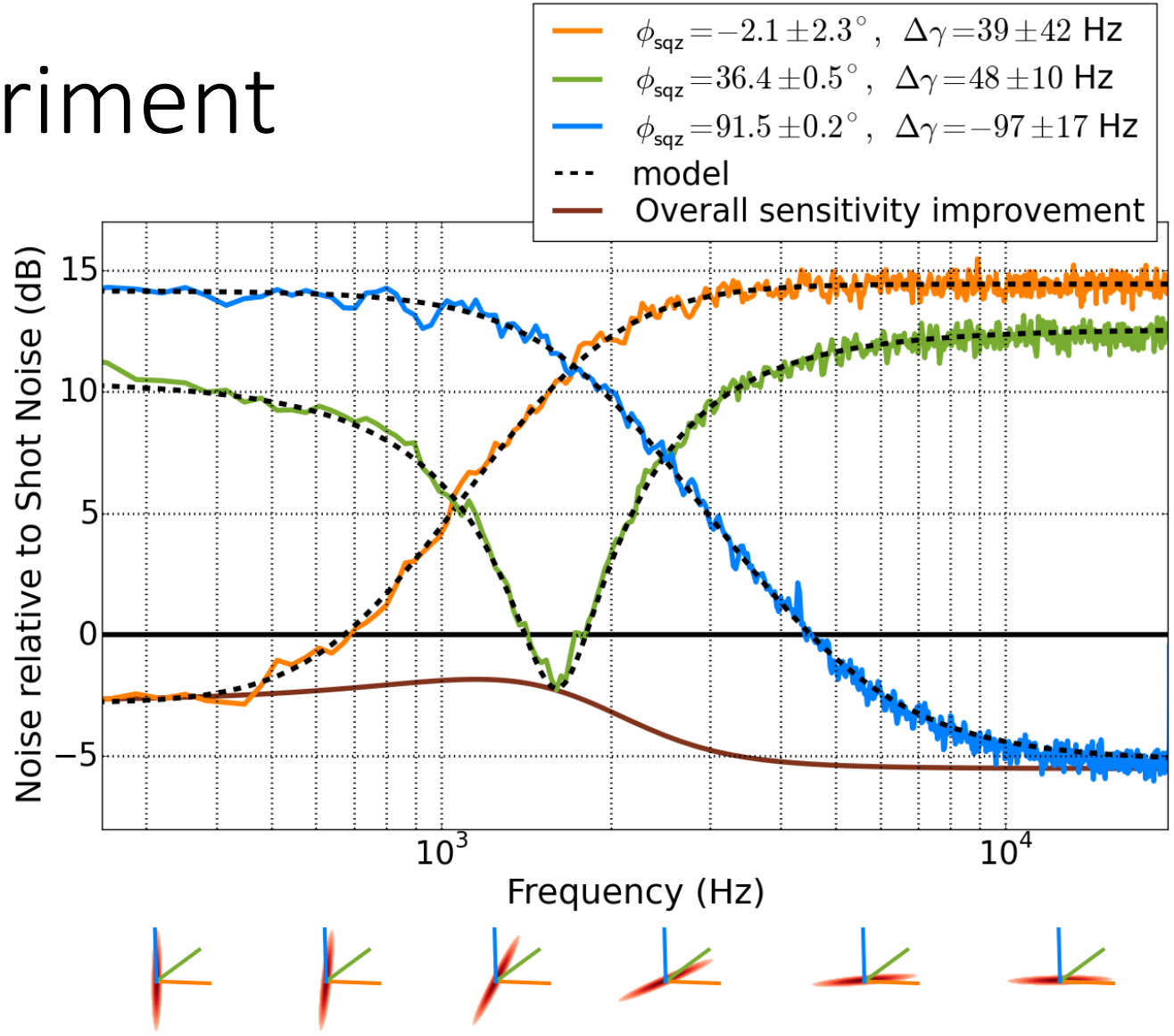
MIT Filter Cavity Demonstration





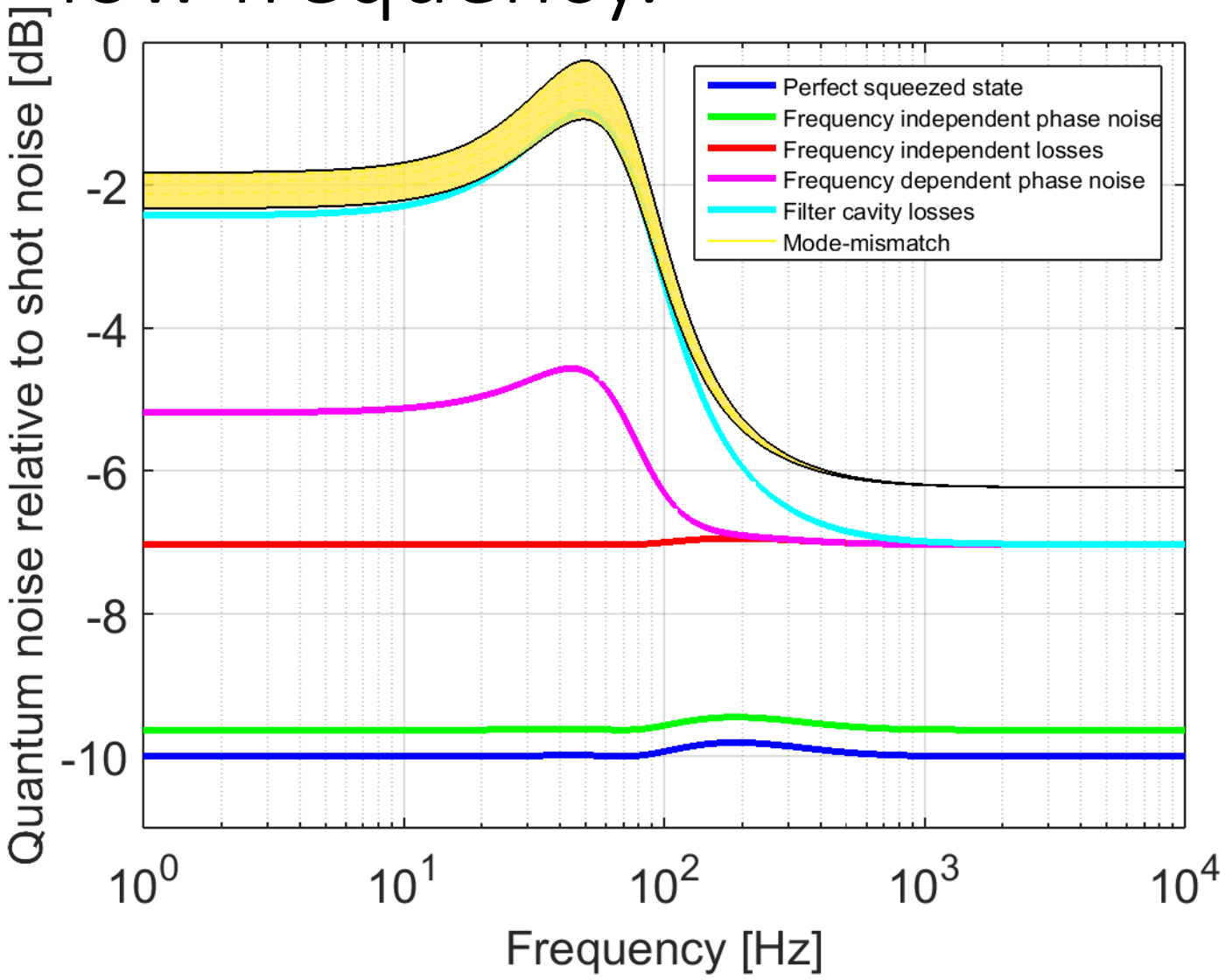
MIT Filter Cavity Experiment

- Cavity line width: about 1.2 kHz
- 5.5dB at high frequency, 2.5 dB at low frequency
- Frequency dependent squeezing is a potential early upgrade for aLIGO
- Verified that the model [1] accounts for most degradation factors



[1] P. Kwee et al. Phys. Rev. D 90, 062006 (2014).

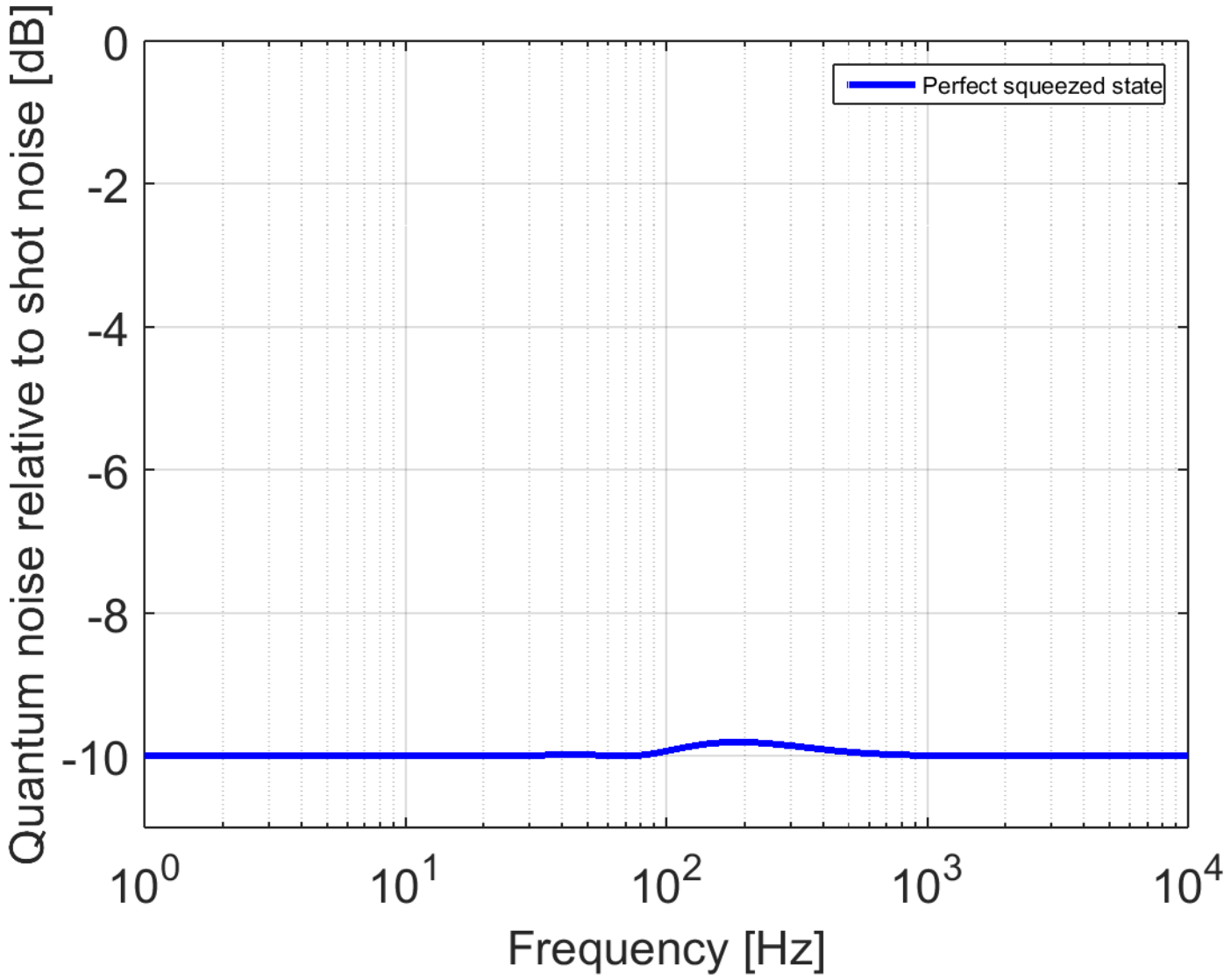
For aLIGO, we can aim for 2 dB squeezing at low frequency.



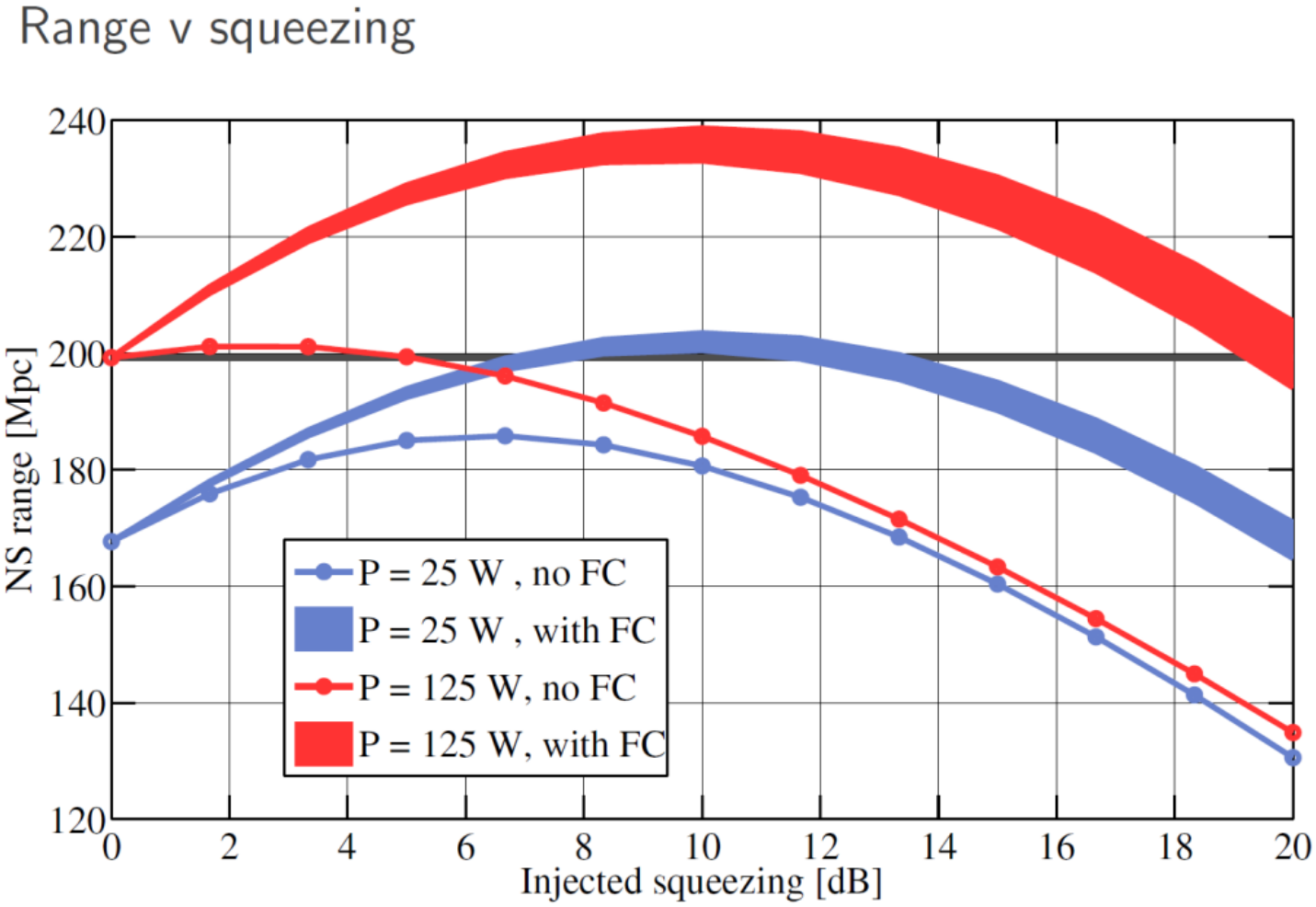
Parameter	Value
Filter cavity length	16 m
Filter cavity loss	16 ppm
Frequency- independent loss	10 %
Mode-mismatch (Squeezer – Filter cavity)	2 %
Mode-mismatch (Squeezer – Local oscillator)	5 %
Frequency-independent phase noise (RMS)	30 mrad
Filter cavity length noise (RMS)	0.3 pm
Injected squeezing	10 dB

P. Kwee et al. Phys. Rev. D 90, 062006 (2014).

Squeezing injected: 10dB



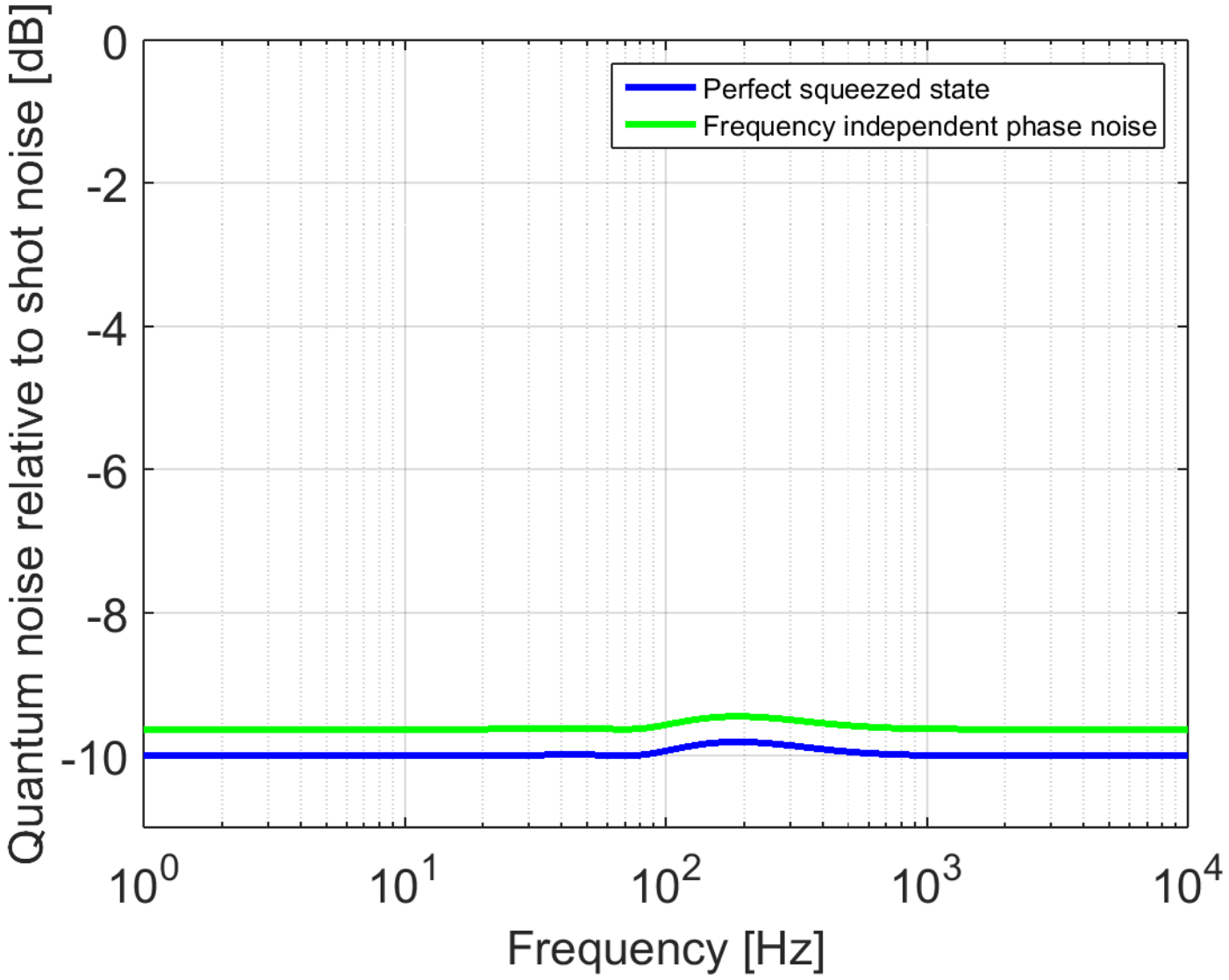
For aLIGO parameters, about 10dB injection is optimal.



- Injecting more squeezing is not always a good thing
- Coupling from anti-squeezing can increase the noise

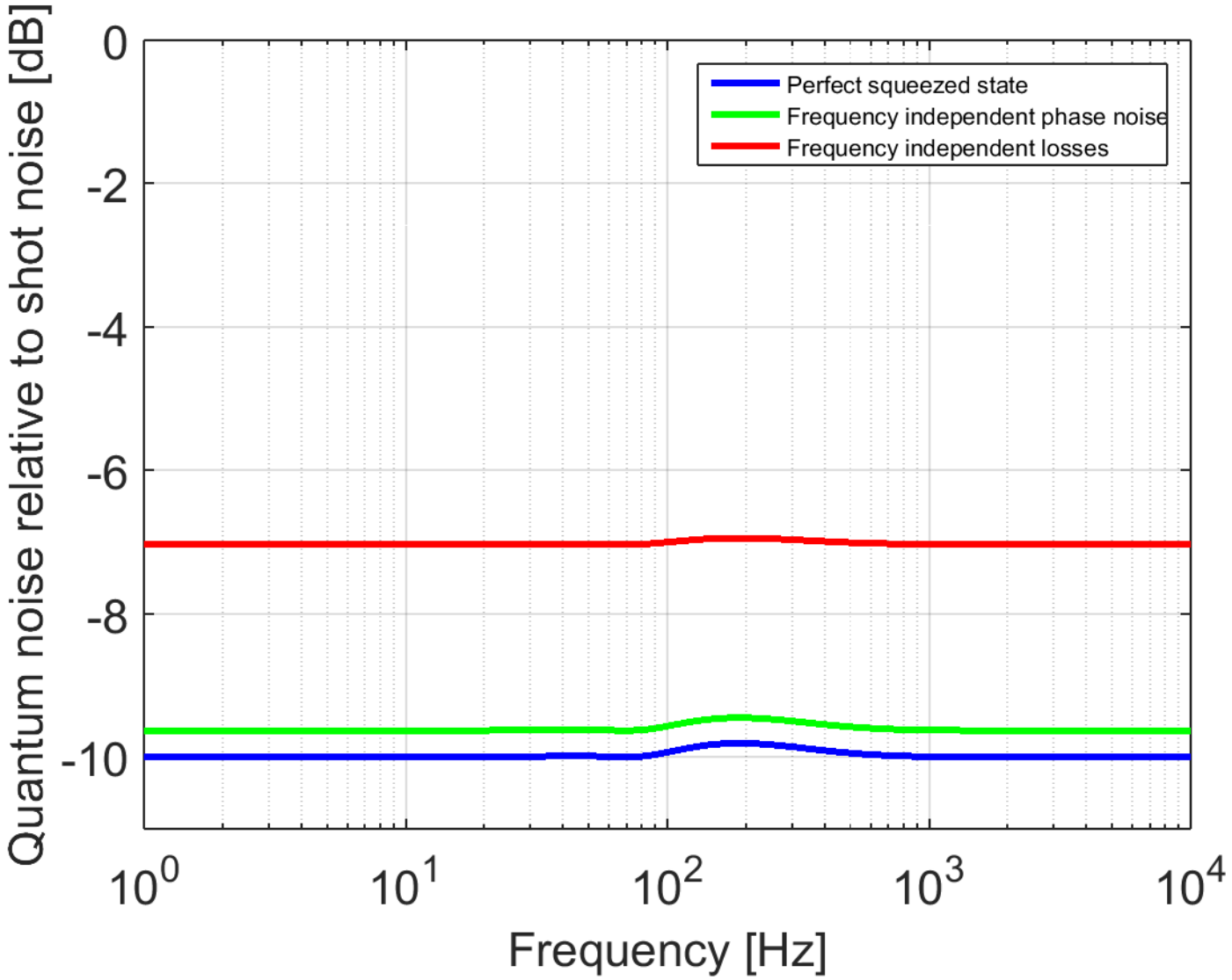
Figure Credit: John Miller

Frequency independent phase noise: 30 mrad



- During the H1 squeezing test, 37 +/- 6 mrad phase noise was measured
- This number is very conservative; For the new in-vacuum OPO design, we can expect a lot of improvement

Frequency independent loss: 10% total



- Faraday isolators
- Wave plates / PBS
- OMC
- Polarization mismatch for pickoff
- PD Quantum Efficiency
- etc.

Frequency Dependent Phase Noise

- Filter cavity length fluctuation adds a phase noise in a frequency dependent way
- We had ~35 mrad phase noise at MIT, but we did not have any vibrational isolation from the ground

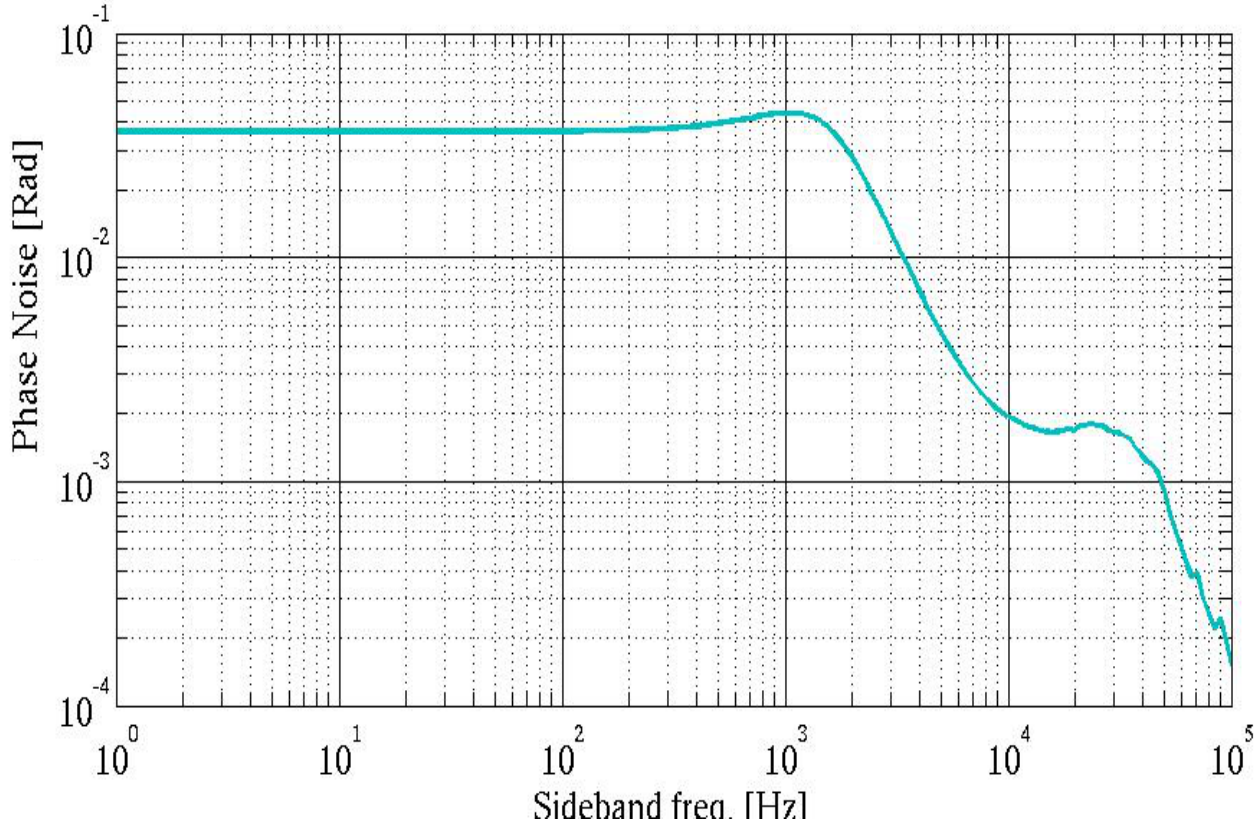
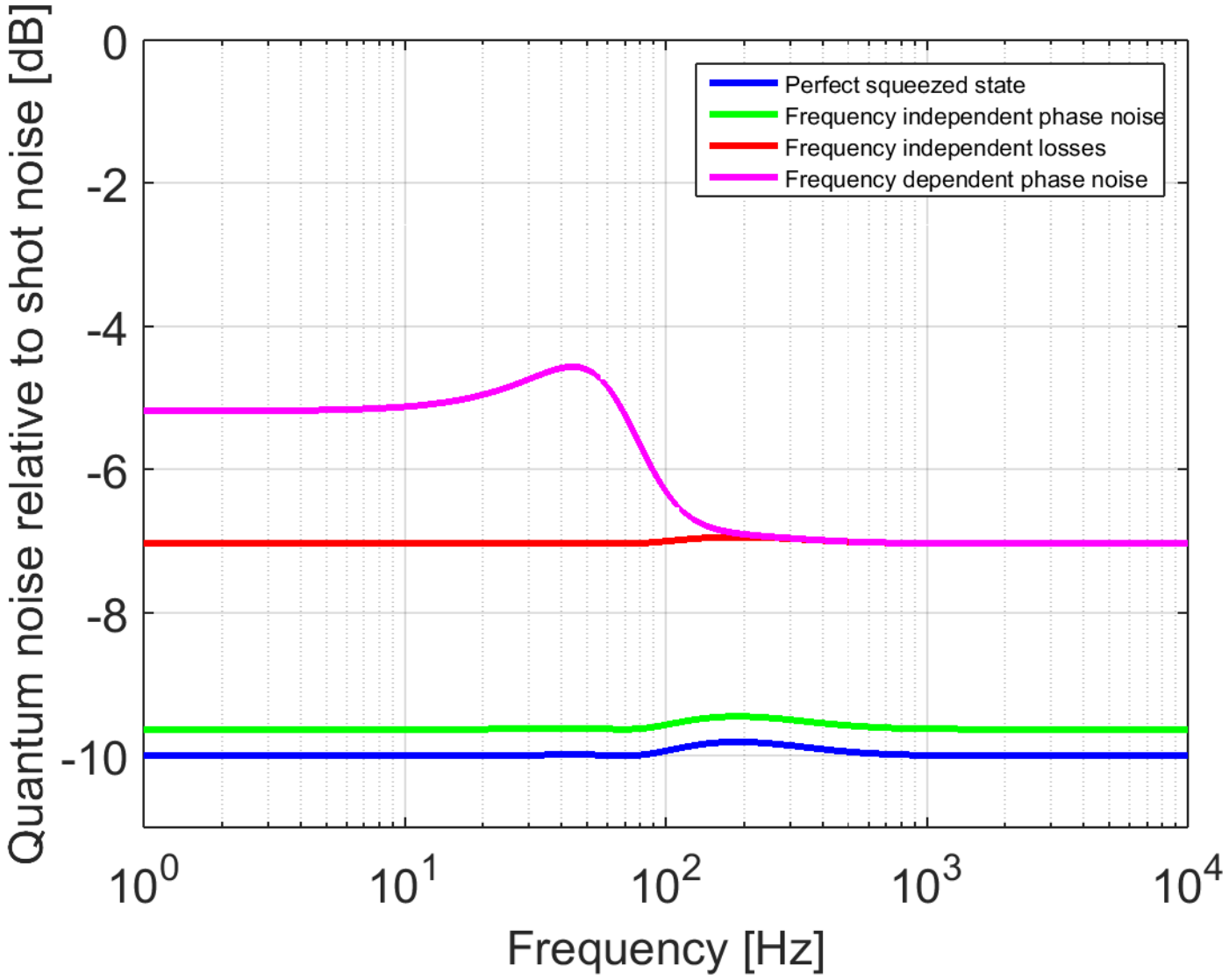


Figure Credit: Eric Oelker

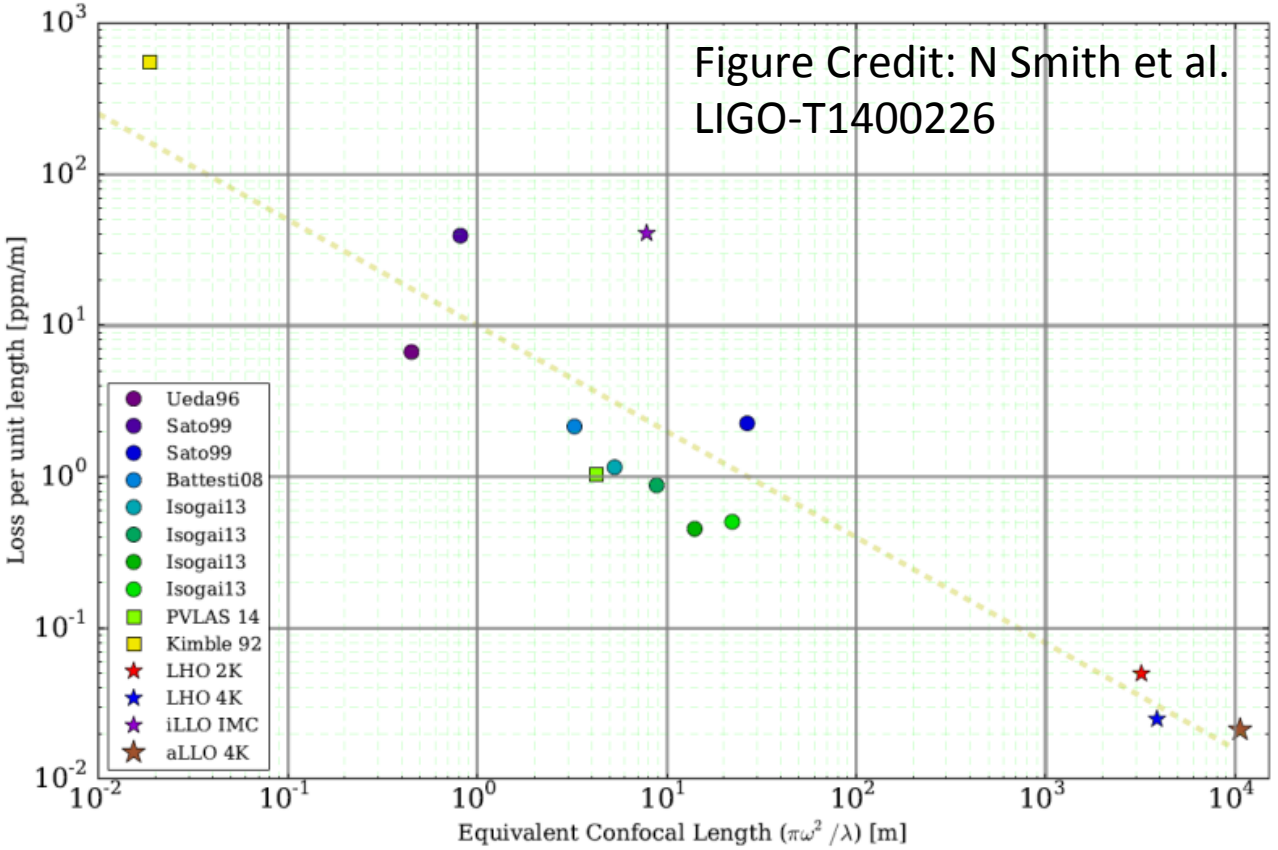
Frequency Dependent Phase Noise



- For aLIGO, we can expect the filter cavity length fluctuation to be much smaller (suspended, in vacuum etc.)
- Cavity length noise: 0.3 pm

Frequency Dependent Loss

- Intra-cavity loss in the filter cavity causes frequency dependent loss
- At MIT, using various methods, the cavity mirror loss was characterized:
  - Over a range of a few mm spot size, loss does not depend on spot size strongly
  - Spot position seems to be more important



Isogai et. al. Optics Express 21 (2013)
LIGO-T1400226

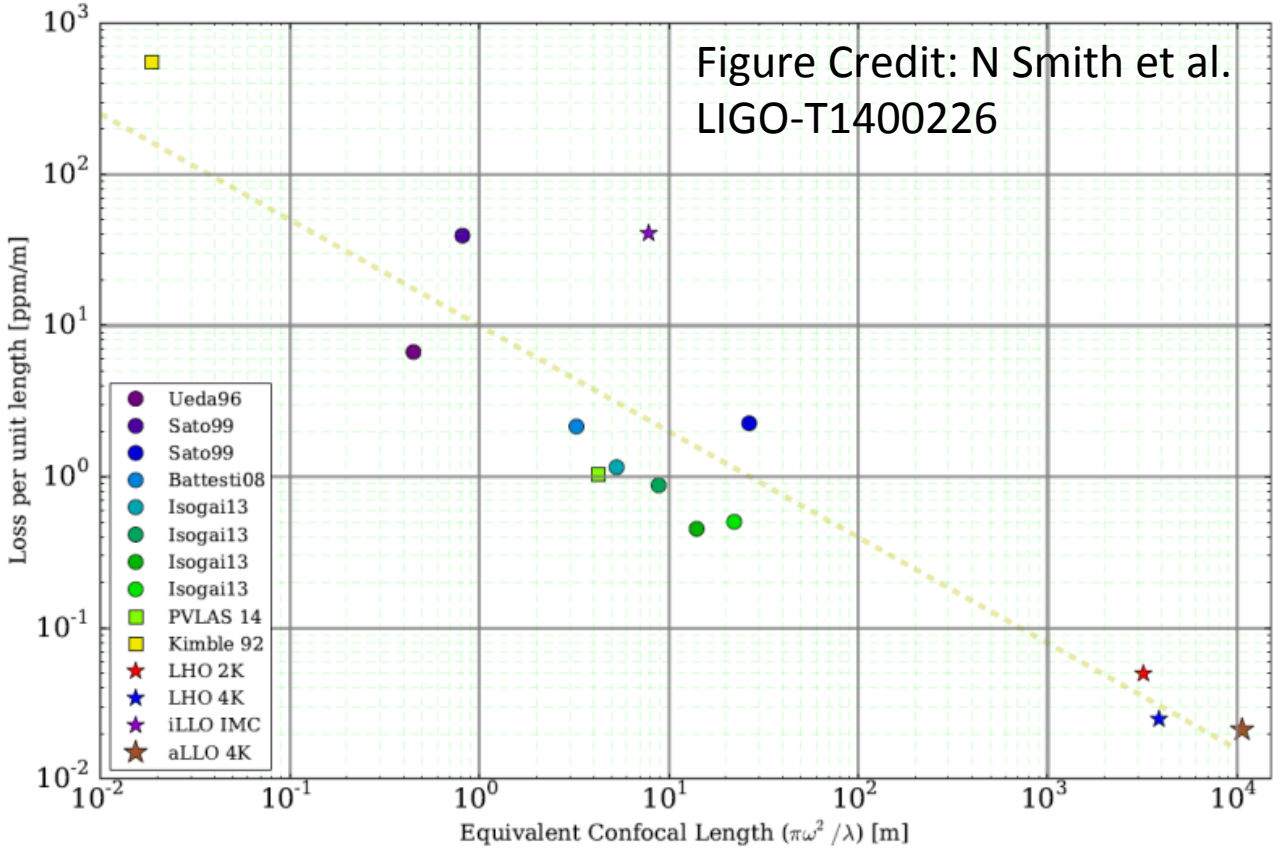
Frequency Dependent Loss

- A rough power law:

  Lrt ~ $10\ ppm\ (d/meter)\hat{}0.3$

  Lrt: roundtrip loss (ppm)

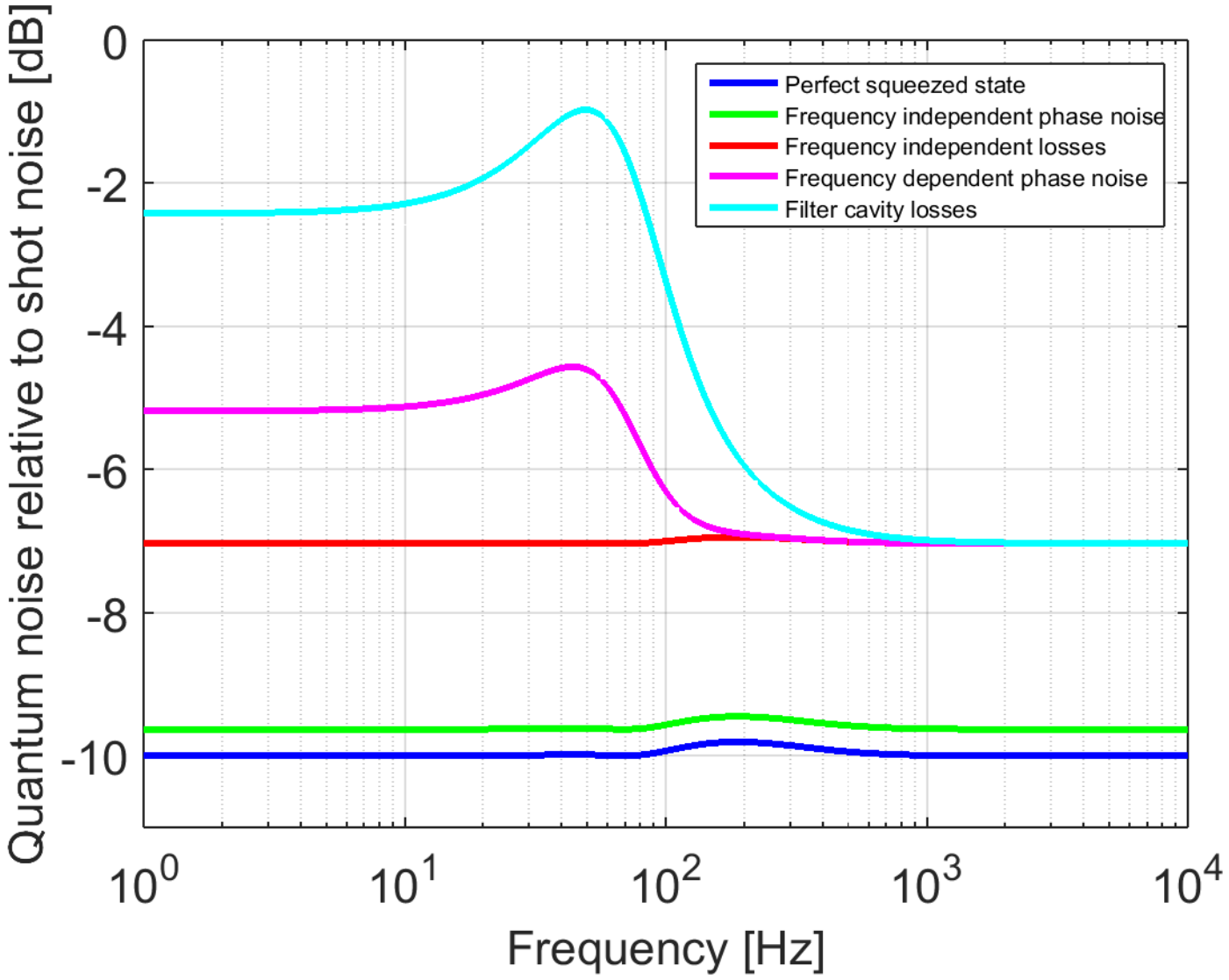
  d: cavity confocal length (meter)
- Need to check if the extrapolation to a different length is really valid



Cavity Length	16m	100m	300m (@ 1560nm)	1km	4km
Roundtrip Loss	16 ppm	40 ppm	20ppm	80 ppm	120 ppm

Isogai et. al. Optics Express 21 (2013)
LIGO-T1400226

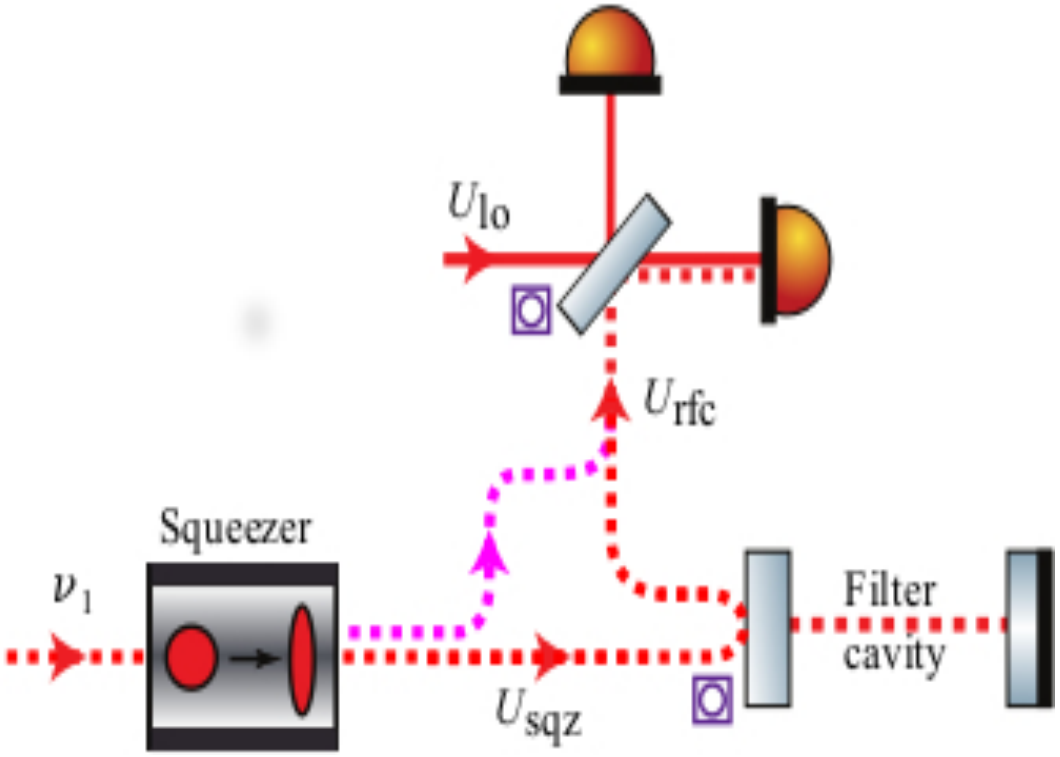
Frequency dependent loss: 16m cavity, 16ppm loss



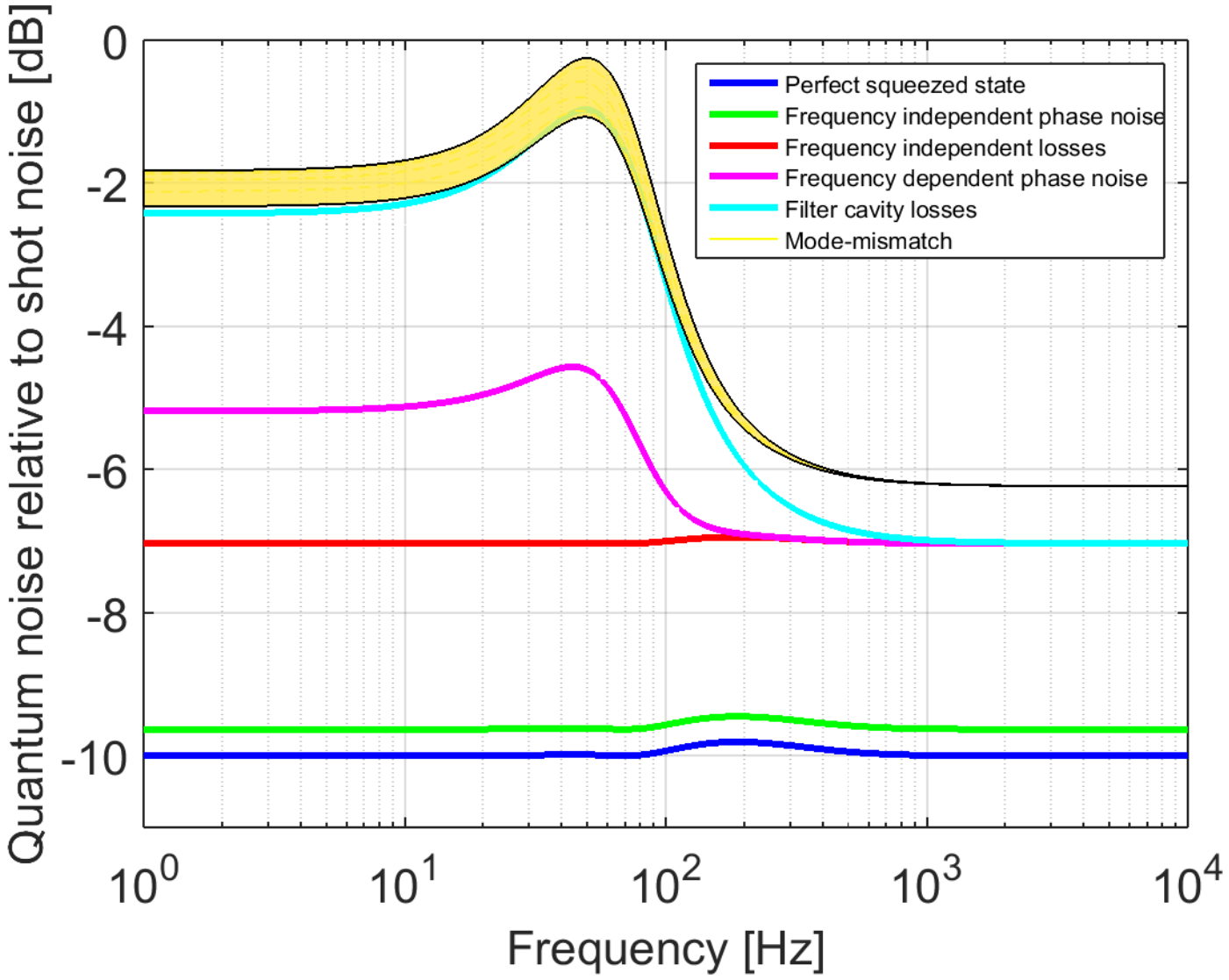
- A big contributor to degrade squeezing in low frequency, where the light couples into the filter cavity
- The peak @ 1.2kHz corresponds to the resonance of the filer cavity

Mode Mismatch

- Squeezed light that does not couple into the filter cavity contaminates our squeezing by mixing anti-squeezing
- This modifies our noise spectrum in a frequency dependent way
- Good mode matching into the filter cavity is essential

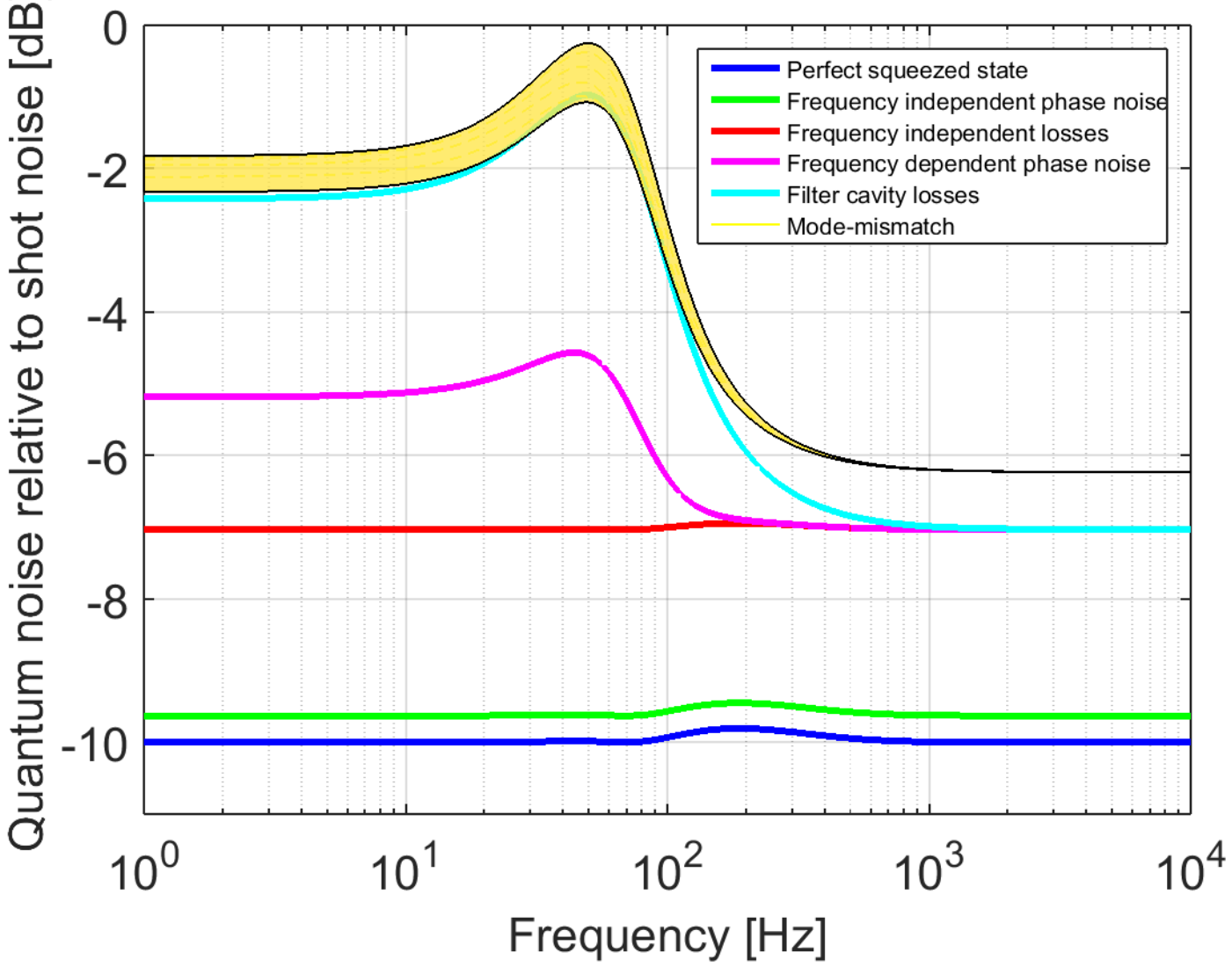


Mode Mismatch:



- From constraints that can easily be measured experimentally, we cannot completely specify the spectrum, and we get some range.

aLIGO with filter cavity:
2 dB @ low freq, 6dB @ high freq



Parameter	Value
Filter cavity length	16 m
Filter cavity loss	16 ppm
Frequency- independent loss	10 %
Mode-mismatch (Squeezer – Filter cavity)	2 %
Mode-mismatch (Squeezer – Local oscillator)	5 %
Frequency-independent phase noise (RMS)	30 mrad
Filter cavity length noise (RMS)	0.3 pm
Injected squeezing	10 dB

With a realistic filter cavity, the binary neutron star range is ~236Mpc.

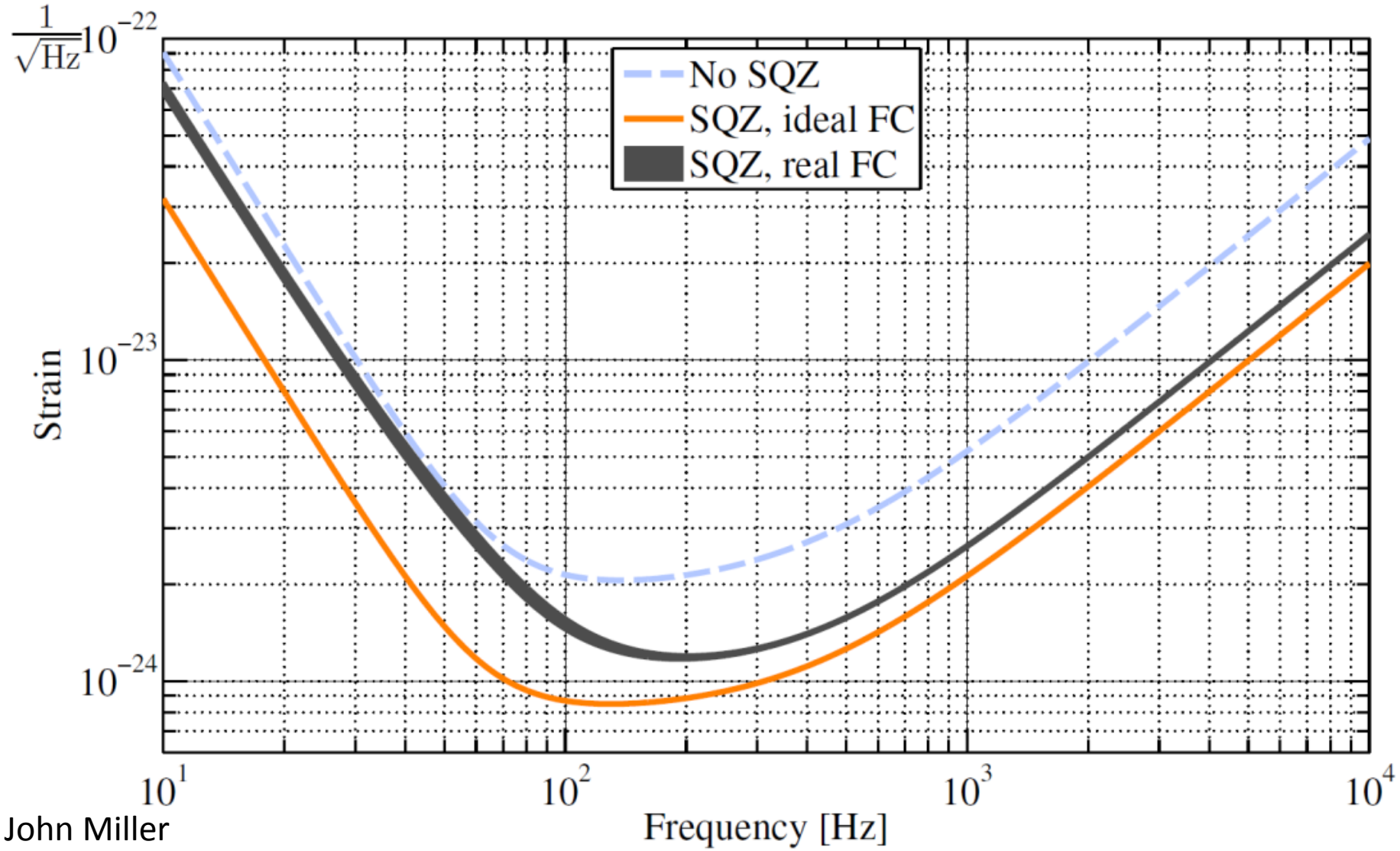
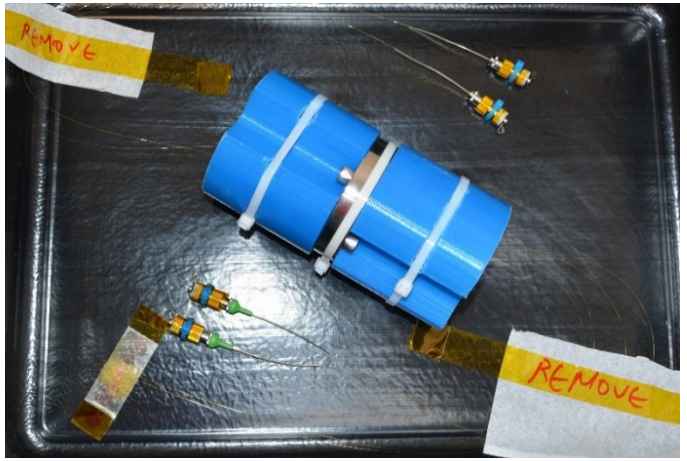


Figure Credit: John Miller

Getting ready for aLIGO installation

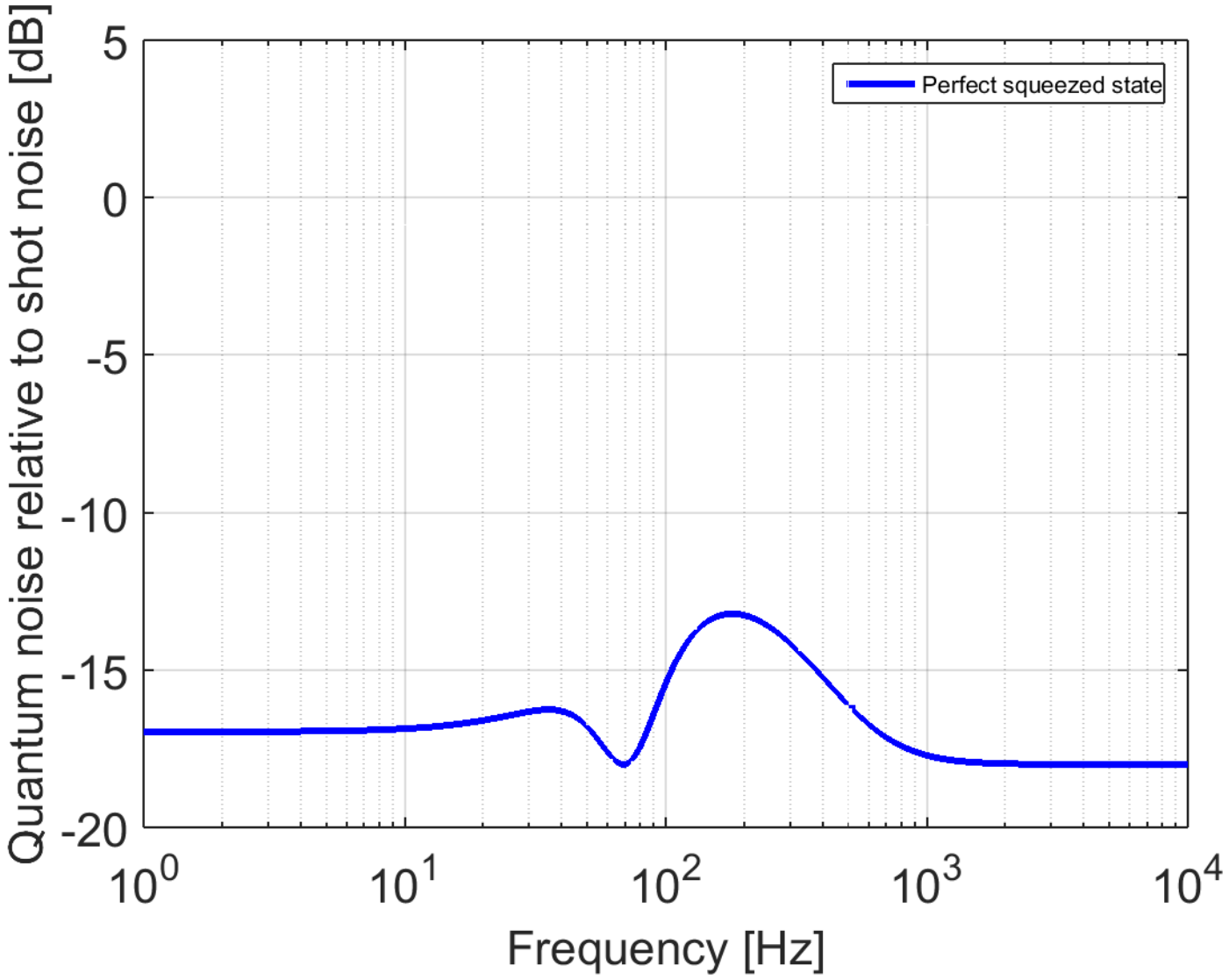
- Prototyping the in-vacuum OPO
  - Fiber coupling the pump and control fields
  - testing aLIGO squeezer control scheme
- Prototyping a full scale Filter Cavity
  - 16 meter filter cavity @ LASTI
  - Suspended optics
  - Combining with the in-vacuum OPO



PM Prototype

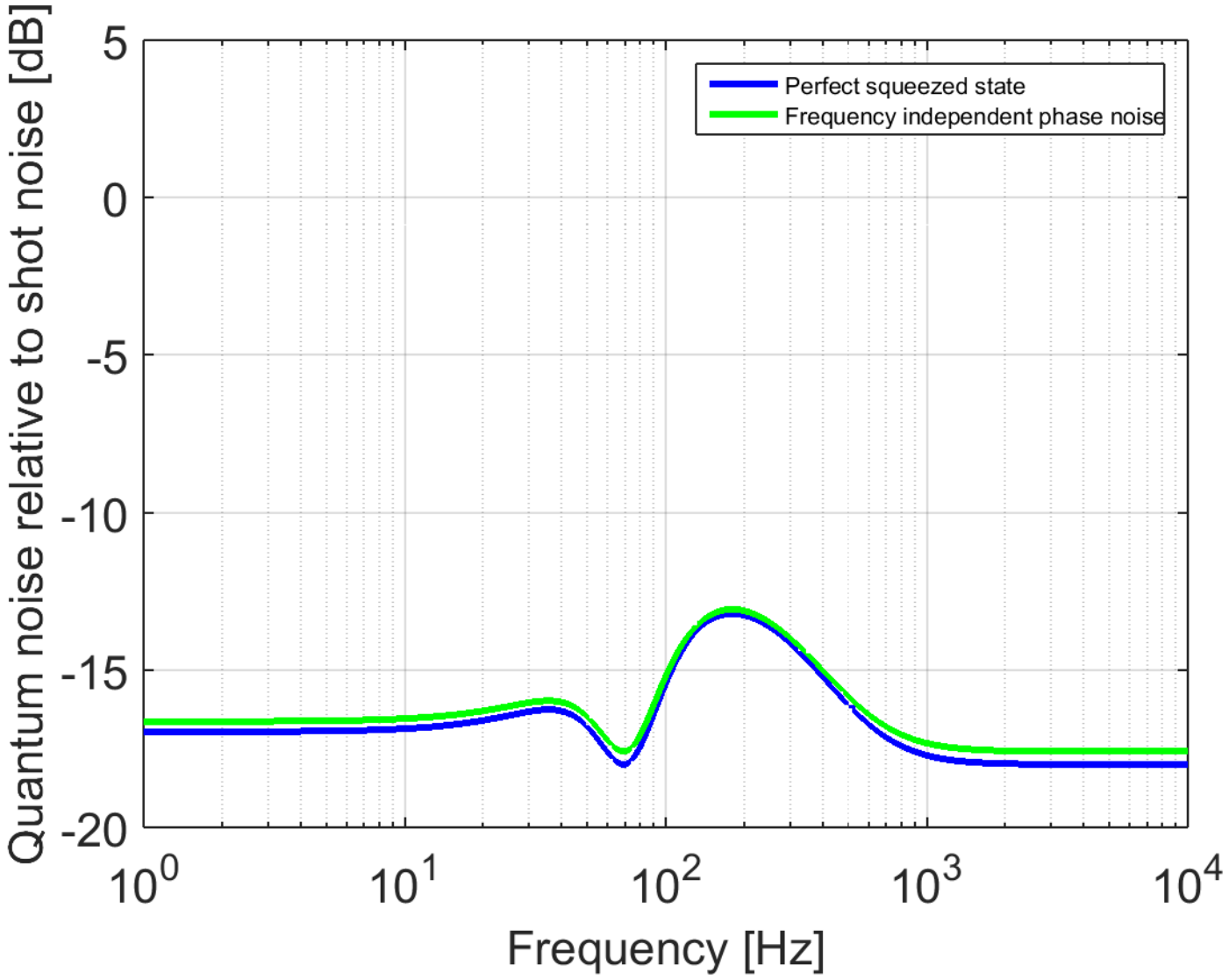
Can we achieve 10dB of squeezing at low frequency?

18dB of injected squeezing



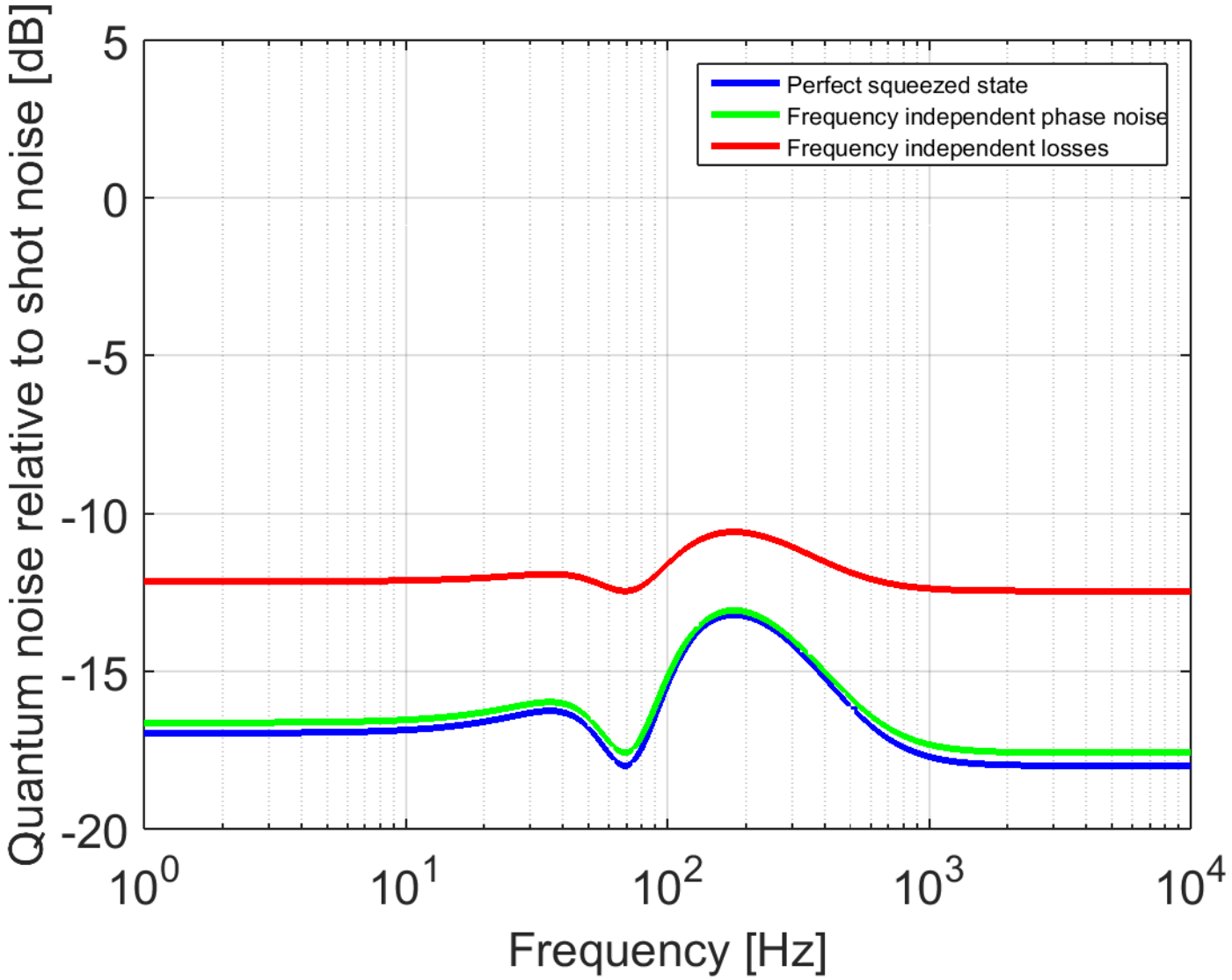
- Again, injecting more squeezing is not always better because of anti-squeezing coupling

Frequency independent phase noise: 5 mrad



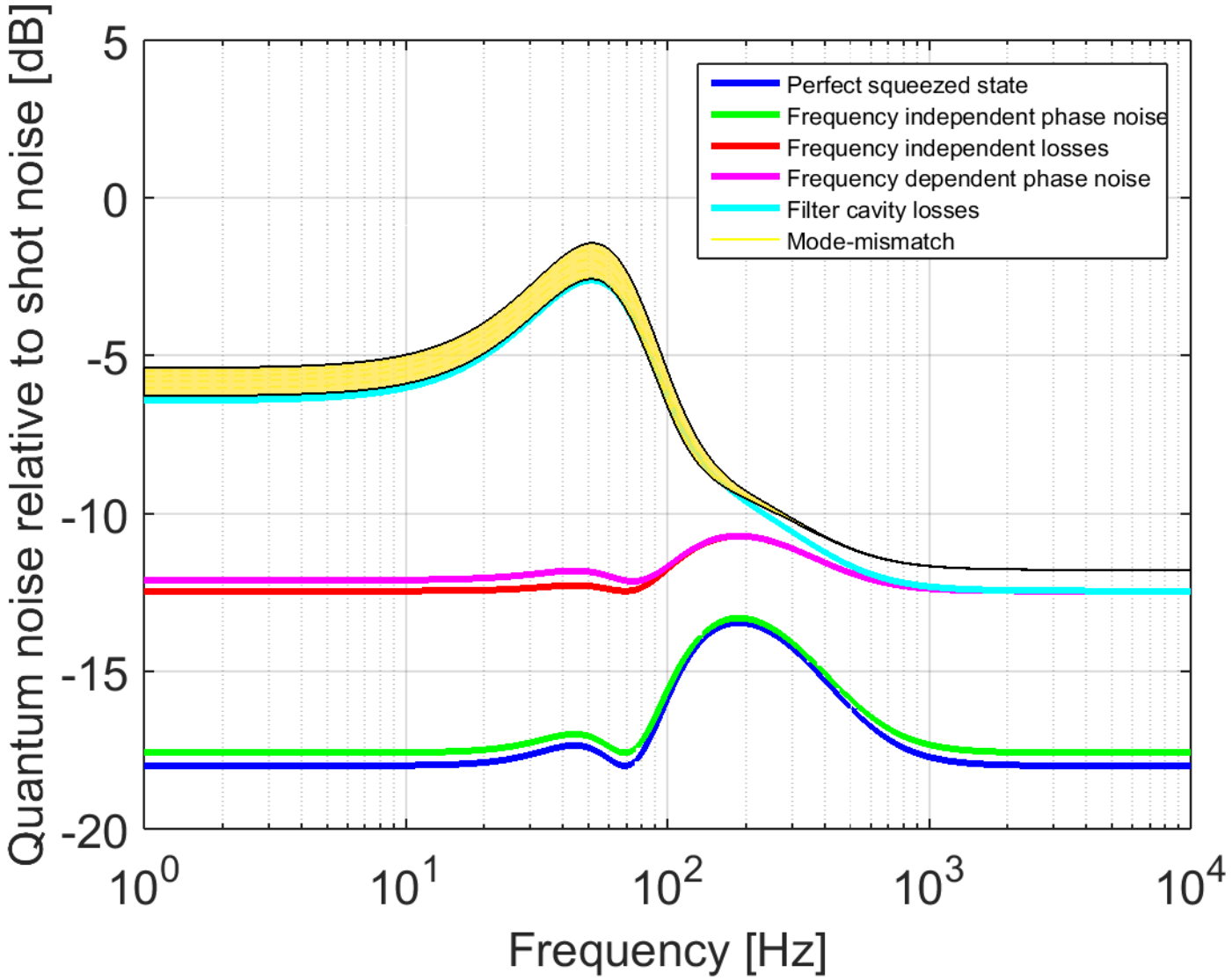
- 30 mrad -> 5 mrad
- May not be too crazy
- Not a big contributor to degrade squeezing (at this squeezing level)

Frequency independent loss: 4% total



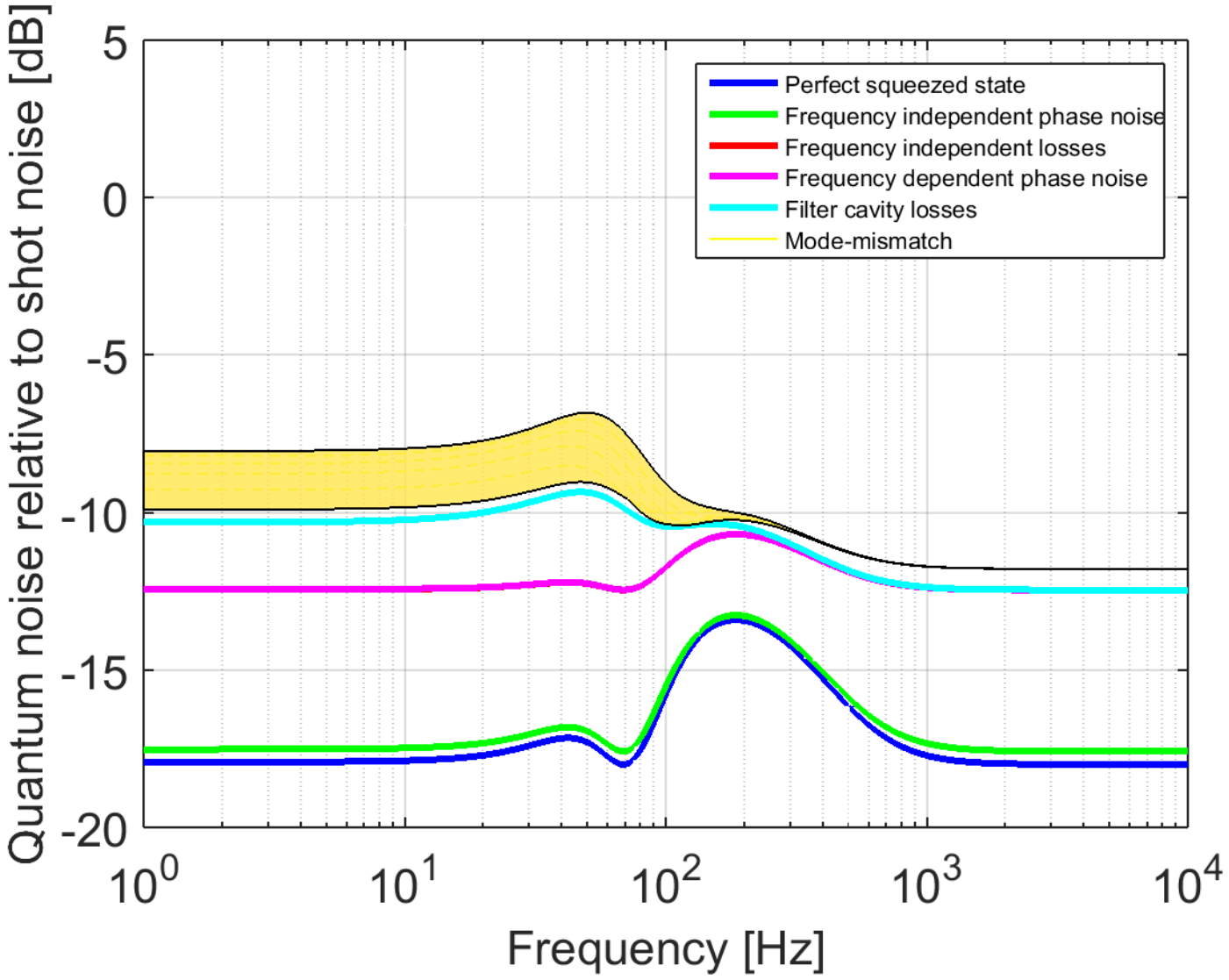
- 10% -> 4%
- Very challenging

100m Filter Cavity: 5 ~ 6 dB @ low freq



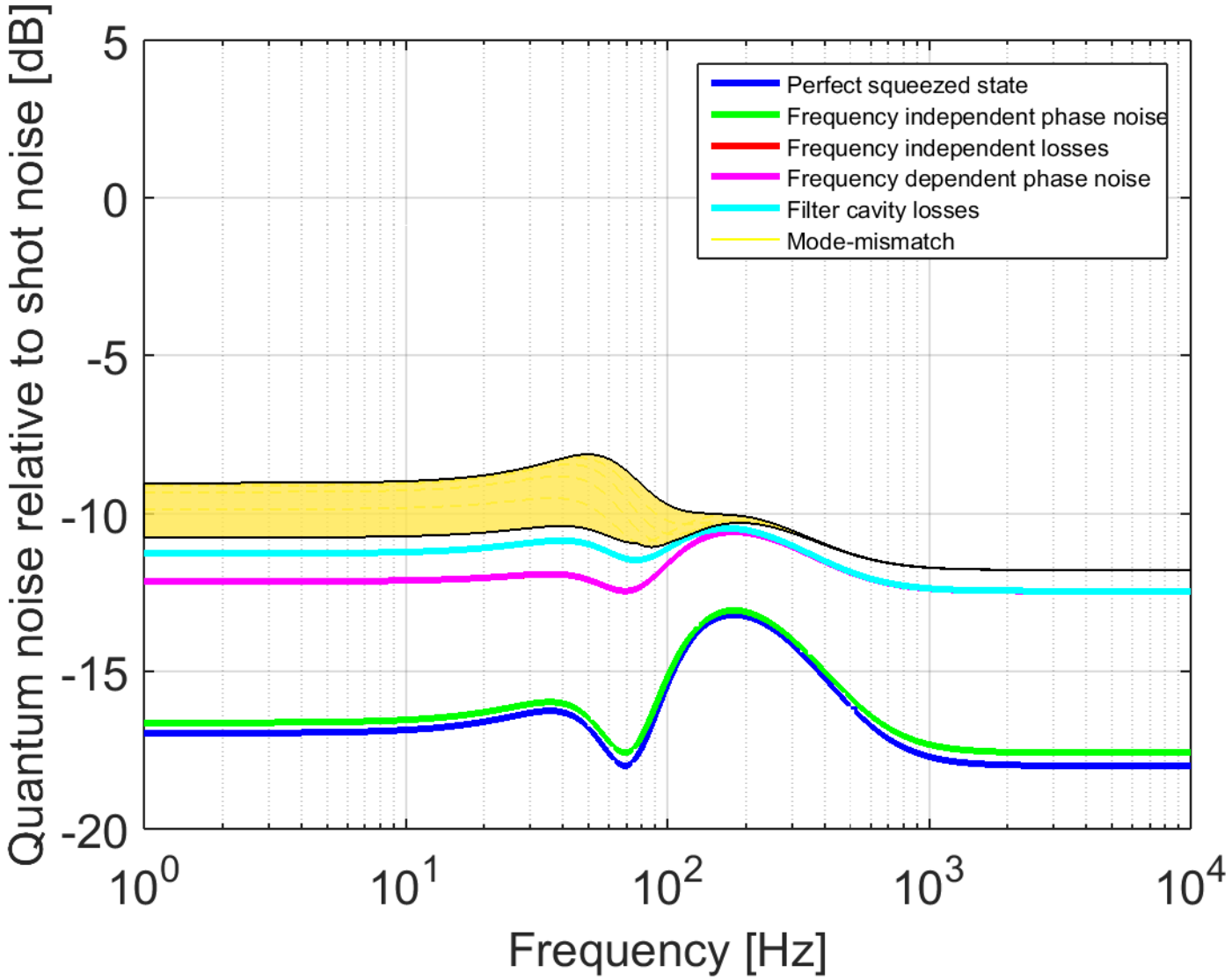
- Cavity length noise
  - 0.3pm -> 0.15 pm
- Mode Mismatch
  - 2% -> 1% (Sqz – FC)
  - 5% -> 1% (Sqz – LO)
- Filter cavity loss
  - 40 ppm

1km Filter Cavity: 8 ~ 10 dB



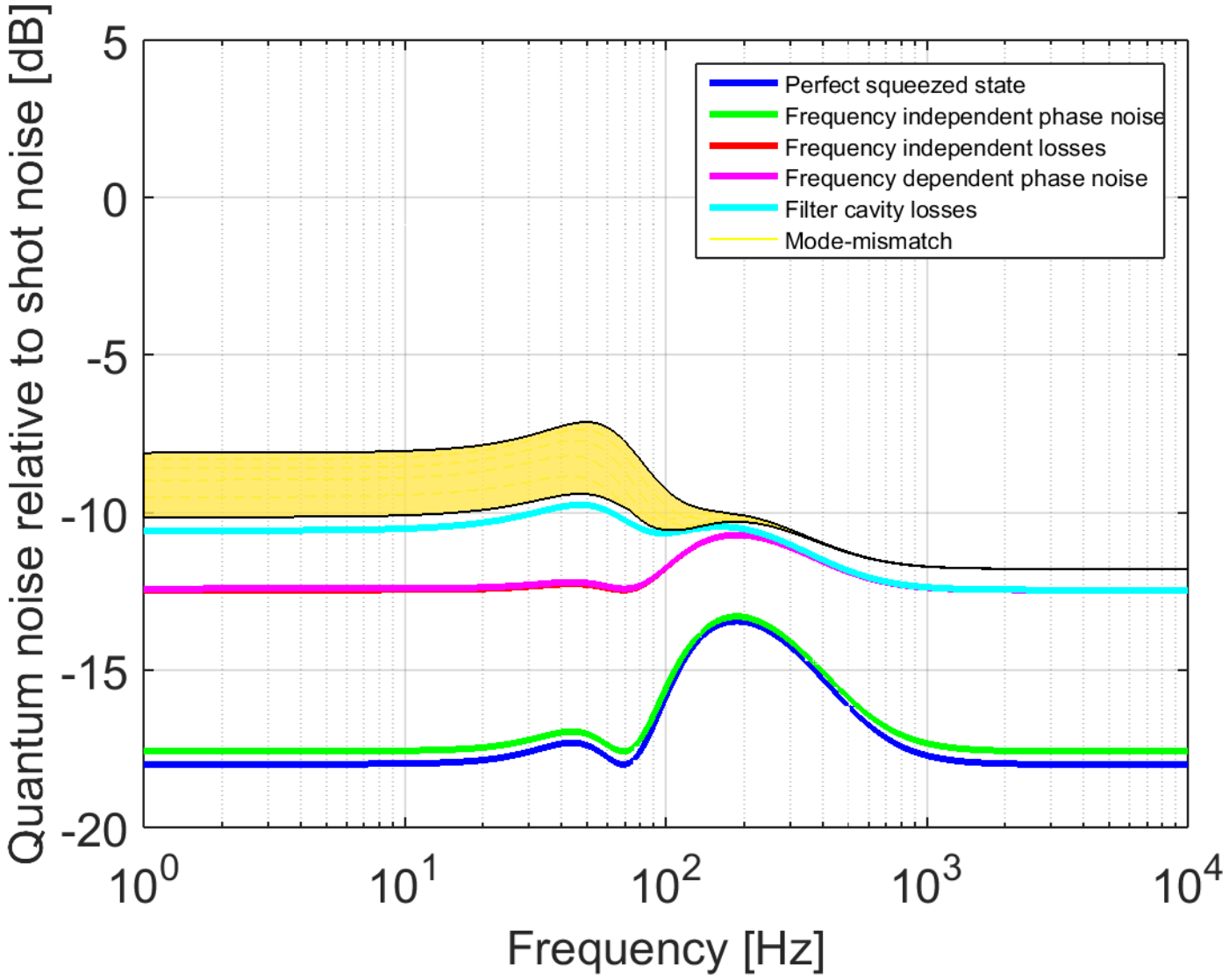
- Cavity length noise
  - 0.3pm -> 0.15 pm
- Mode Mismatch
  - 2% -> 1% (Sqz – FC)
  - 5% -> 1% (Sqz – LO)
- Filter cavity loss
  - 80 ppm
- Suggested in Lungo (40km interferometer)

4km Filter Cavity: 9 ~ 11 dB @ low freq



- Cavity length noise
  - 0.3pm -> 0.15 pm
- Mode Mismatch
  - 2% -> 1% (Sqz – FC)
  - 5% -> 1% (Sqz – LO)
- Filter cavity loss
  - 120 ppm

1560nm wavelength: 300m length



- "LIGO III Blue Paper" (LIGO-T1400226) discusses changing the wavelength
- For a few mm spot size, the "golden rule" might apply:

$$L = \left(\frac{4\pi\sigma}{\lambda}\right)^2$$

- 20 ppm loss is assumed

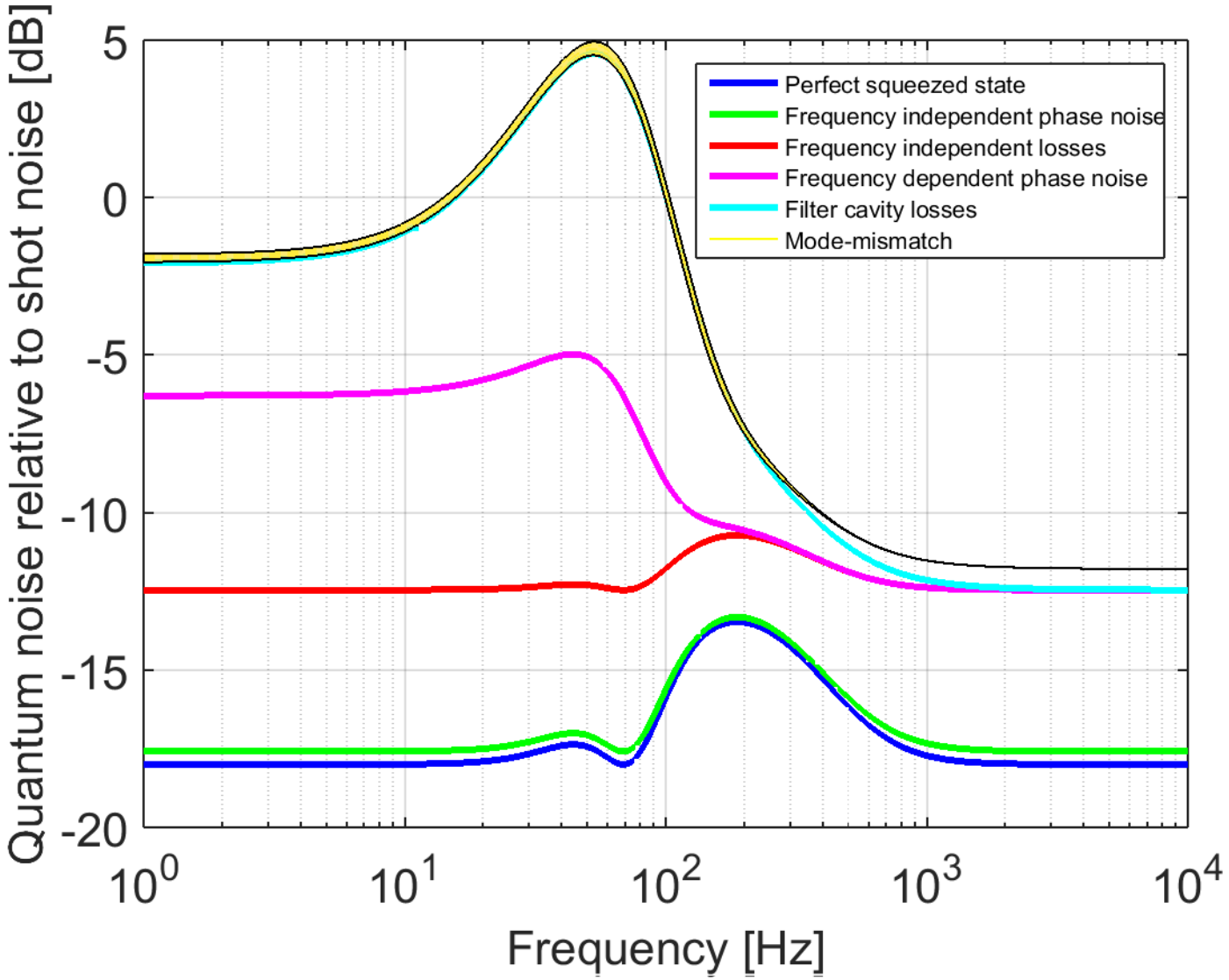
Parameter Summary: getting to 10dB is challenging!

Parameter	Value
Filter cavity length	16 m
Filter cavity loss	16 ppm
Frequency- independent loss	10 %
Mode-mismatch (Squeezer – Filter cavity)	2 %
Mode-mismatch (Squeezer – Local oscillator)	5 %
Frequency-independent phase noise (RMS)	30 mrad
Filter cavity length noise (RMS)	0.3 pm
Injected squeezing	10 dB

Toward 10dB

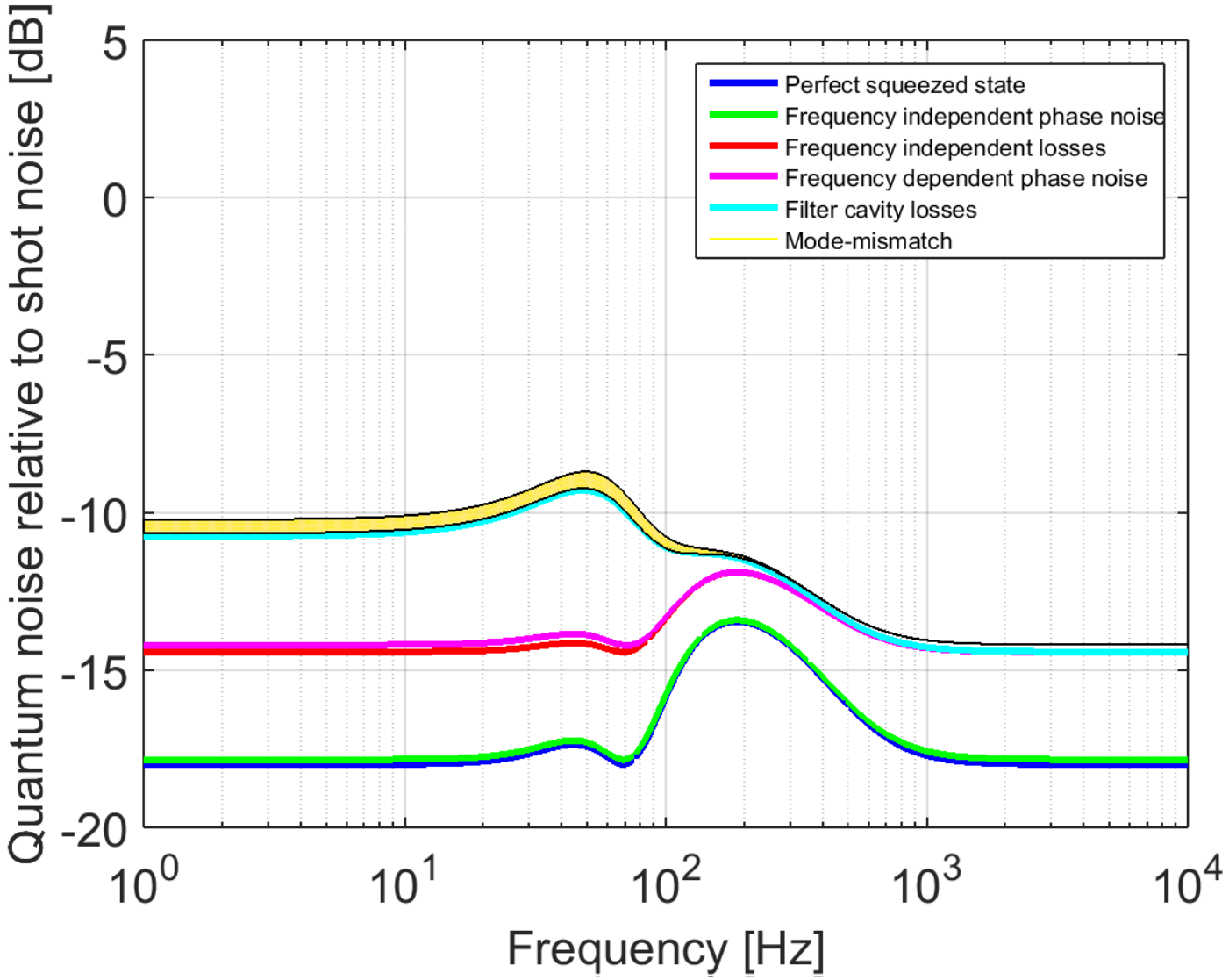
Parameter	Value
Filter cavity length	4 km
Filter cavity loss	120 ppm
Frequency- independent loss	4 %
Mode-mismatch (Squeezer – Filter cavity)	1 %
Mode-mismatch (Squeezer – Local oscillator)	1 %
Frequency-independent phase noise (RMS)	5 mrad
Filter cavity length noise (RMS)	0.15 pm
Injected squeezing	18 dB

16m Filter Cavity:



Parameter	Value
Filter cavity length	16 m
Filter cavity loss	16 ppm
Frequency- independent loss	4 %
Mode-mismatch (Squeezer – Filter cavity)	1 %
Mode-mismatch (Squeezer – Local oscillator)	1 %
Frequency-independent phase noise (RMS)	5 mrad
Filter cavity length noise (RMS)	0.15 pm
Injected squeezing	18 dB

16m Filter Cavity:

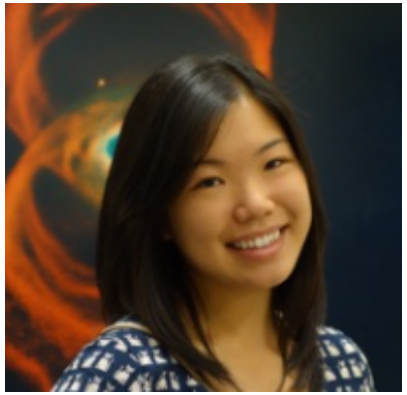


Parameter	Value
Filter cavity length	16 m
Filter cavity loss	1.6 ppm
Frequency- independent loss	2 %
Mode-mismatch (Squeezer – Filter cavity)	0.2 %
Mode-mismatch (Squeezer – Local oscillator)	0.2 %
Frequency-independent phase noise (RMS)	3 mrad
Filter cavity length noise (RMS)	0.015 pm
Injected squeezing	18 dB

Summary

- Squeezing with an input filtering looks promising and can be an upgrade option for aLIGO
- To get a 10 dB of squeezing, loss and phase noise need to be controlled very well.
- For low frequency squeezing, lowering cavity roundtrip loss is crucial, and unless there is a technology advancement to reduce mirror's scattering loss, we need a km scale filter cavity to reach 10 dB squeezing

Filter Cavity Team @ MIT



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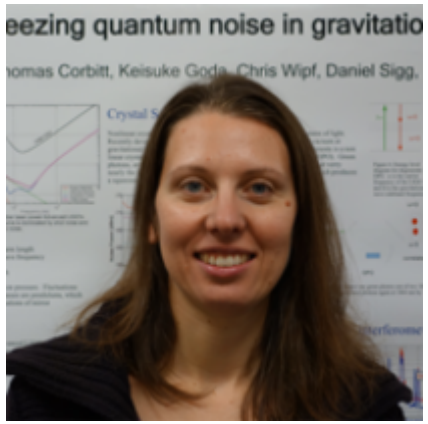
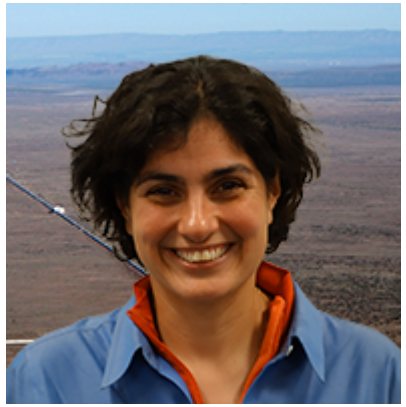


Lisa Barsotti

Matthew Evans

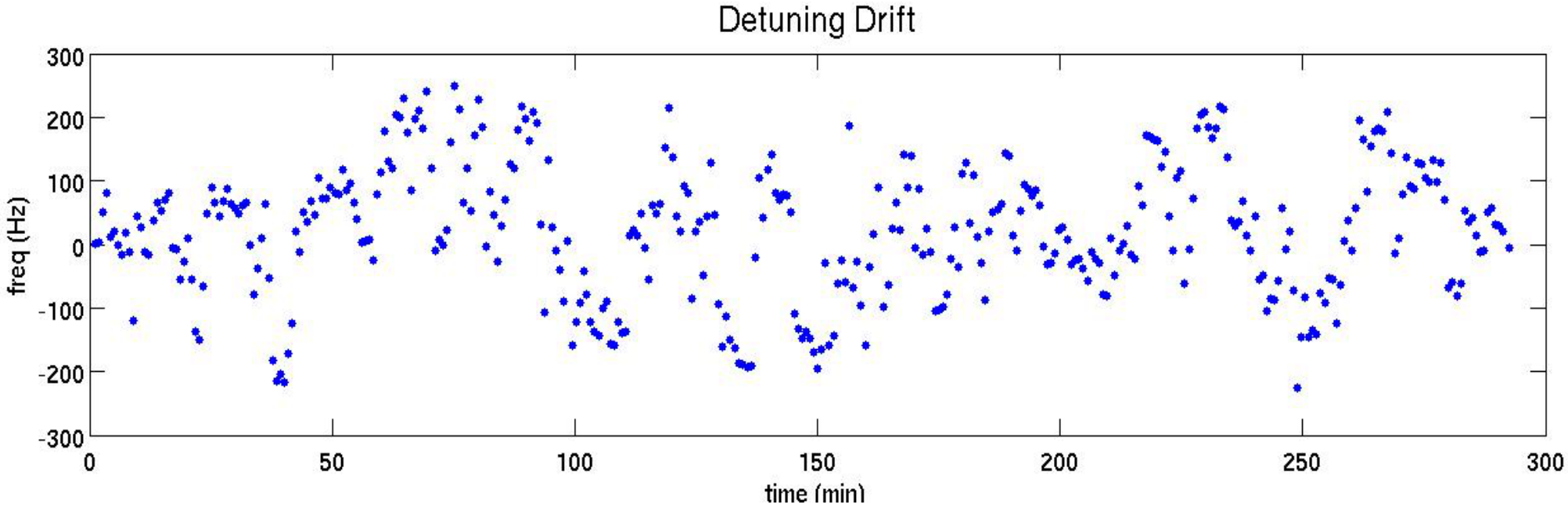


Nergis Mavalvala

Peter Fritschel

Other things to watch out for

- Need to control the filter cavity detuning
  - Observed a quite large drift during the filter cavity experiment at MIT
- Other noise sources we did not account for?
  - E.g. as we go to a higher finesse
- Balanced homodyne readout?



aLIGO with filter cavity:
2.5 dB @ low, 6dB at high

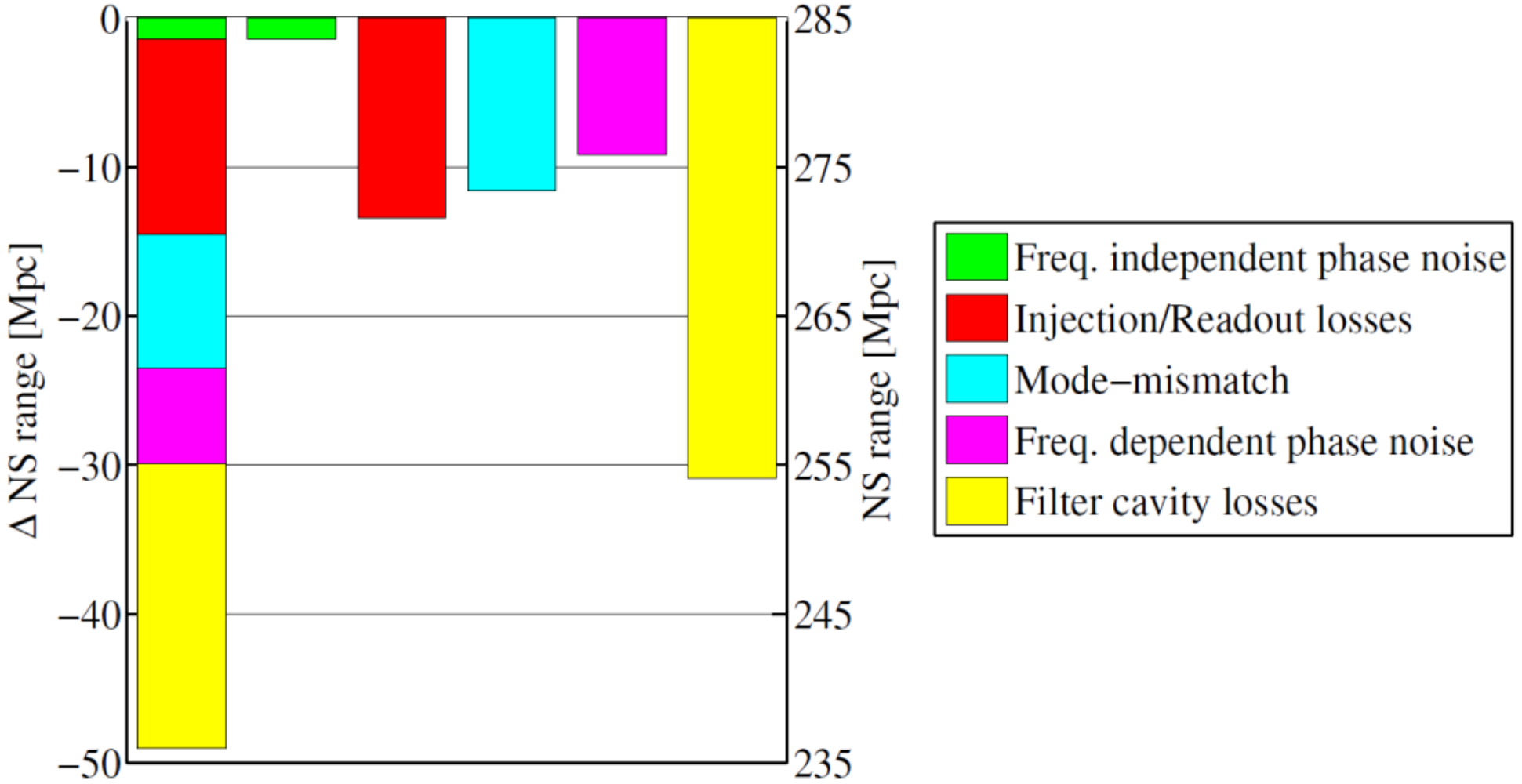


Figure Credit: John Miller

Modeling: what we still needs

- Loss extrapolation
- Mode mathing
- IFO loss consideration

Modeling: where we are

	Filter Cavity	Power / Signal Recycling	IFO Loss	SQZ Propagation Loss	Phase Noise	Cavity Loss	Cavity Length Noise	Mode Matching	Note
KLMTV	Yes	No							
BC	No	Yes	Yes						
Jan's	Yes	No PR							
Realistic Filter Cavity'	Yes	Only tuned SR case							Input transmission values are set incorrectly
D&D	Yes	Only tuned SR case	No	Yes	Yes	Yes	Yes	Yes but has some errors	