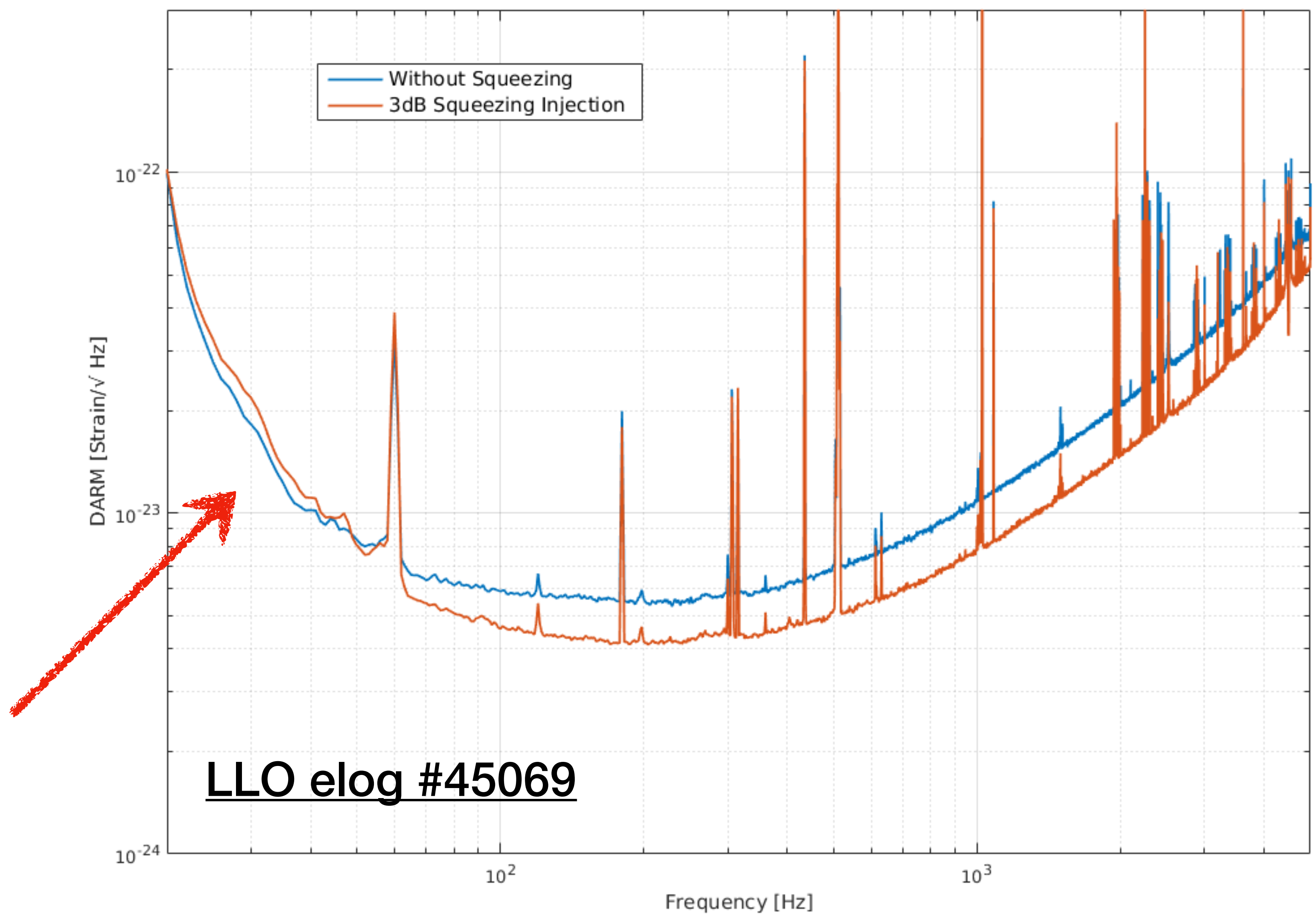
Frequency-dependent squeezing simulation and filter cavity implementation in KAGRA

E.Capocasa, M. Leonardi

F2F Satellite meeting - 18/04/19

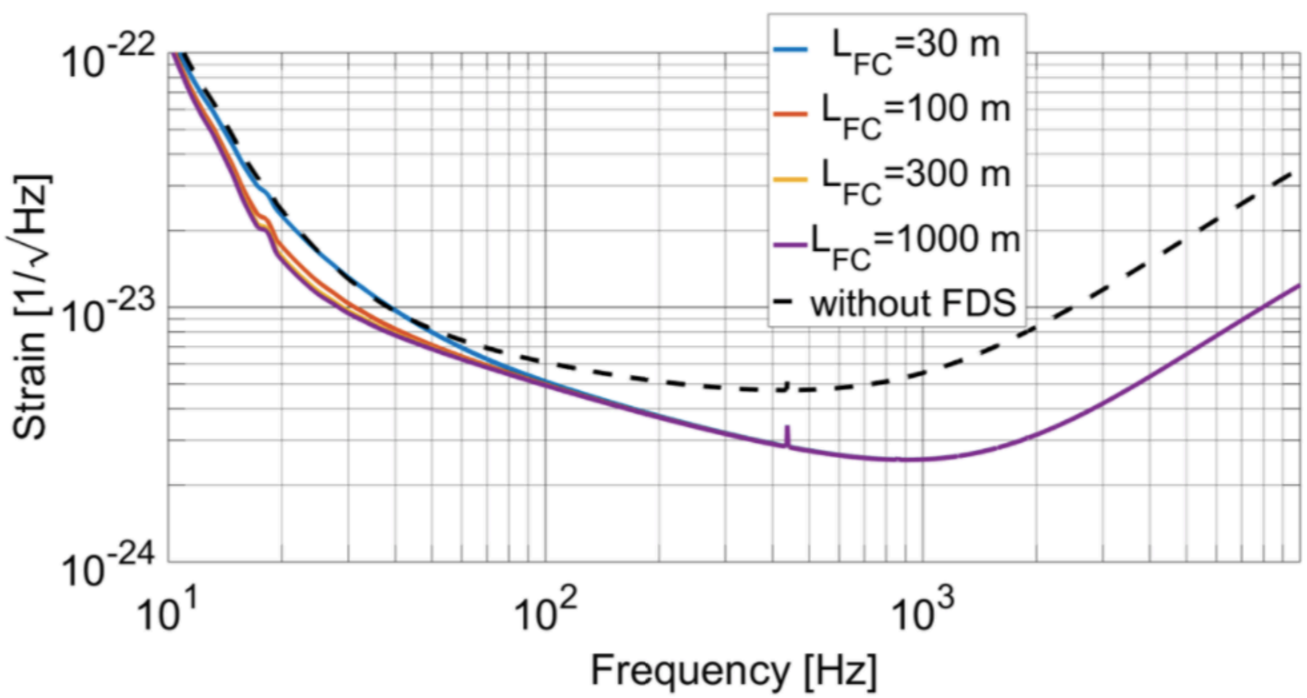
2G detectors already see the increase of radiation pressure when frequency independent squeezing is injected

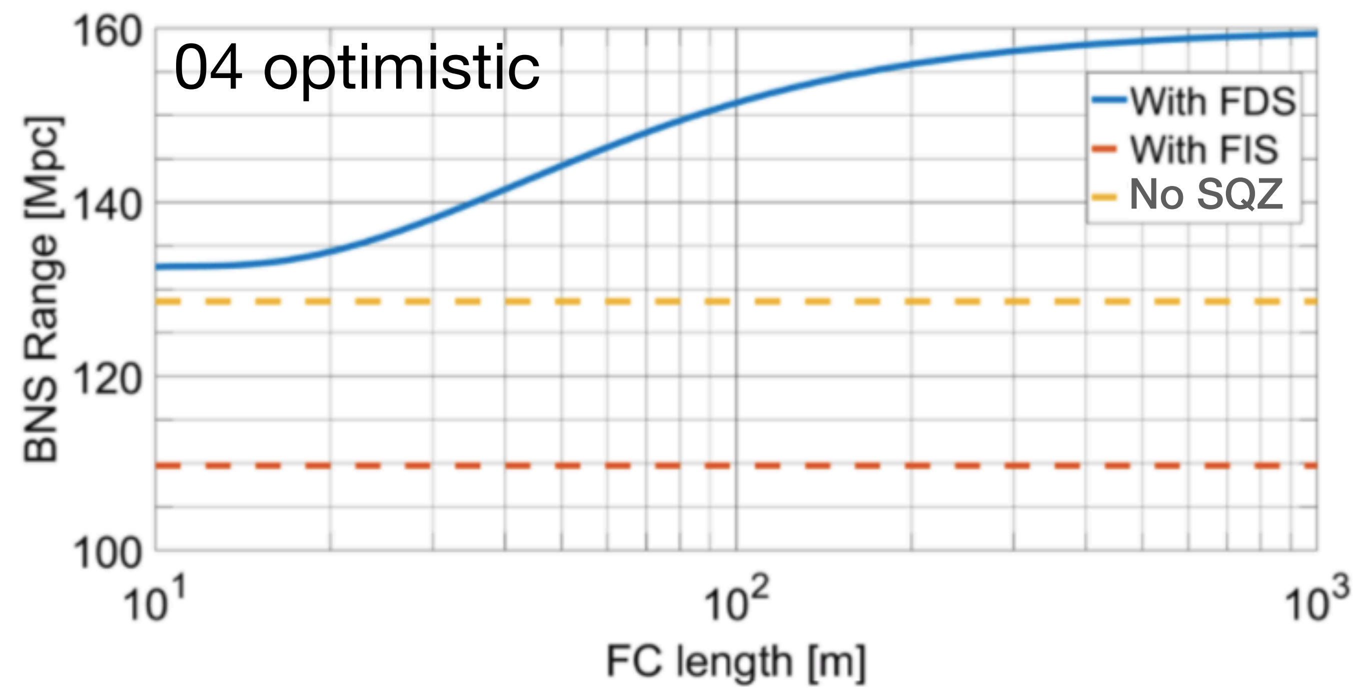


- Virgo and LIGO will install 300 m filter cavity between O3 and O4 (2020-21)
- KAGRA will takes advantage of frequency dependent squeezing (FDS)

Main question: how long should the cavity be ?

- Without having any space constrain, 300 m seem a good compromise

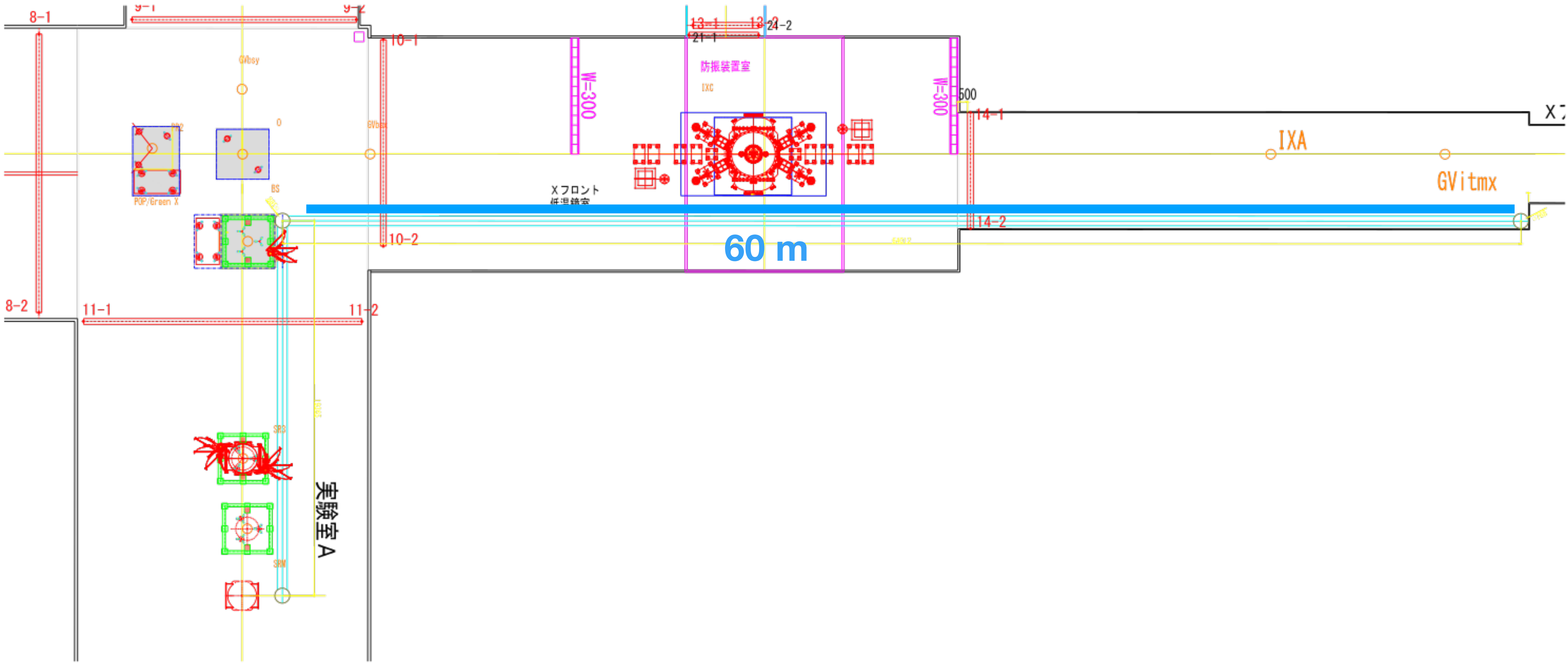




Virgo note: **VIR-0312A-18** (Eisenmann et al.)

How long can we make FC in KAGRA?

- It seems that it can be at maximum 60 m



Filter cavity parameters choice

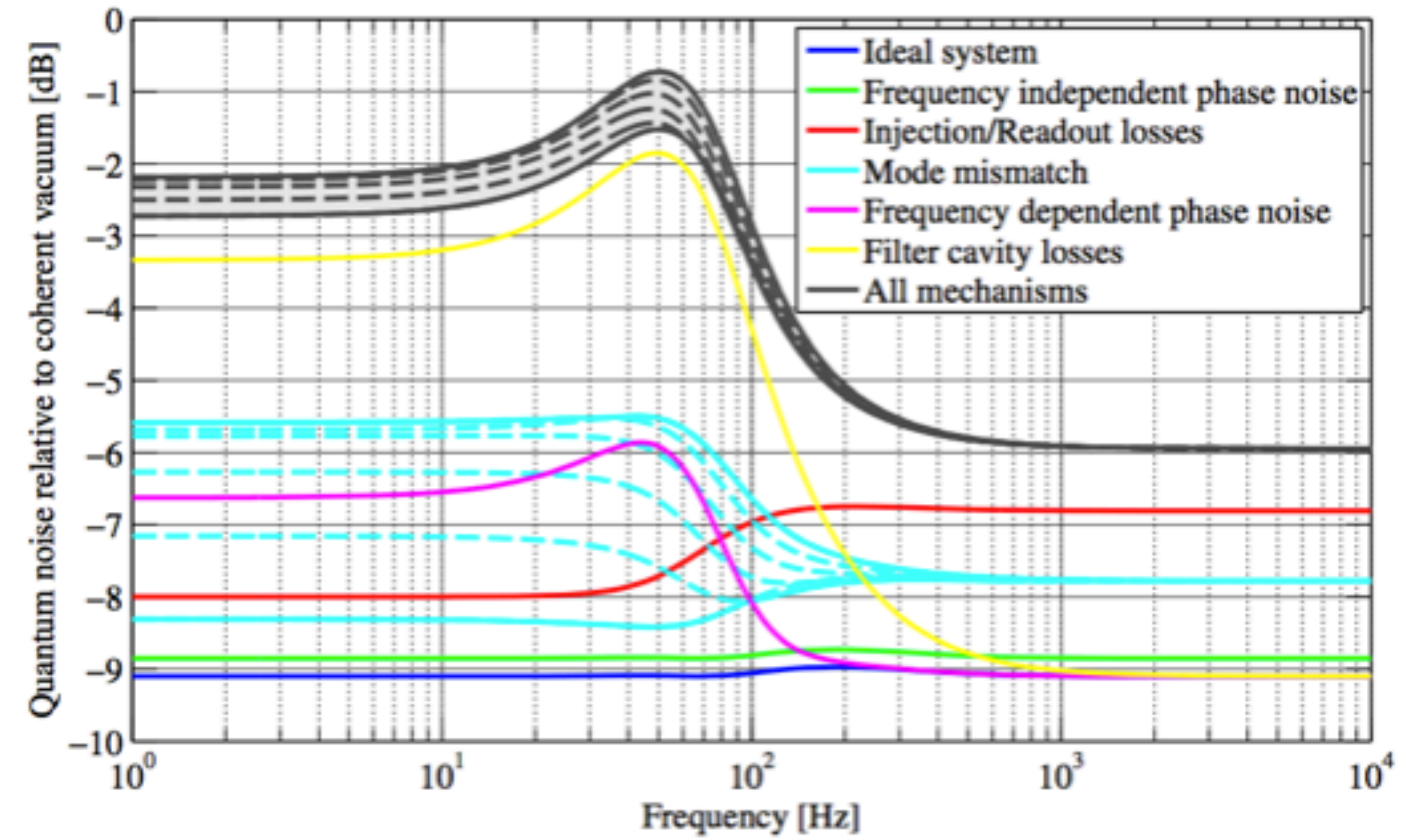
- Filter cavity bandwidth should match Standard quantum limit frequency to produce optimal squeezing angle rotation.

In the case of a losses cavity

$$\gamma_{\rm fc} = \frac{\Omega_{\rm SQL}}{\sqrt{2}}$$

Parameter	Symbol	300 m	60 m
Round trip losses	$\Lambda_{\rm rt}$	30 ppm	15 ppm
Loss related correction factor	ϵ	0.04	0.1
Filter cavity bandwidth	$\gamma_{\rm fc}$	55 Hz	57 Hz
Input mirror transmissivity	$t_{\rm in}^2$	0.0014	0.00027
Finesse	F	4620	23000
Beam diameter at waist		1.62 cm	0.7 cm
Beam diameter at the mirror		2.05 cm	0.9 cm

Squeezing degradation mechanisms



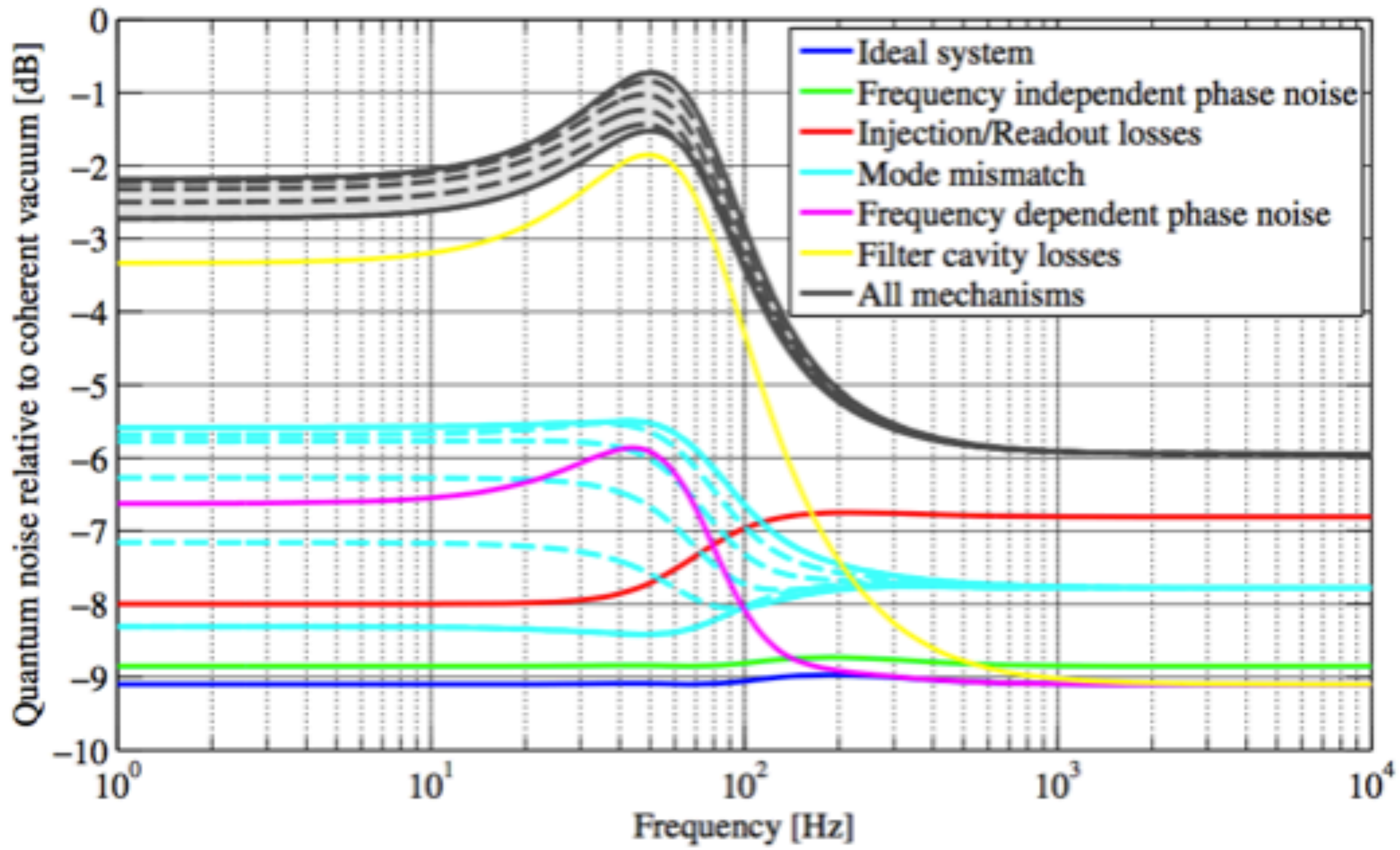
PHYSICAL REVIEW D **90**, 062006 (2014)

Decoherence and degradation of squeezed states in quantum filter cavities

P. Kwee, J. Miller,* T. Isogai, L. Barsotti, and M. Evans

- Filter cavity losses
- Injection/readout losses
- Mode mismatch
- Frequency-dependent phase noise
- Frequency-independent phase noise
- Losses inside IFO (not considered here)

Squeezing degradation mechanisms



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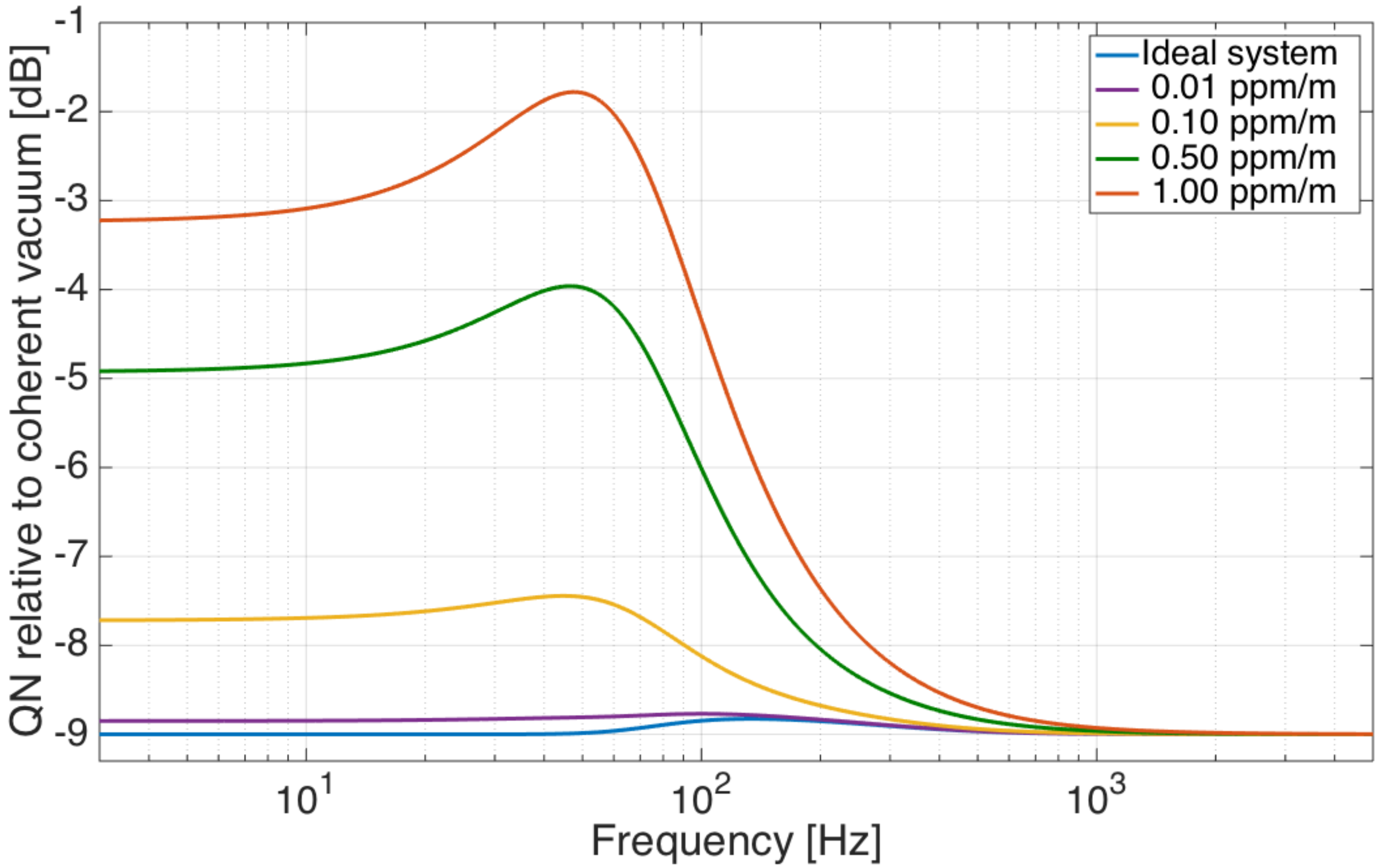
Length dependent mechanisms

- Filter cavity losses
- Injection/readout losses
- Mode mismatch
- Frequency-dependent phase noise
- Frequency-independent phase noise
- Losses inside IFO (not considered here)

Squeezing degradation from filter cavity losses

- Losses are more influent at low frequency where the squeezing experiences the rotation
- The cavity performance depends on the loss per unit length



Losses effect in the filter cavity

- Total losses: Round trip losses per number of round trip $N \sim 1/T_f$

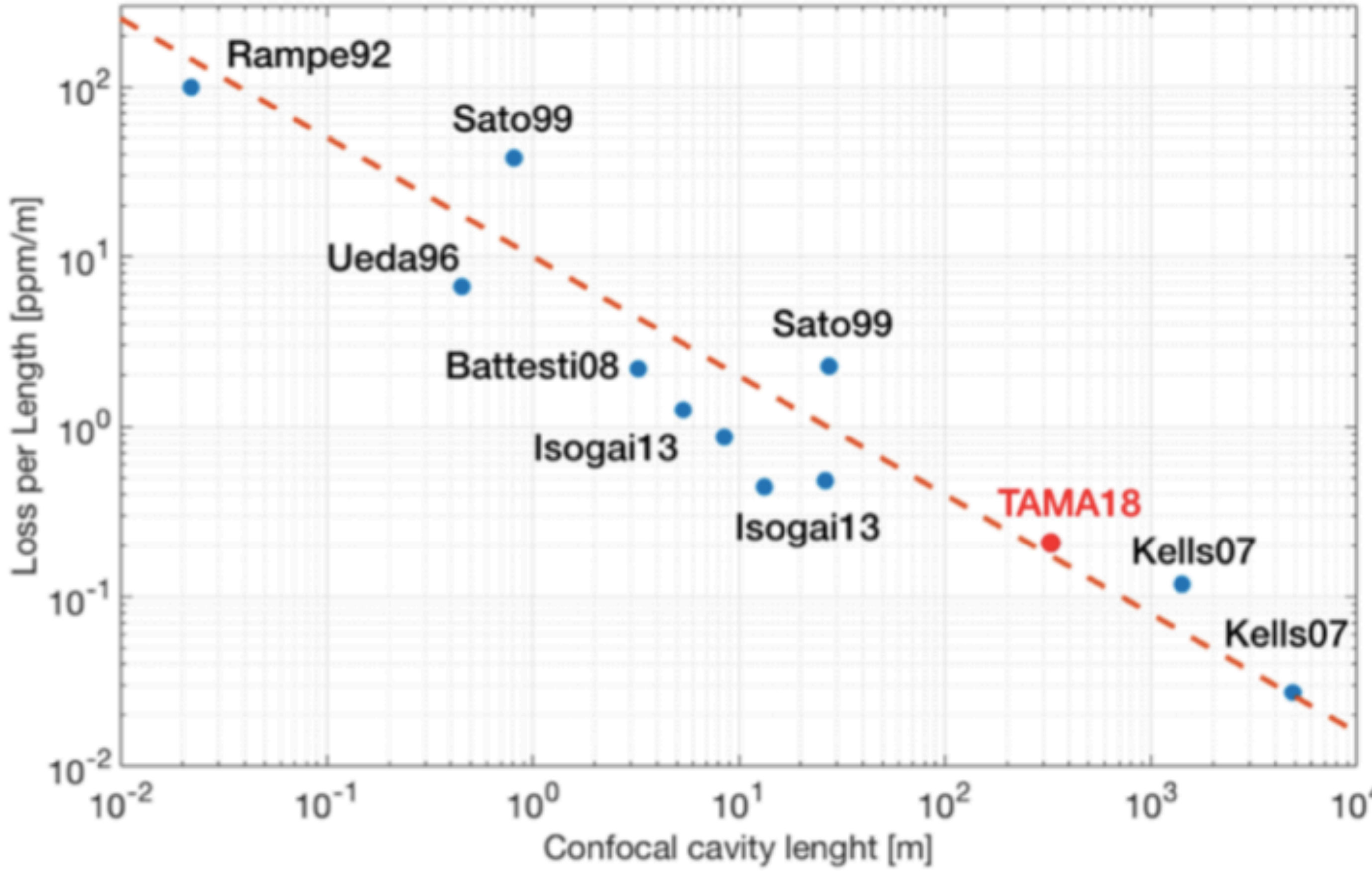
$$\mathcal{E} \approx \frac{\epsilon}{T_f}$$

- Input transmission depends on the length and on the required bandwidth

$$T_f \approx \frac{4\gamma L_f}{c} \quad \longrightarrow \quad \mathcal{E} \approx \frac{c\,\epsilon}{4\gamma L_f} \propto \frac{\epsilon}{L_f}$$

- RTL increase with the beam size which increases with length

The loss per unit length decreases with cavity length



$$L_{\mathrm{rt}}(\mathscr{L}_{\mathrm{confocal}}) = 10\ \mathrm{ppm} \cdot \left(\frac{\mathscr{L}_{\mathrm{confocal}}}{1\ \mathrm{m}}\right)^{0.3}$$

Longer cavities reduce the degradation effect

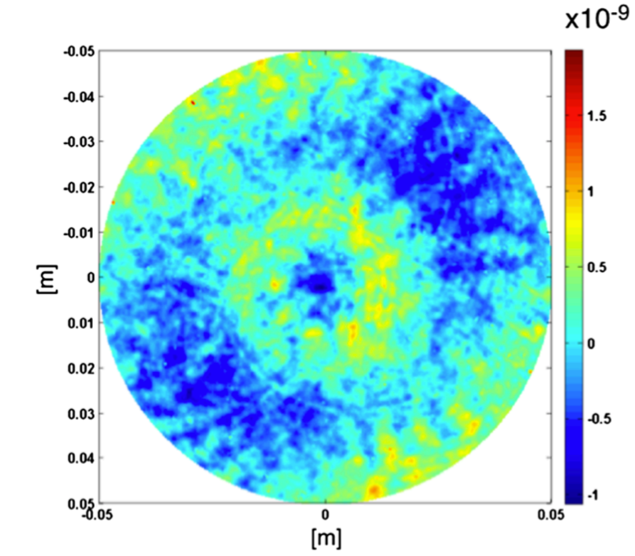
Loss in long-storage-time optical cavities
T. Isogai, J. Miller, P. Kwee, L. Barsotti, M. Evans
Optics Express, Vol. 21, Issue 24

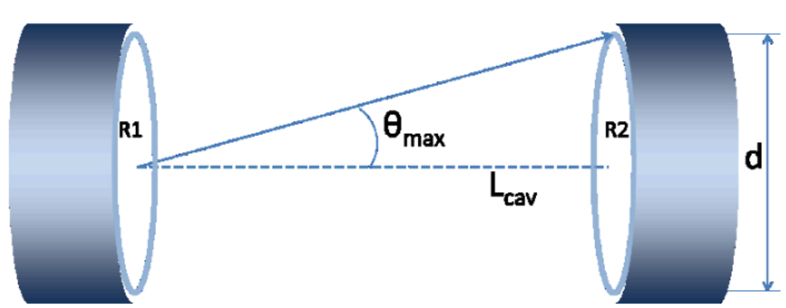
Where do round trip losses come from?

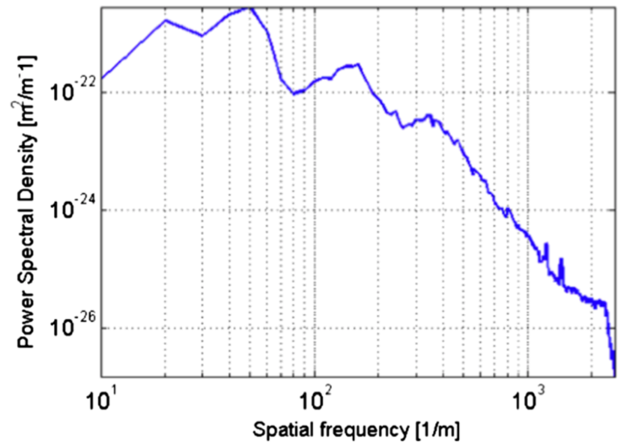
- Absorption
- Transmissions
- Clipping
- Scattering from mirror defects

Diffraction angle: $\theta = \lambda \times f$

- Flatness: 10 m^{-1} - 10^3 m^{-1} (simulation)
- Roughness: 10^3 m^{-1} - 10^5 m^{-1} (measurement)
- Point defects $> 10^5$ m^{-1} (measurement)

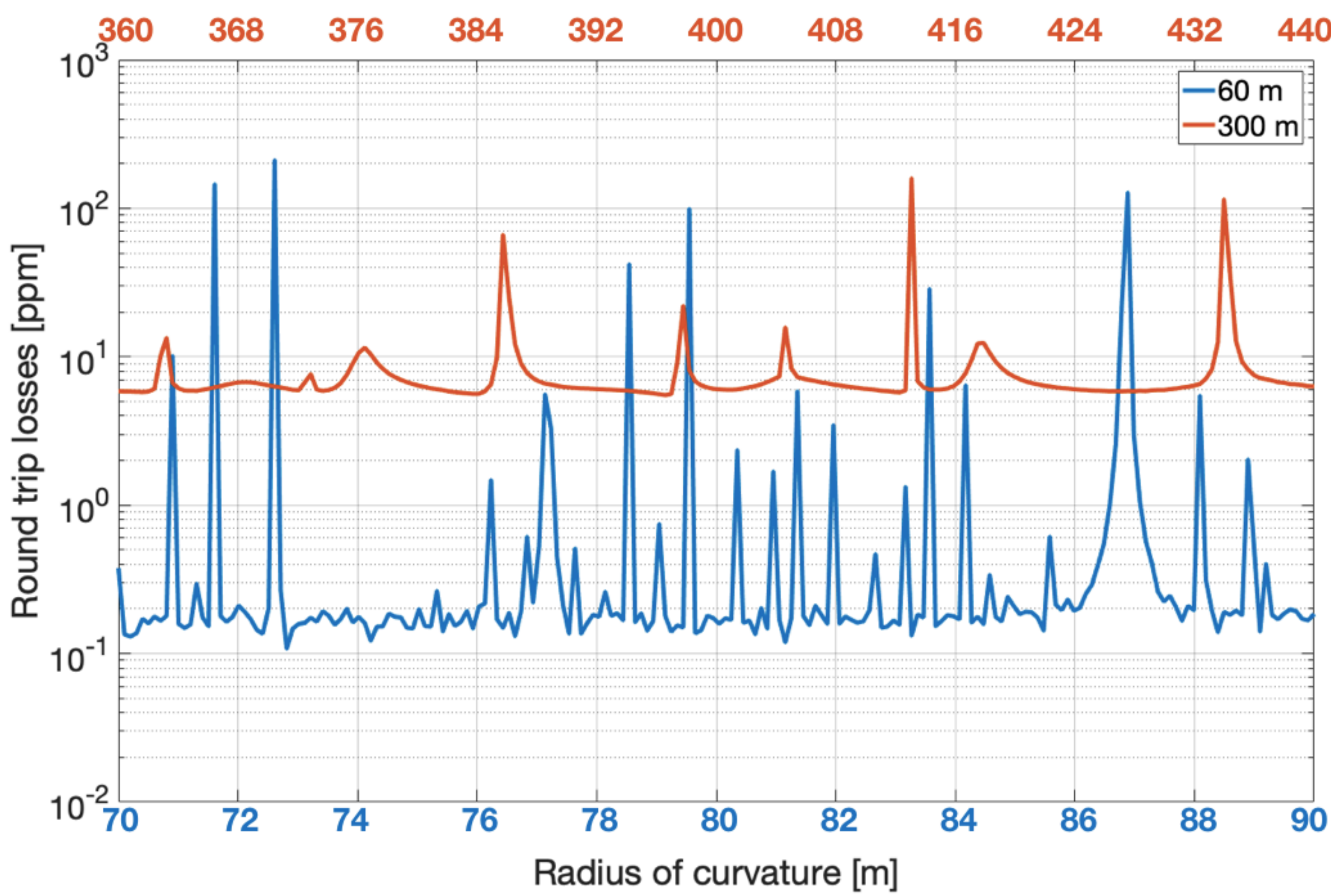






Round trip losses budget

- Flatness(FFT simulation)
  - Smaller beam and higher finesse reduce losses
  - Peaks density (due to cavity quasidegeneracy) increases
  - Investigate the losses as function of the mirror diameter

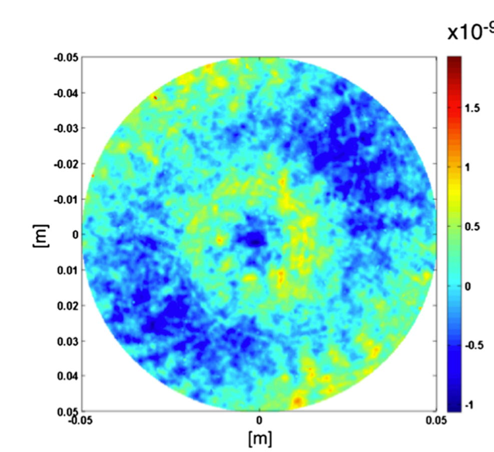


5 ppm

0.2 ppm

AdVirgo mirror quality

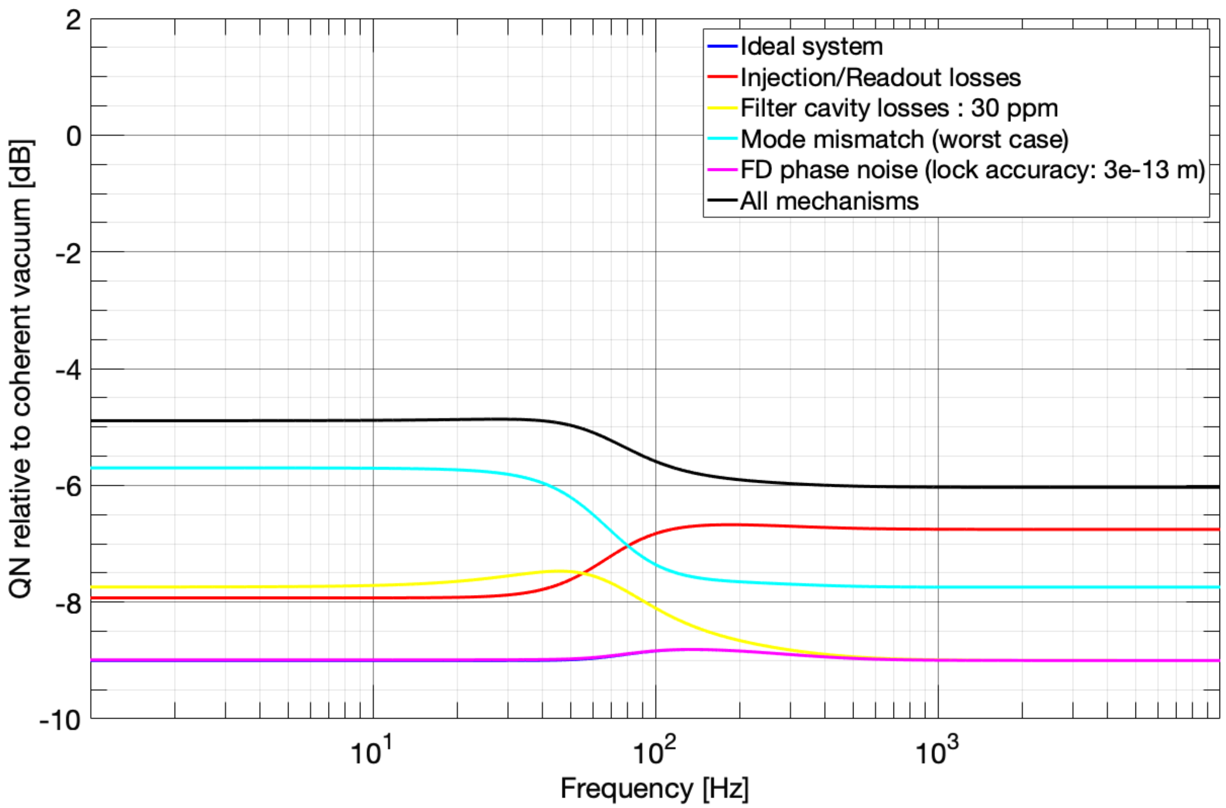
	diameter[m]	
	0.05	0.01
RMS [nm]	0.27	0.18



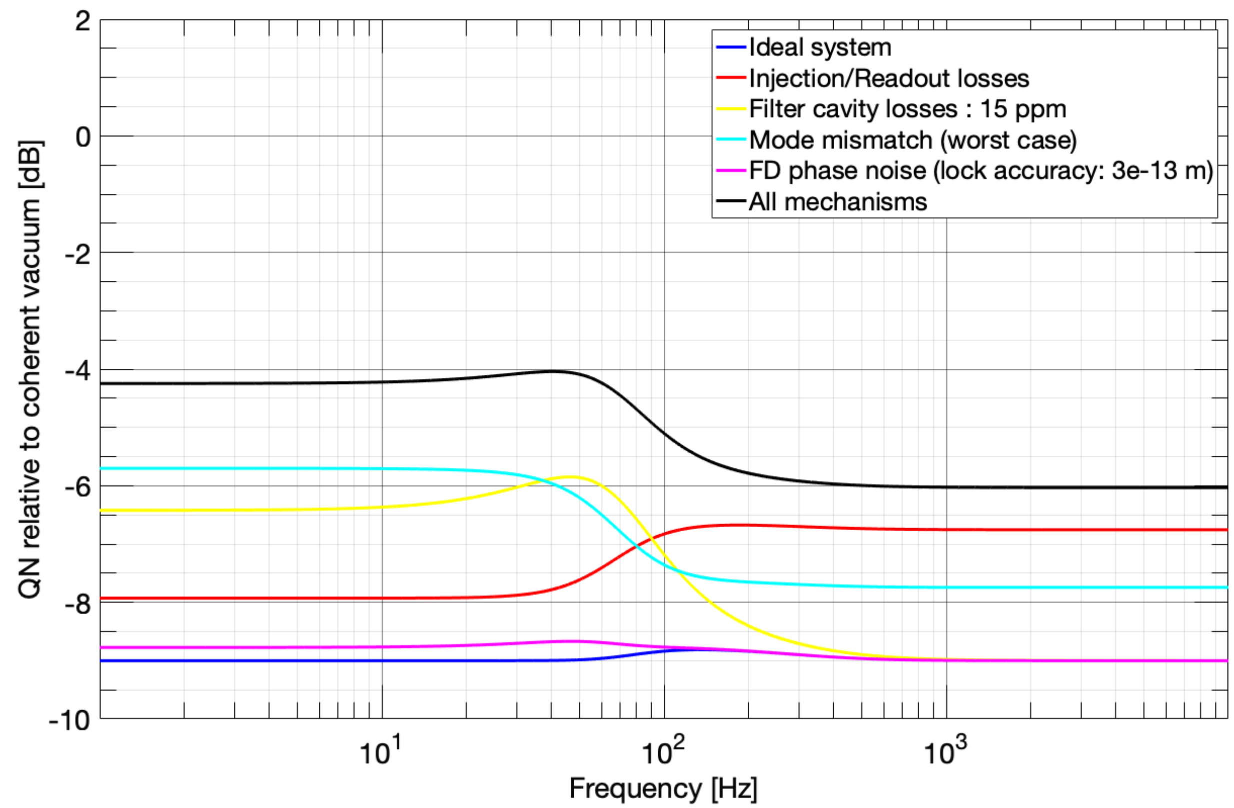
- Transmission and absorption ~ 5 ppm (measured)
- Roughness and point defects ~5 ppm each mirror (measured)

Squeezing degradation comparison

300 m



60 m



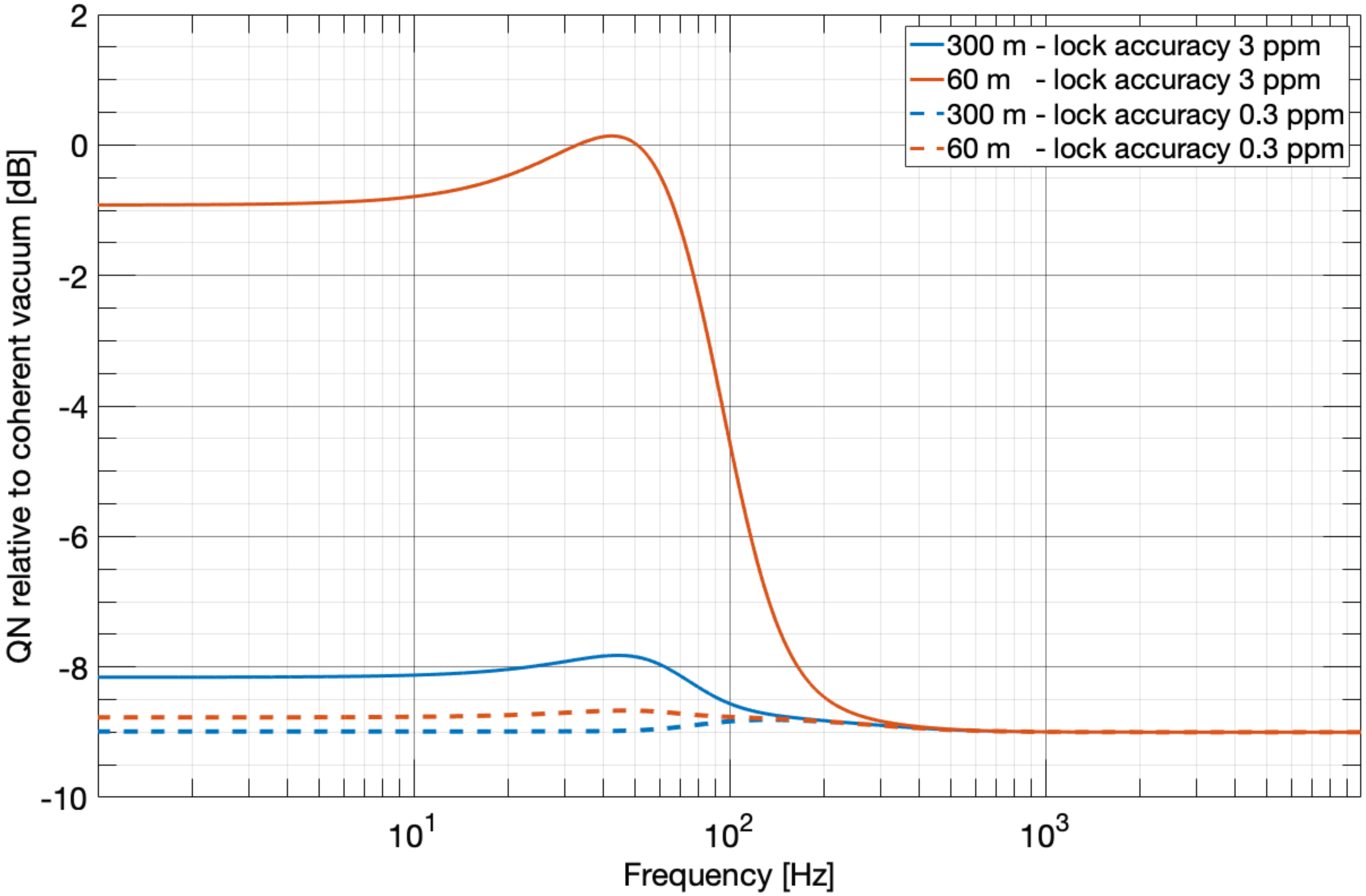
TAMA code (MATLAB): no SR and arm loss effect

injection losses	5%
readout losses	5%
mismatch squeezer-filter cavity	2%
mismatch squeezer-local oscillator	5%
δL (rms)	0.3 pm

Phase noise due to lock accuracy

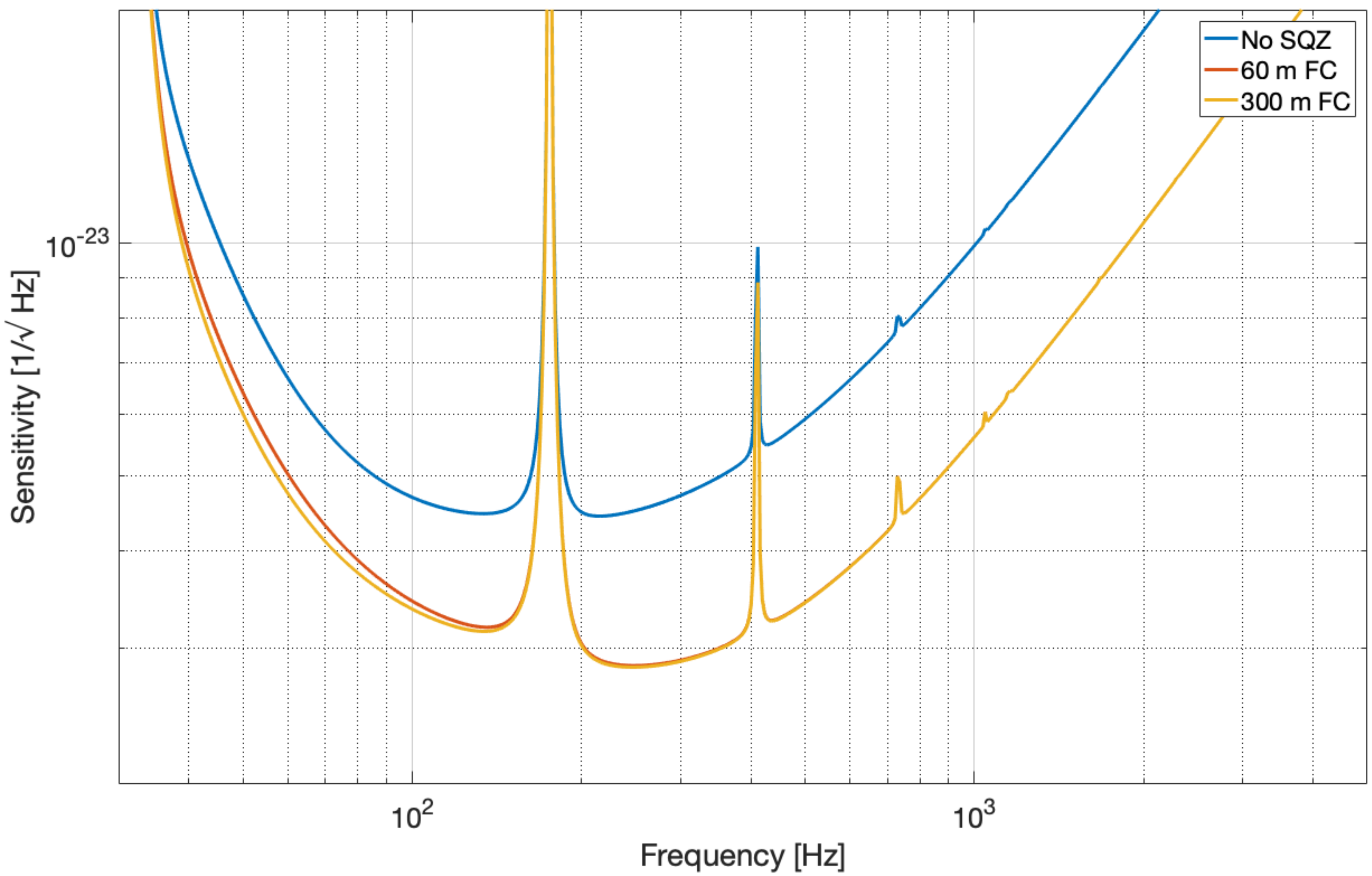
A length noise of the filter cavity δL results in a shift of the optimal detuning:

$$\delta\Delta\omega_{\mathrm{fc}} = \omega_{\mathrm{fc}} \cdot \frac{\delta L}{L}$$



Since δL doesn't depend on L ➔ longer cavities reduce the squeezing degradation

Sensitivity improvement

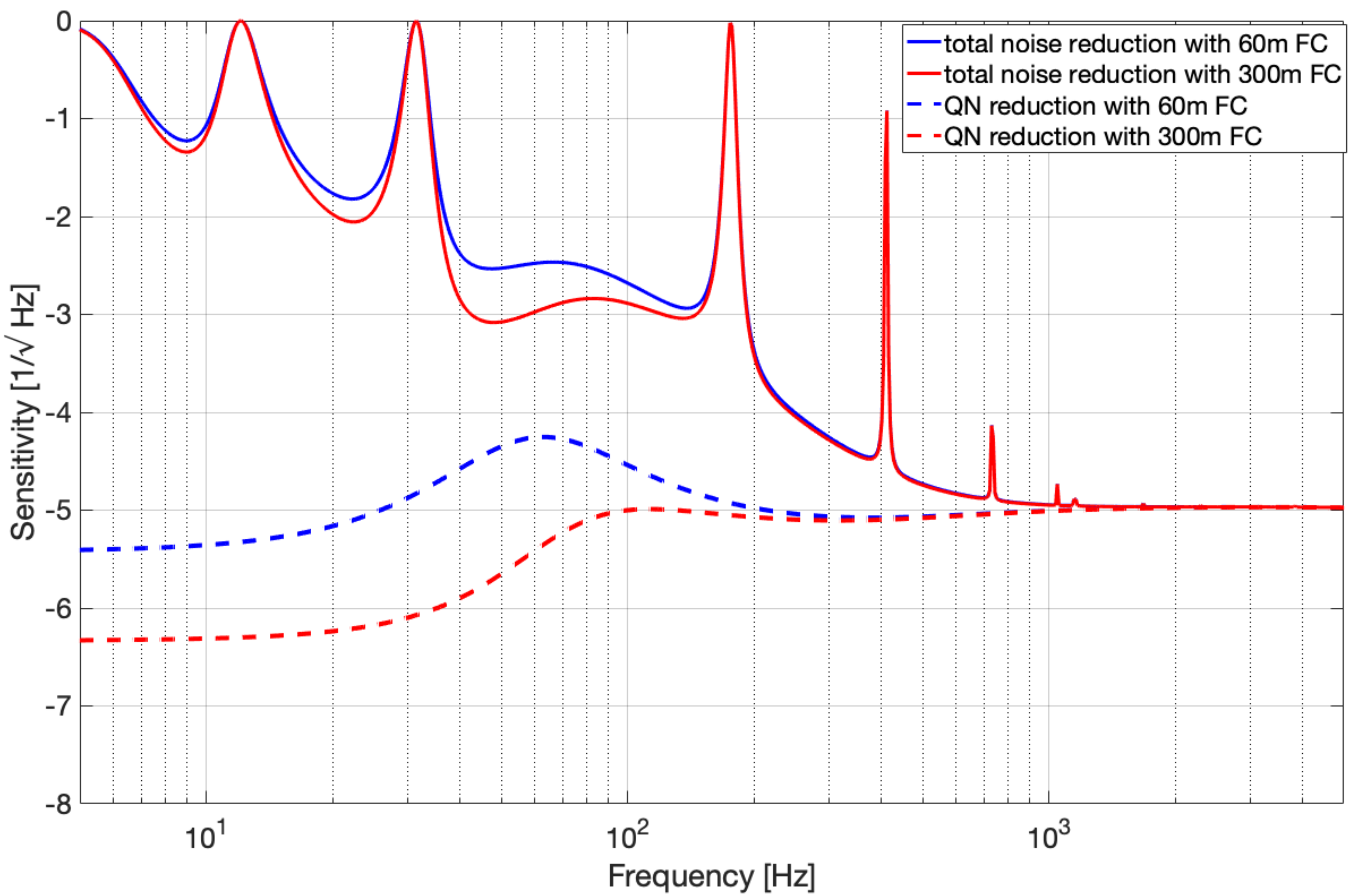


Loss btw squeezer and FC	5%
Loss btw FC and ITF	10%
Quantum efficiency	90%
Phase noise (RMS)	30mrad

	BNS range [MPc]
NO SQZ	128
60 m	176
300 m	182

KAGRA GWINC (python): no frequency dependent phase noise, mismatch as simple loss

Sensitivity improvement



- The sensitivity improvement with a 300 m FC is limited by other noises

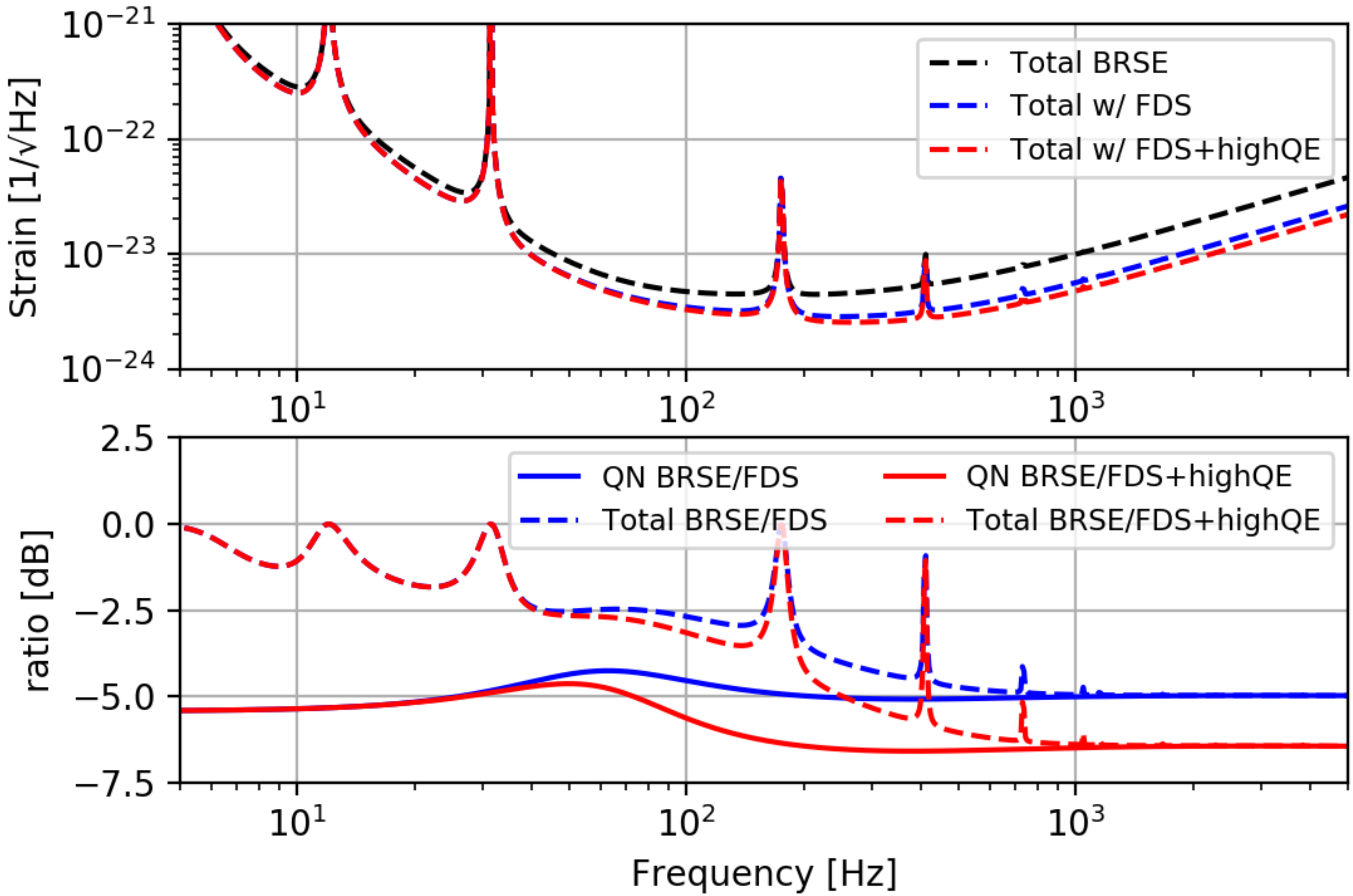
Accurate loss budget is necessary

	Loss source	H1 experiment	Near term goal (6dB)	Longer term goal (10 dB)	Dreaming(15dB)
1	OPO escape efficiency	96%	98%	99%	99.8%
2	Injection path optics	80%	99.7%	99.7%	99.99%
3	viewport	99.8%	99.8%	99.8%	99.99%
4	3 faraday passes	94%, 94%, unknown	97% each (aLIGO input Faradays)	99% each	99.7 % each
7	RF pick off beamsplitter (beam for ISCT4)	98.8%	99%	99.5%	99.8%
5	Reflection off of Signal recycling cavity@100 Hz	arm cavity and michelson =98%	97.5%(Tsrm=35%)	99.2% (Tsrm=50%)	99.5%
6	Circulator for filter cavity	NA	98%	99.5%	99.8%
8	Squeezer mode matching to OMC	71% (inferred from total)	96%	98%	99.7%
10	OMC transmission	82%	97%	99.5%	99.7%
11	QE of PDs		99%	99.7%	99.99%
	Total efficiency (escape * detection)	40-45%	77.6%	91.3%	97.4%
	Total phase noise allowable		17mrad	7 mrad	2.5 mrad
	Measured squeezing (dB)		6	10	15.25

From A+ with paper

Quantum efficiency

- Major improvement can be obtained increasing QE: 90% -> 99%

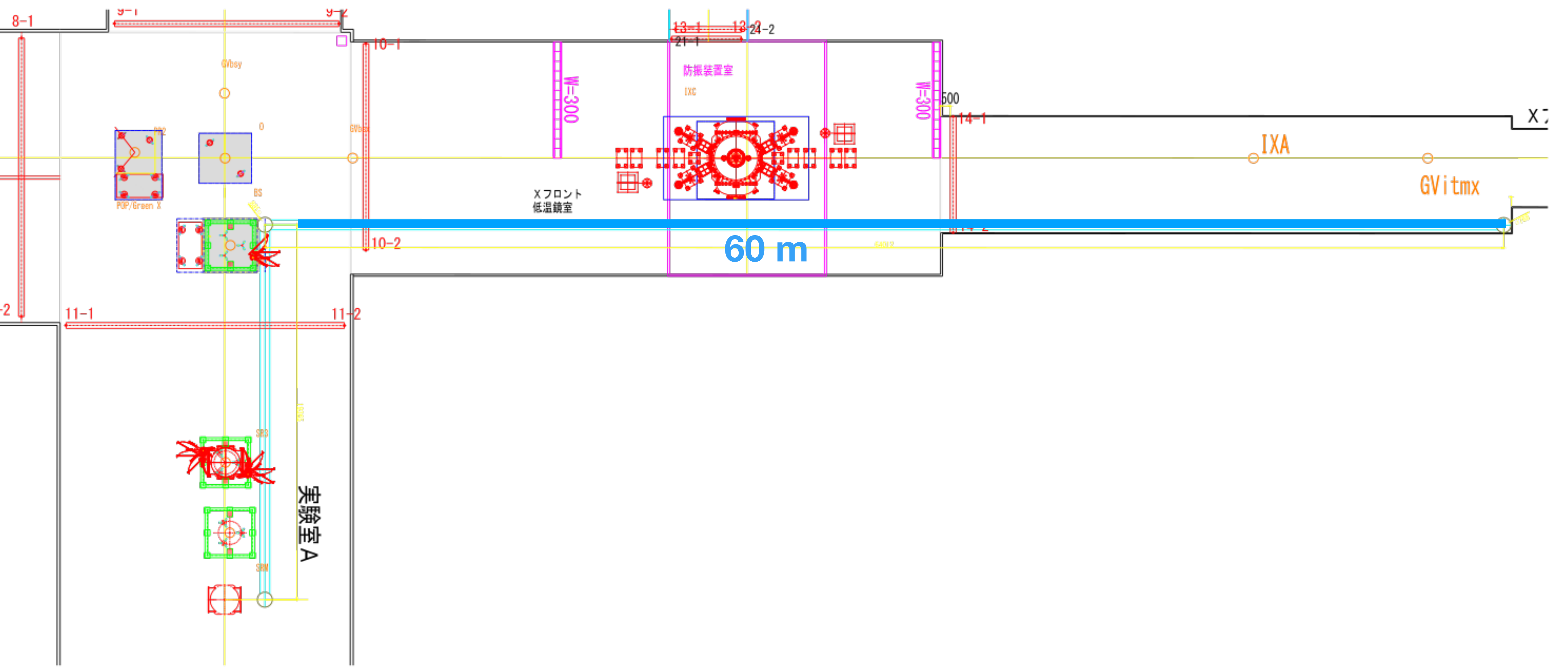


Summary and next steps

- AdV and aLIGO will use frequency independent squeezing in O3 and plan to install 300 m filter cavity for O4
- For KAGRA, 60 m seems good but might be not enough in the future (assuming thermal noise reduction)
- To do: set tentative requirements on IFO parameters which are expected to degrade squeezing (optical losses from mirror scattering, faraday isolator etc, mismatching, lock accuracy)
- Set requirement on suspension residual mirror motion to reduce back scattering effect

Discussion: where to put the filter cavity

- Very low pipe below cryostat aperture?
- Which suspensions?
- Other possibilities?



Bibliography /1

- ***"Quantum-mechanical noise in an interferometer"*** C. M. Caves
  Physical Review D, Volume 23, Issue 8, 1981 DOI: 10.1103/PhysRevD.23.1693
- **"*Realistic Filter Cavities for Advanced Gravitational Wave Detectors*"** M. Evans, L. Barsotti, J. Harms, P. Kwee, and H. Miao - Physical Review D, Volume 88, Issue 2, 2013. DOI: 10.1103/PhysRevD.88.022002
- "**Decoherence and degradation of squeezed states in quantum filter cavities"** P. Kwee, J. Miller, T. Isogai, L. Barsotti, and M. Evans , Physical Review D, Volume 90, 062006, 2014, DOI: 10.1103/PhysRevD.90.062006
- ***"Estimation of losses in a 300 m filter cavity and quantum noise reduction in the KAGRA gravitational-wave detector"*** E. Capocasa, M. Barsuglia, J. Degallaix, L. Pinard, N. Straniero, R. Schnabel, K. Somiya, Y. Aso, D. Tatsumi, and R. Flaminio
  Physical Review D, Volume 93, Issue 8, 2016 DOI: 10.1103/PhysRevD.93.082004
- ***"Measurement of optical losses in a high-finesse 300 m filter cavity for broadband quantum noise reduction in gravitational-wave detectors"***
  E. Capocasa, Y. Guo, M. Eisenmann, Y. Zhao, A. Tomura, K. Arai, Y. Aso, M. Marchi`o, L. Pinard, P. Prat, K. Somiya, R. Schnabel, M. Tacca, R. Takahashi, D. Tatsumi, M. Leonardi, M. Barsuglia, and R. Flaminio
  Physical Review D, Volume 98, Issue 2, 2018 DOI: 10.1103/PhysRevD.98.022010

Bibliography /2

- **“*Squeezed vacuum states of light for gravitational wave detectors*“** L. Barsotti, J. Harms, and R. Schnabel Reports on Progress in Physics, Volume 82, Number 1, 2018 DOI 10.1088/1361-6633/aab906 (Effect of SR and arm loss)
- ***“AdV Frequency Dependent Squeezing: Conceptual Design”*** *VIR-0660A-18*
- **”*Effect of optical losses and Filter Cavity length on the Frequency-Dependent Squeezing performances*”** M. Barsuglia, A. Bertolini, E. Capocasa, M. De Laurentis, M. Eisenmann, R. Flaminio, P. Gruning, H. Heitmann, M. Tacca, J-P. Zendri Virgo technical note: VIR-0312A-18