Squeezing with long (100 m scale) filter cavities

Eleonora Capocasa, Matteo Barsuglia, Raffaele Flaminio

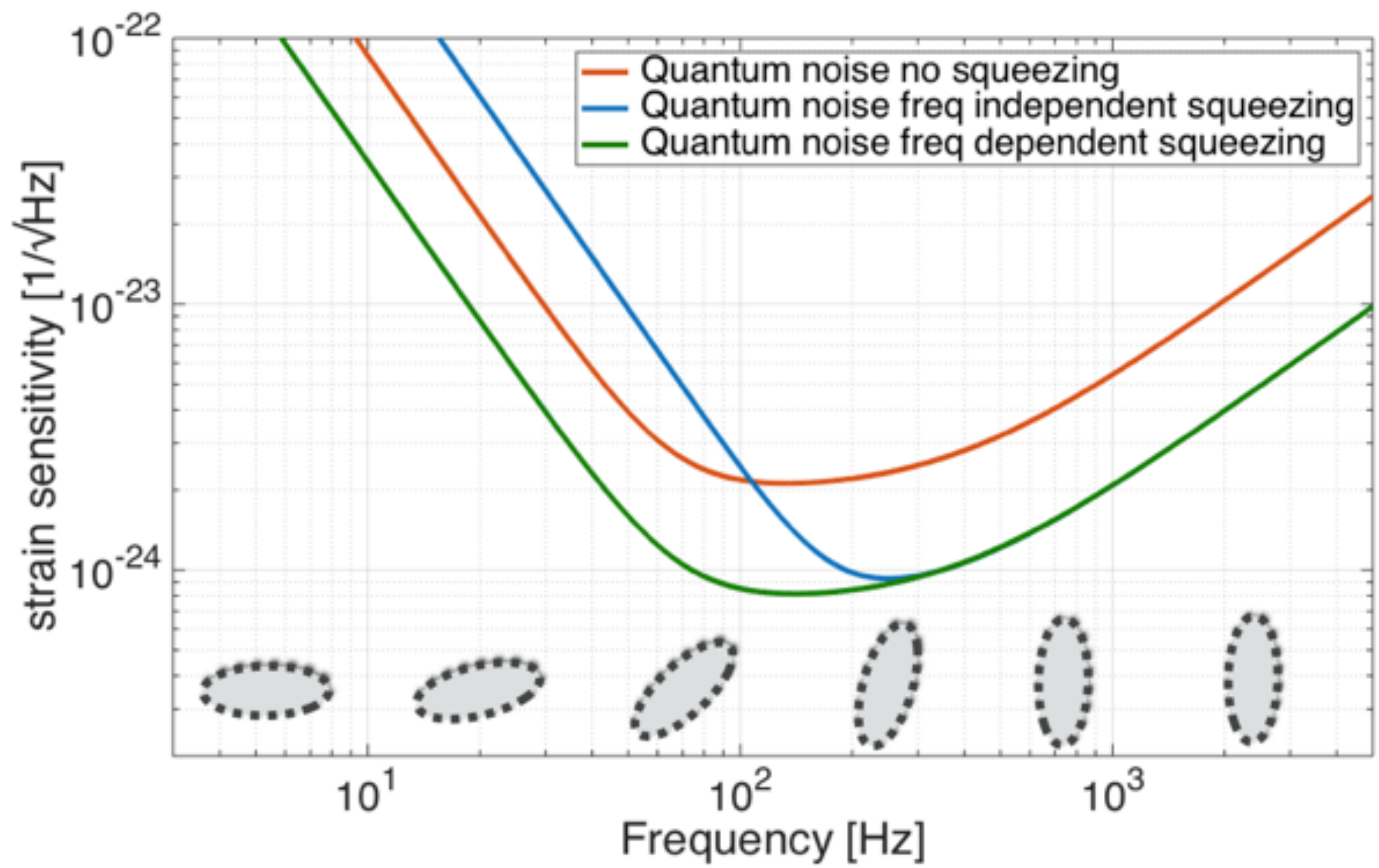
APC - Université Paris Diderot

NAOJ

- Why using long filter cavities in enhanced interferometers ?
- What performances are required?
- What is the state of the art?
- Which are the experimental challenges and the improvements needed to achieve optimal performances?

Why using filter cavities in enhanced interferometer?

- Filter cavities impress a frequency dependent rotation on the squeezing ellipse
- Reduced noise quadrature always aligned with the signal
- First implementation: only one filter cavity (broadband ITF)

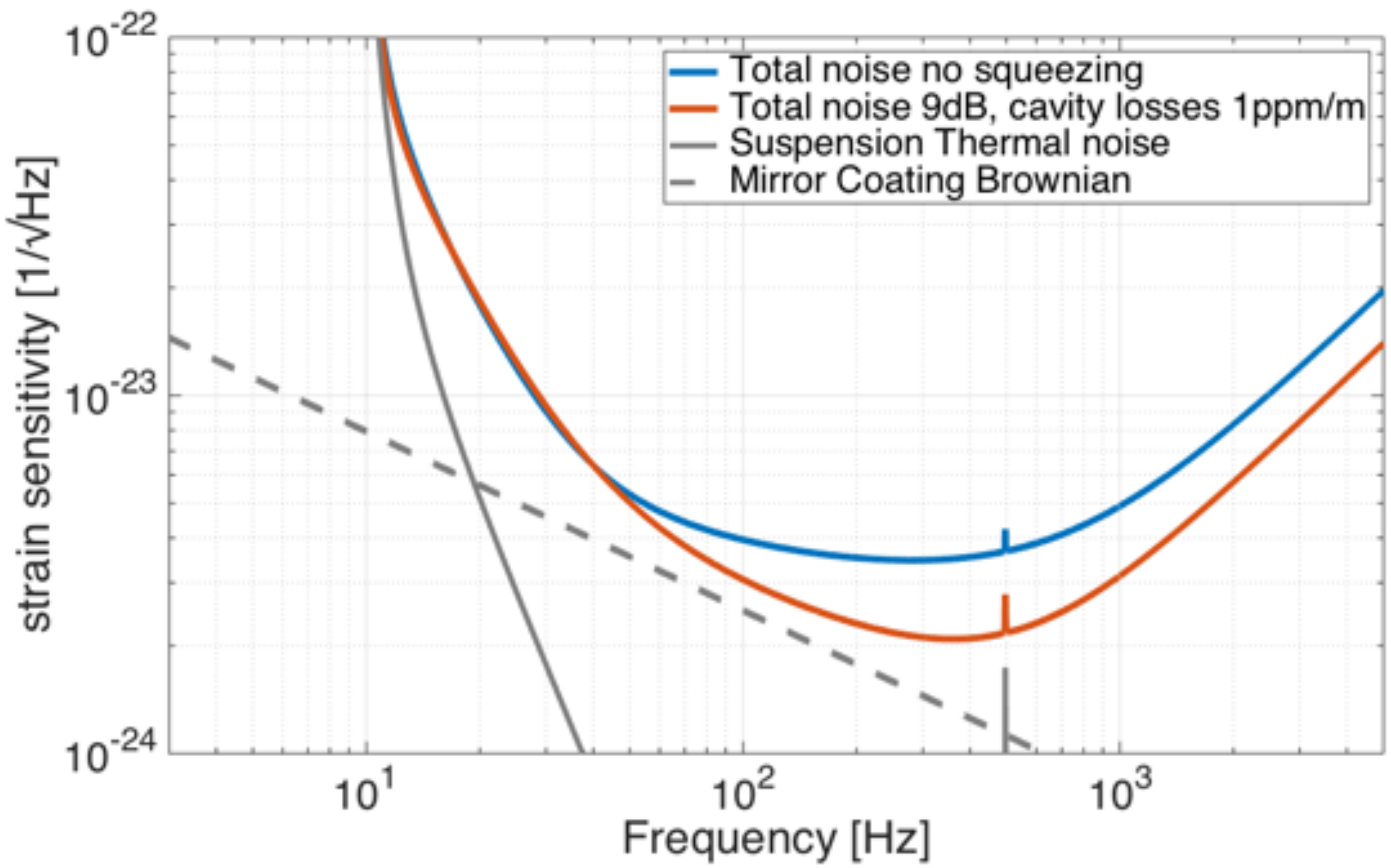


Why using (long) filter cavities in enhanced interferometer?

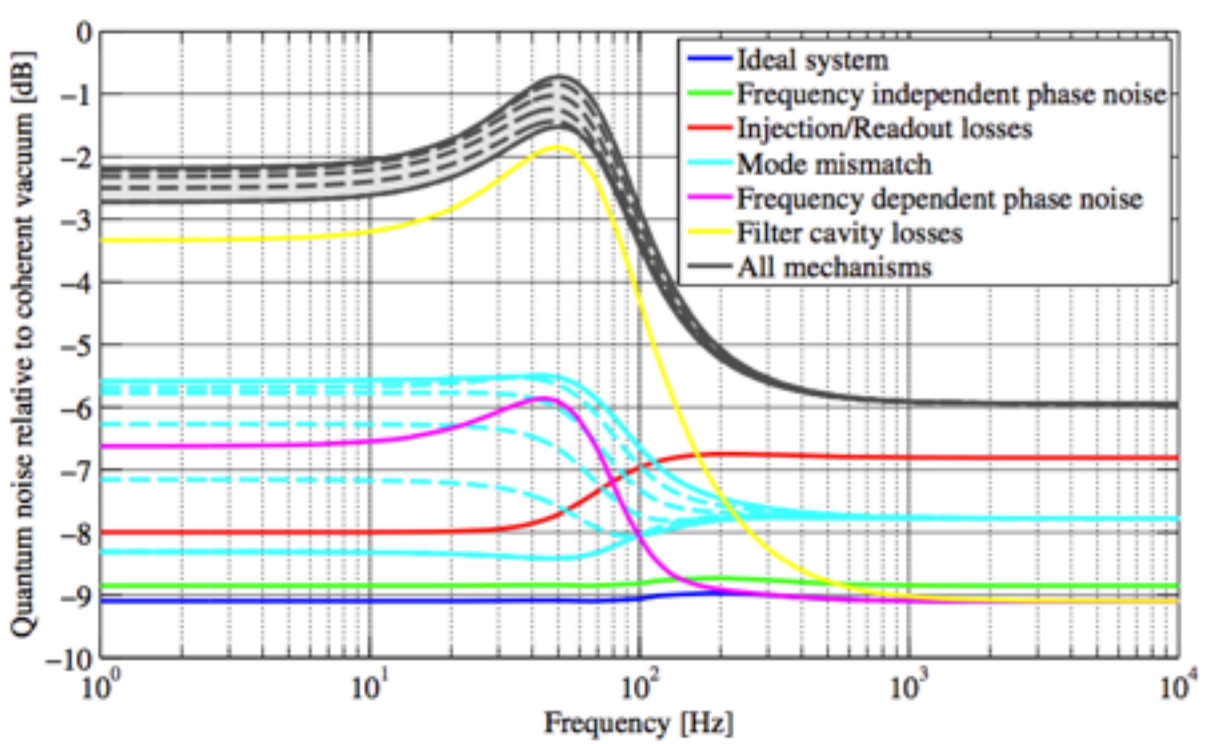
- First implementation of frequency dependent squeezing in Advanced LIGO: 16 m filter cavity with losses target 1 ppm/m

- Squeezing is deteriorated by cavity losses at low frequency but thermal noise is relevant in that region (little room for improvements)

- Goal : avoid to spoil sensitivity at low frequency

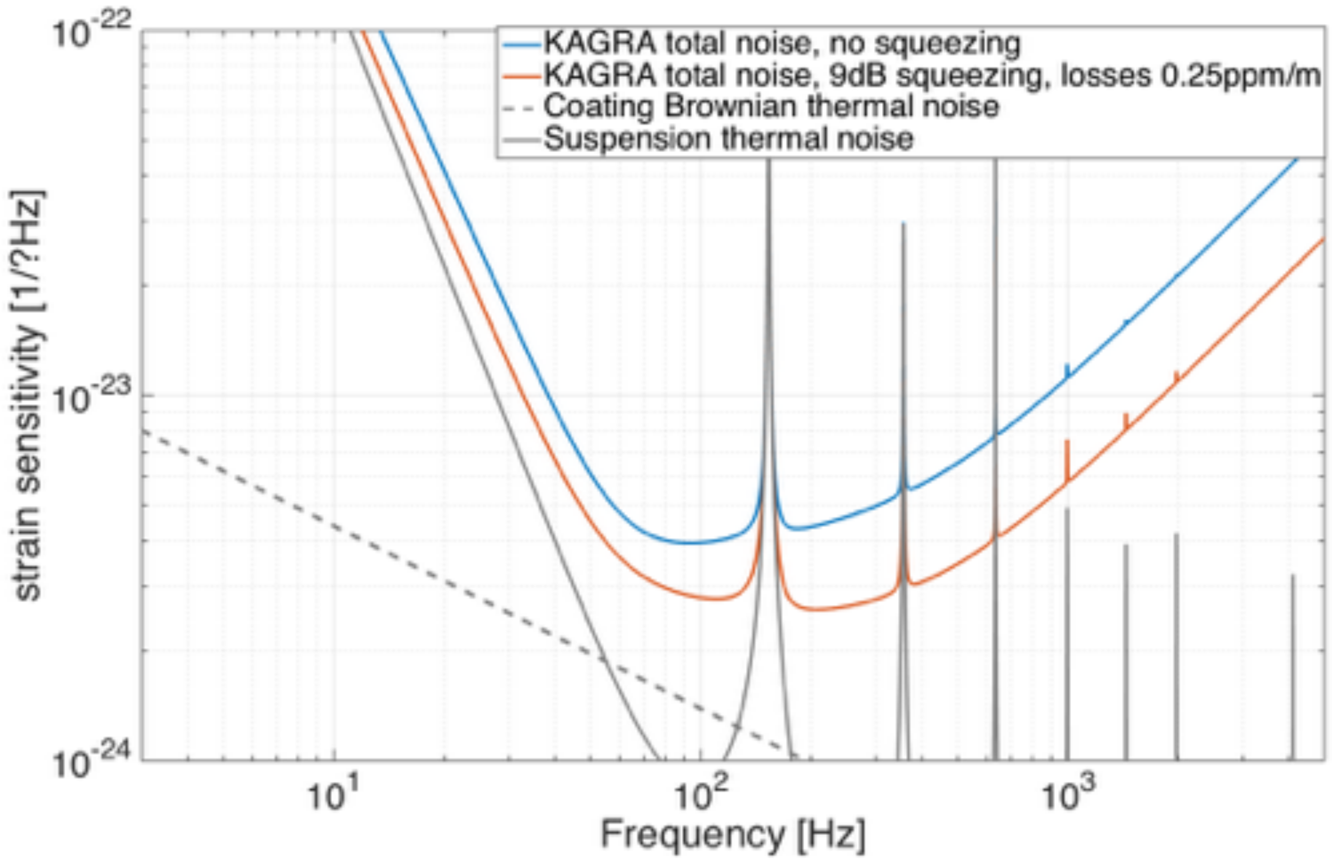


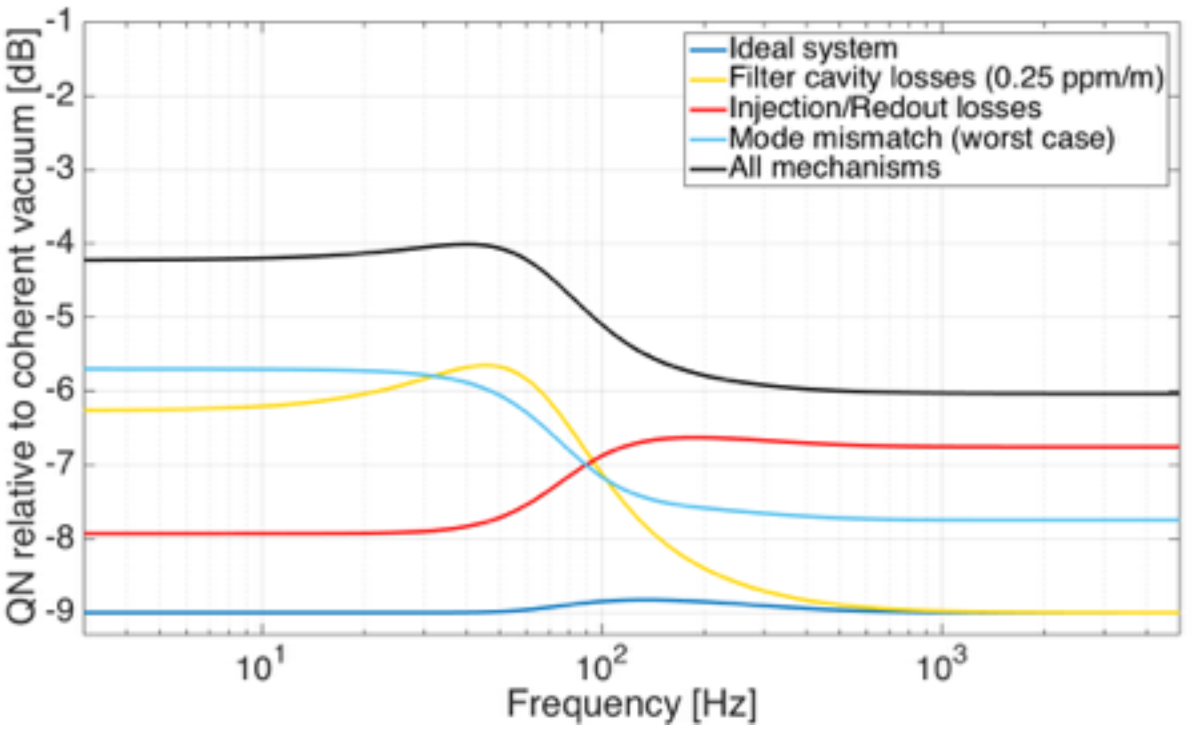
Advanced LIGO sensitivity, 16 m filter cavity with loss of 1 ppm/m



PHY. REV. D 90, 062006 (2014)
Decoherence and degradation of squeezed states in quantum filter cavities
P. Kwee et al.

Why using long filter cavities in enhanced interferometer?

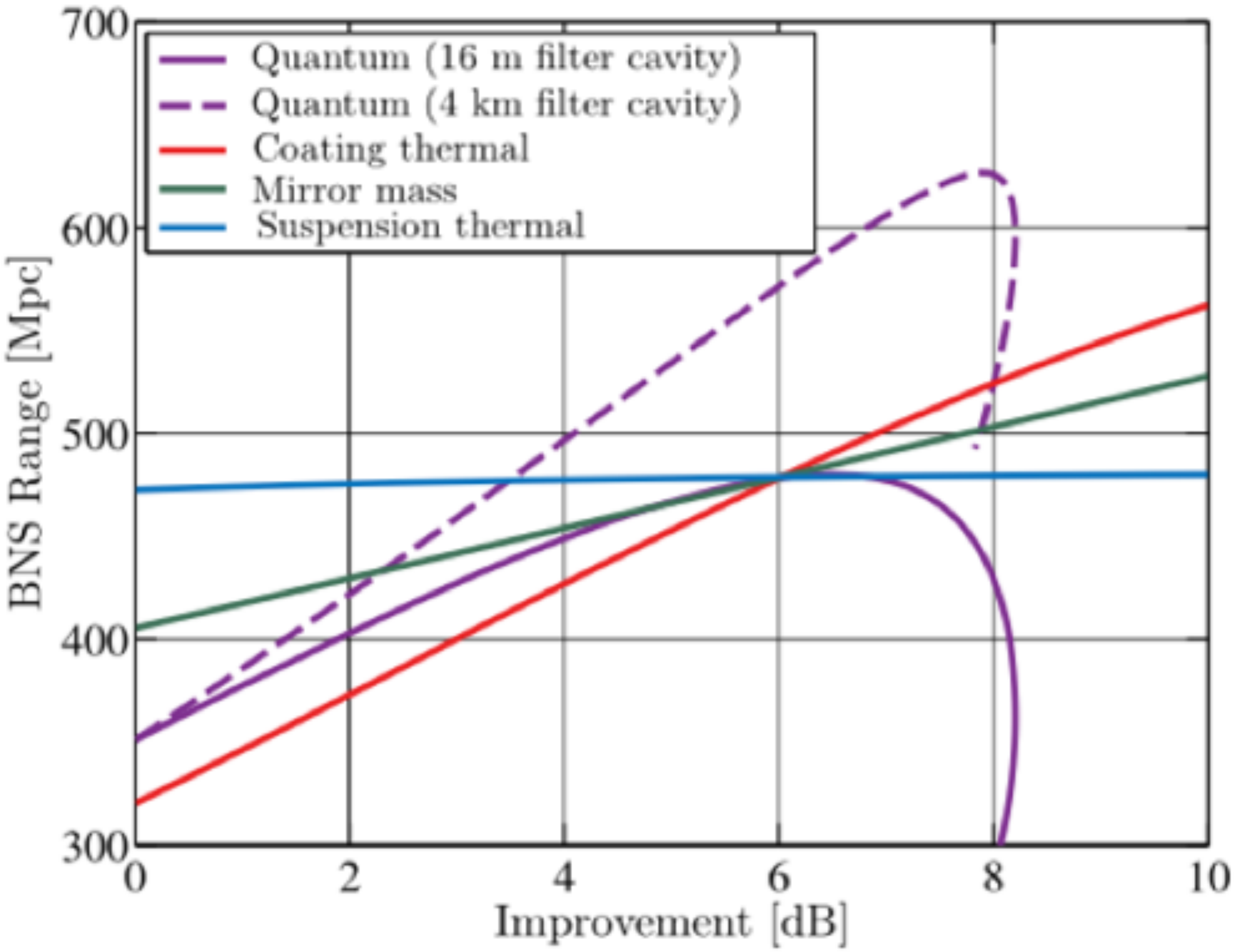




KAGRA sensitivity, 300 m filter cavity
with loss of 0.25 ppm/m

- Effect of the cavity losses is reduced since the cavity is longer
- Thermal noise is lower due to cryogenic operation
- Sensitivity can be improved also at low frequency

Why using long filter cavities in enhanced interferometer?



- The use of a long filter cavity will improve of 20% the BNS range with respect to a short filter cavity in an upgrade version of Advanced LIGO


PHYSICAL REVIEW D **91,** 062005 (2015)

Prospects for doubling the range of Advanced LIGO

John Miller,* Lisa Barsotti, Salvatore Vitale, Peter Fritschel, and Matthew Evans
LIGO Laboratory, Massachusetts Institute of Technology,
185 Albany Street, Cambridge, Massachusetts 02139, USA

Daniel Sigg
LIGO Hanford Observatory, P.O. Box 159, Richland, Washington 99352, USA
(Received 29 October 2014; published 16 March 2015)

What performances do we need for achieving an optimal rotation?

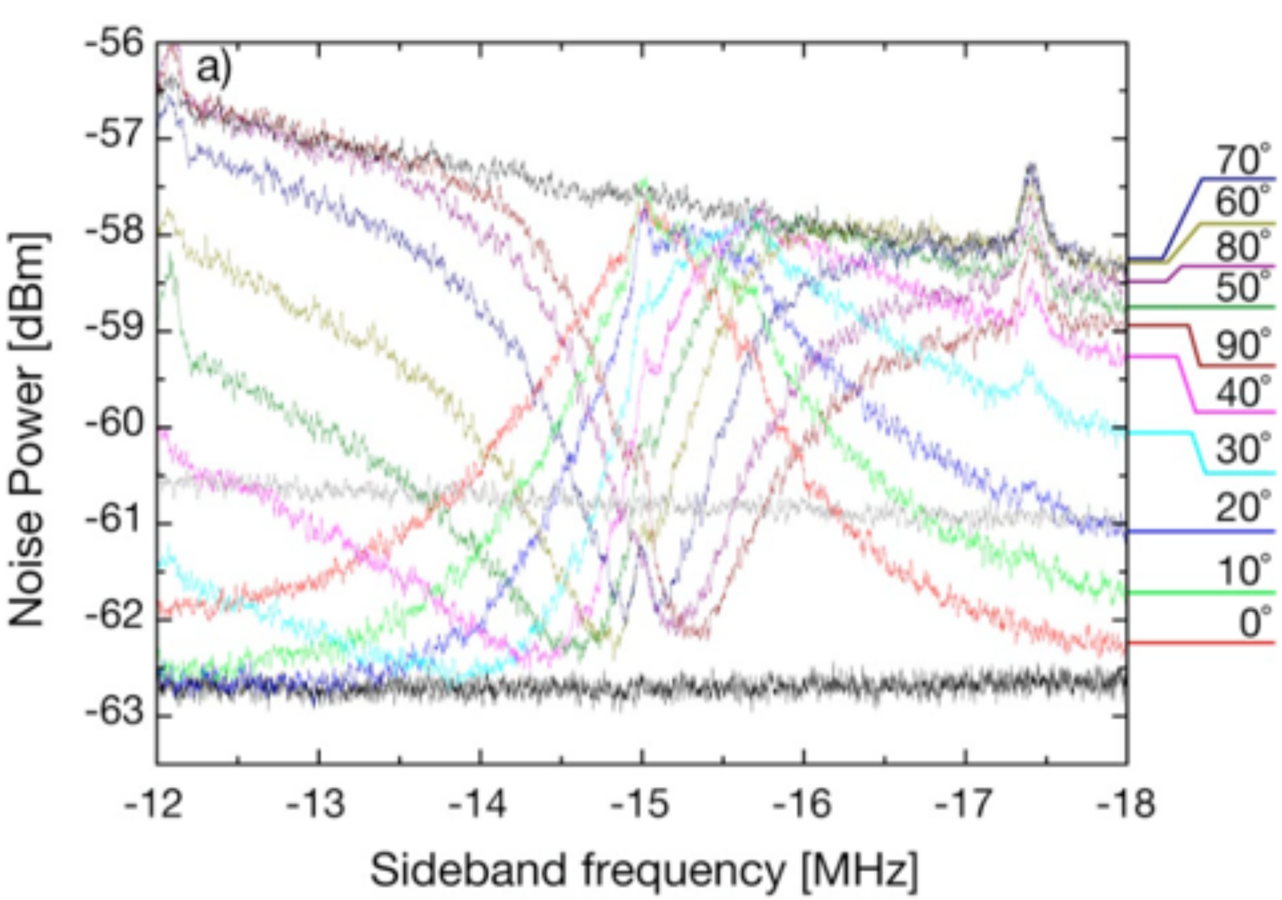
- The target frequency Ω_{SQL} at which the squeezing rotation should take place is about 2π x 70 Hz (depending on the power)
- The storage time need to achieve it is more than 2.5 ms (among the highest storage time ever achieved)

The realistic target: 6 dB of measured squeezing at high frequency

What has been done so far?

- Rotation of the squeezing angle already demonstrated

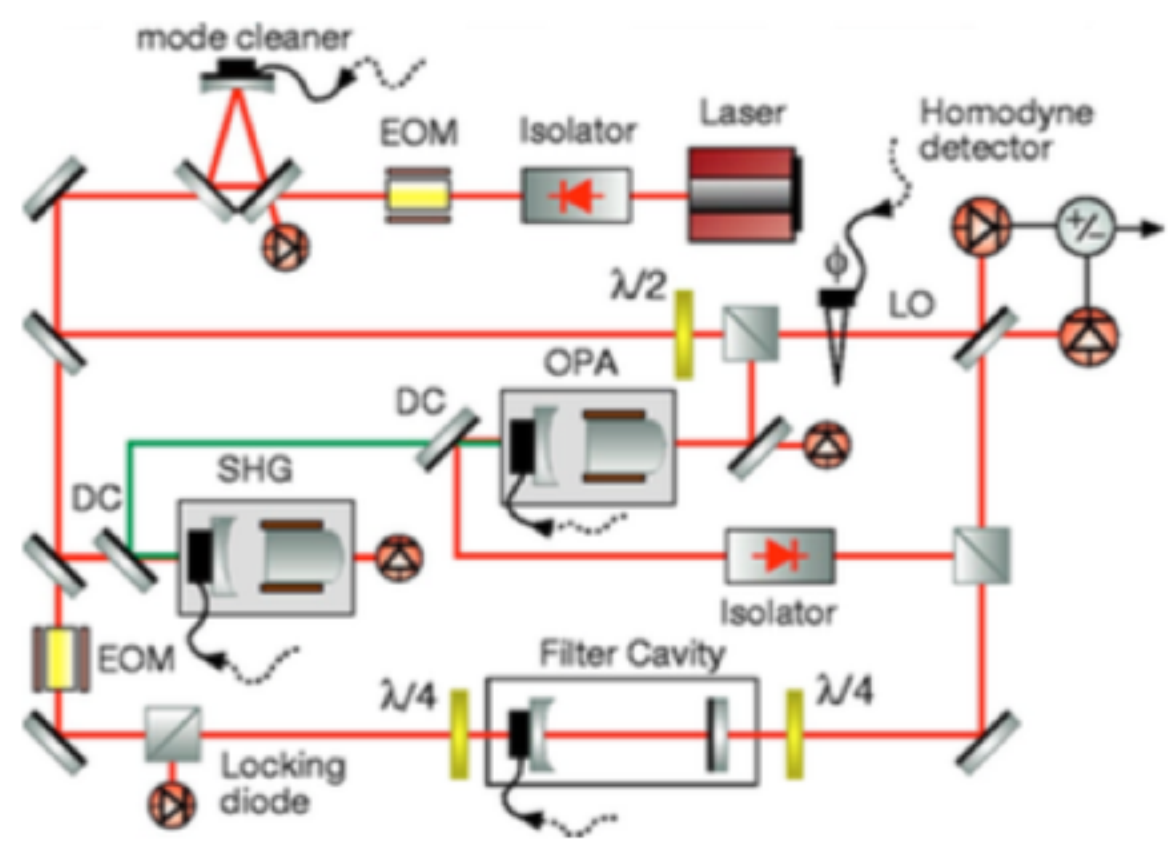
@ MHz



PHYSICAL REVIEW A 71, 013806 (2005)

Experimental characterization of frequency-dependent squeezed light

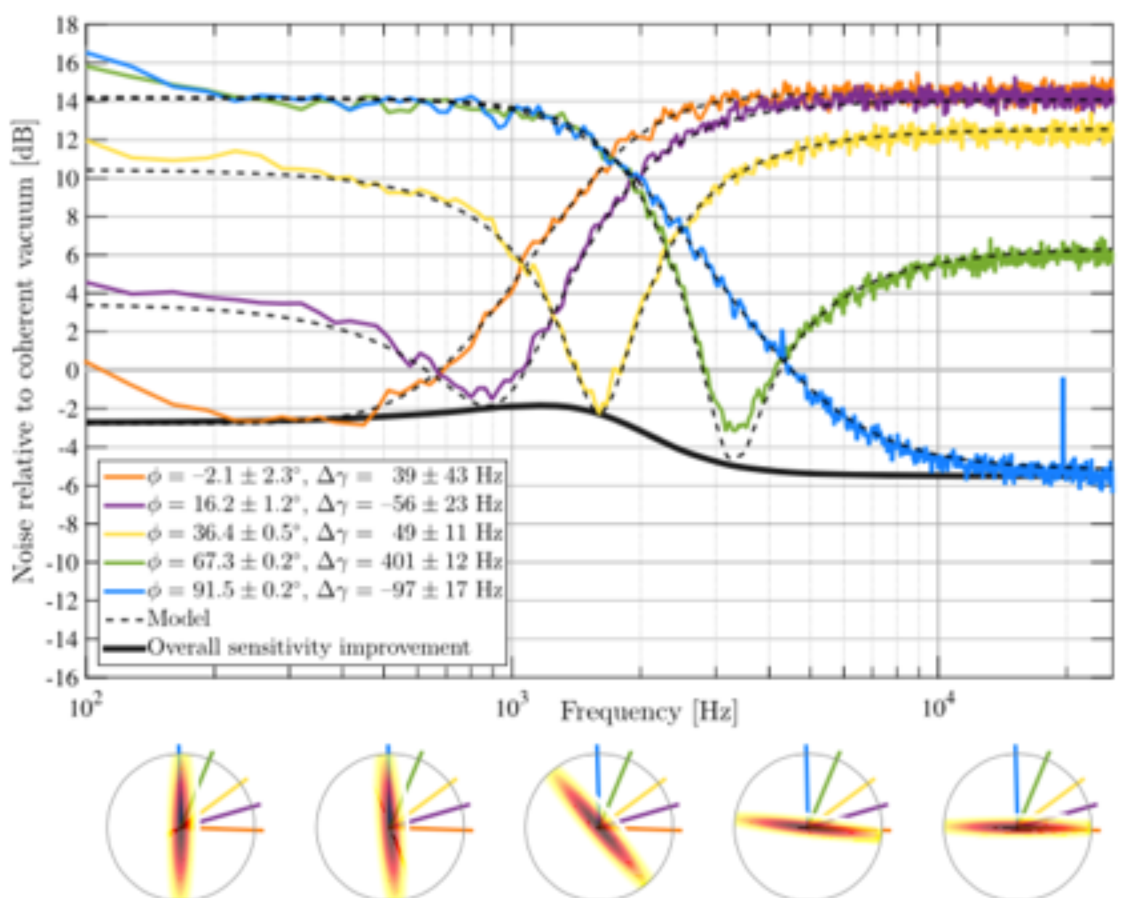
Simon Chelkowski, Henning Vahlbruch, Boris Hage, Alexander Franzen, Nico Lastzka, Karsten Danzmann, and Roman Schnabel
Institut für Atom- und Molekülphysik, Universität Hannover and Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut), Callinstrasse 38, 30167 Hannover, Germany
(Received 2 August 2004; published 10 January 2005)

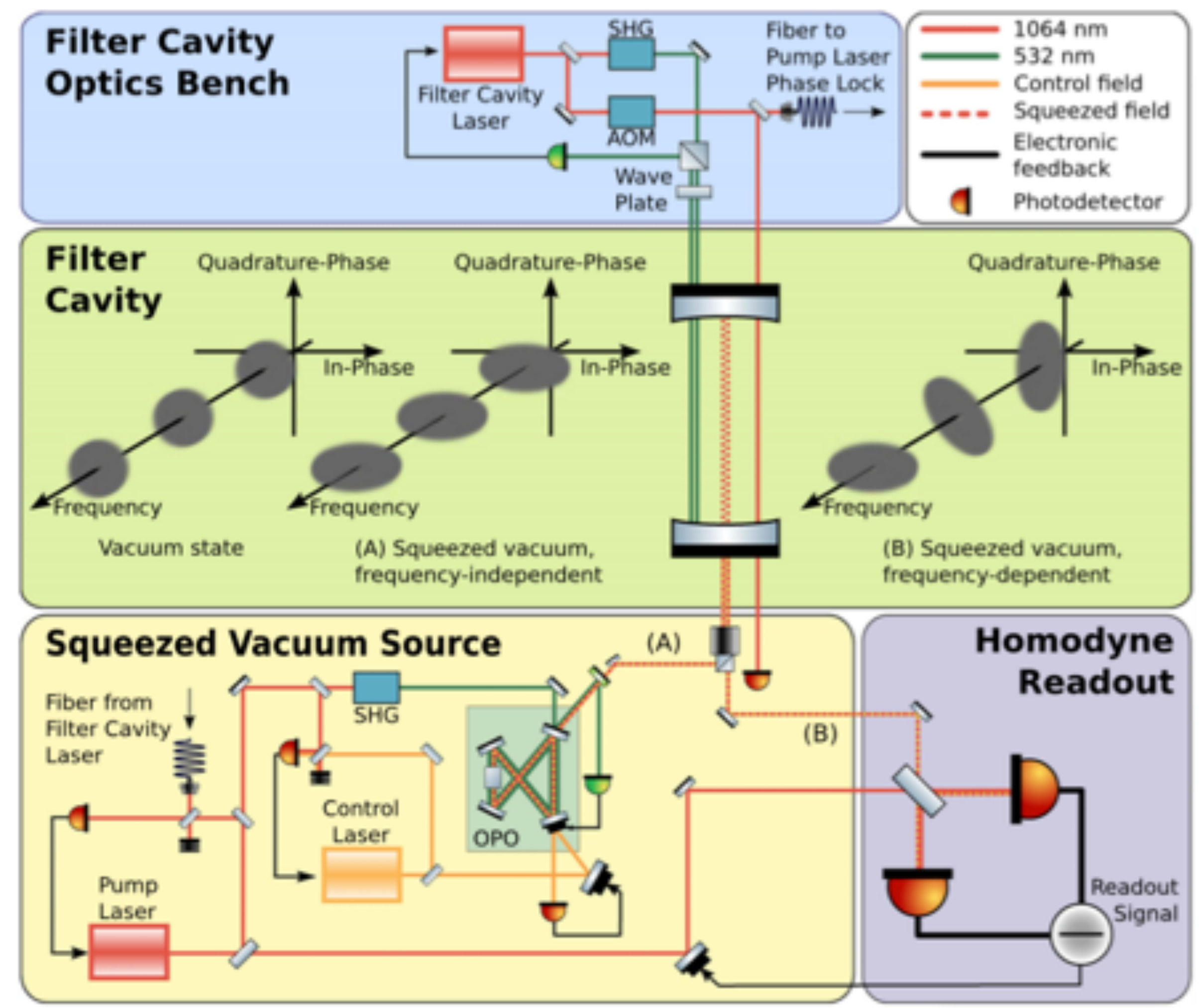


What has been done so far?

- Rotation of the squeezing angle already demonstrated

  @ KHz





PRL 116, 041102 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

Audio-Band Frequency-Dependent Squeezing for Gravitational-Wave Detectors

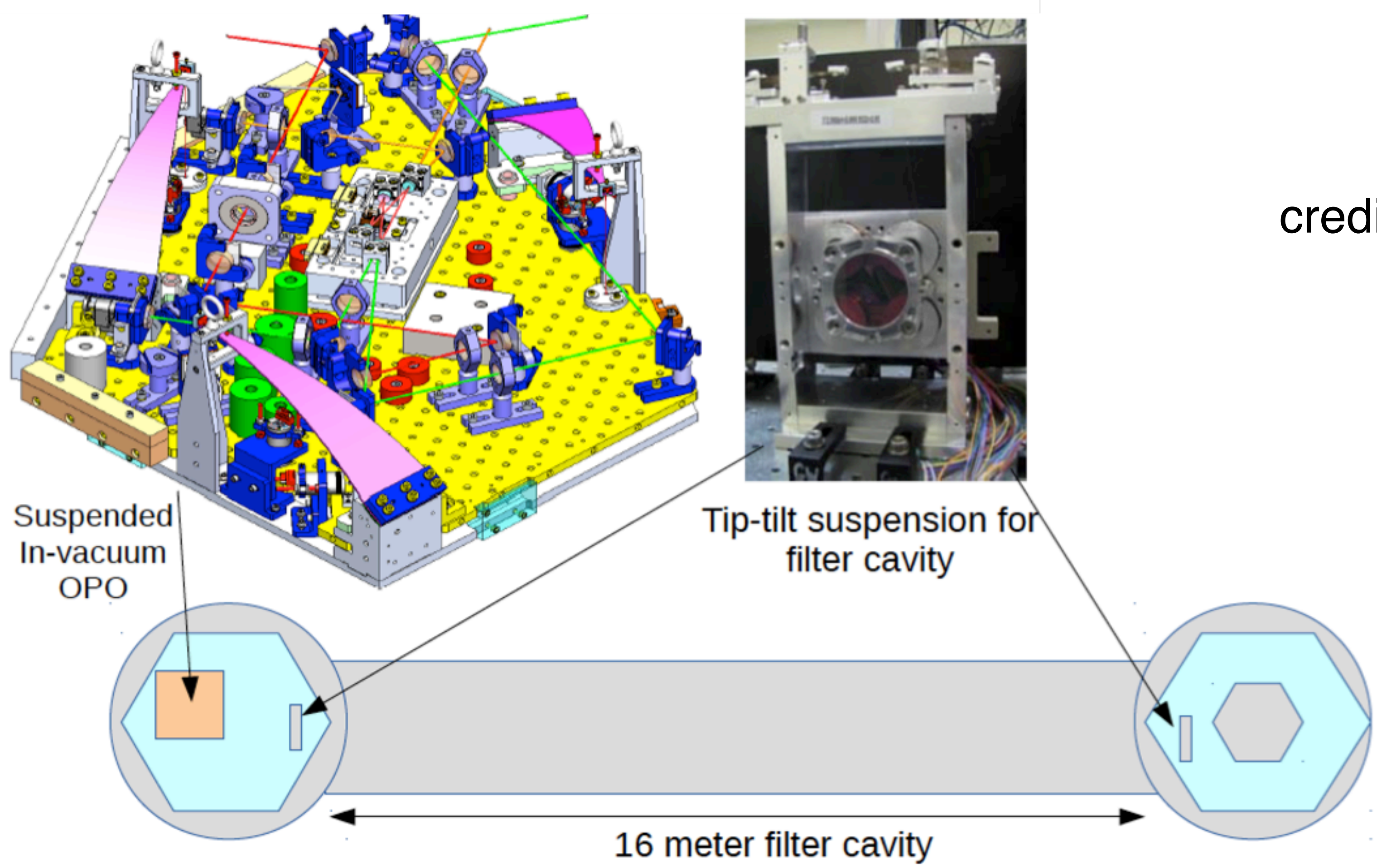
Eric Oelker, Tomoki Isogai, John Miller, Maggie Tse, Lisa Barsotti, Nergis Mavalvala, and Matthew Evans*

Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

(Received 20 August 2015; revised manuscript received 10 December 2015; published 29 January 2016)

Ongoing activities

- 16 m filter cavity and full scale prototype of in-vacuum squeezed source for aLIGO at MIT in the LASTI facility. Assembly is starting now.

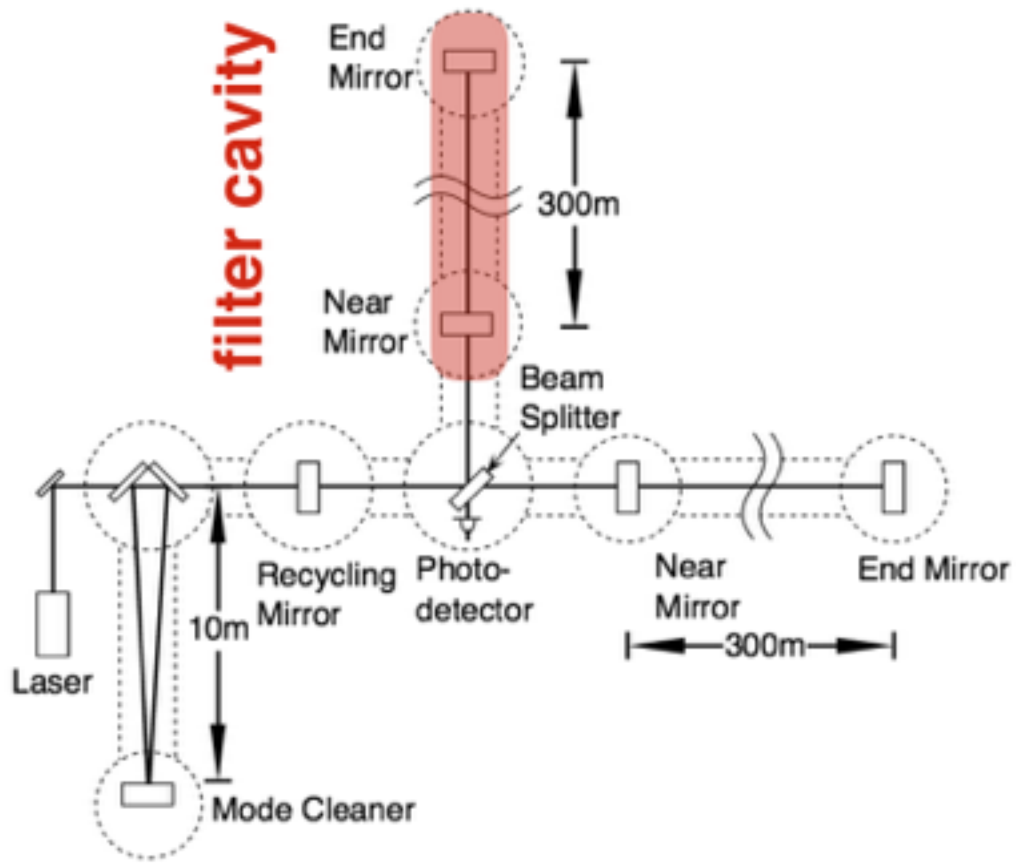


credit: Lisa Barsotti

- 50 m filter cavity prototype (CALVA) in Orsay. Optical design ongoing.

Ongoing activities

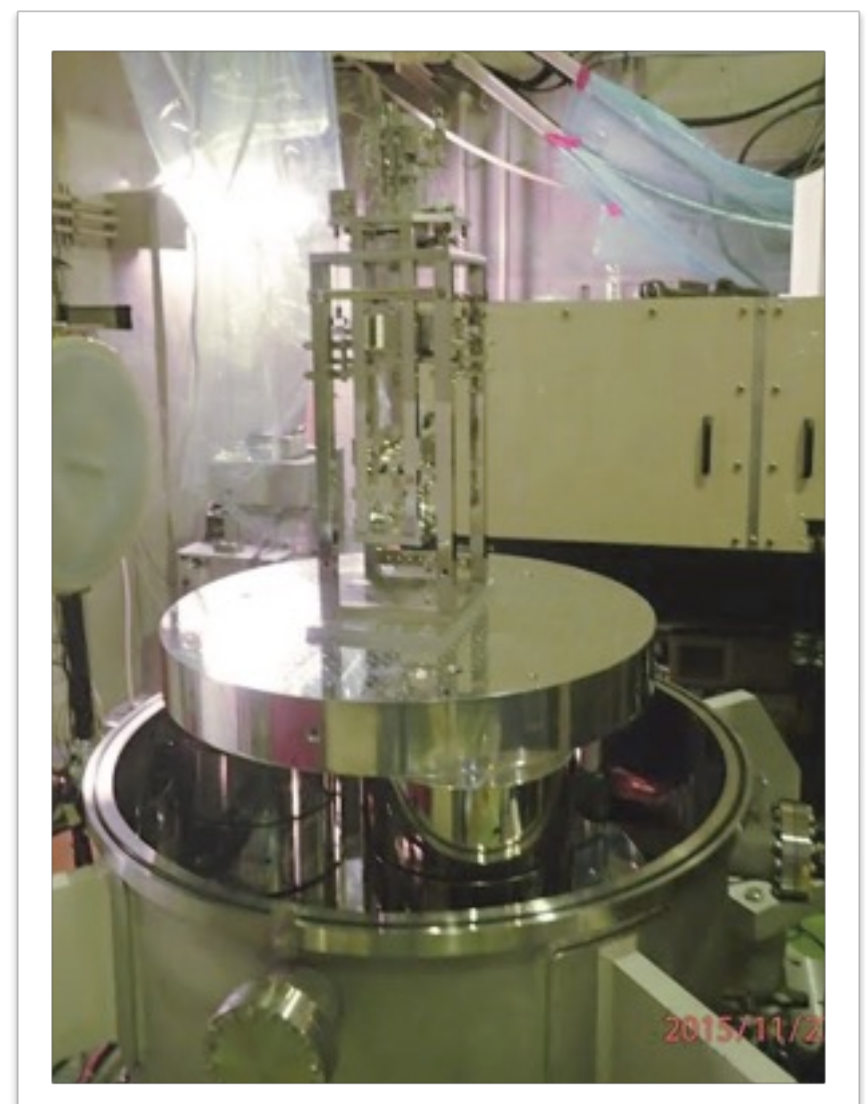
- 300 m filter cavity prototype is being installed at NAOJ in TAMA infrastructure



PHYSICAL REVIEW D **93**, 082004 (2016)

Estimation of losses in a 300 m filter cavity and quantum noise reduction in the KAGRA gravitational-wave detector

Eleonora Capocasa,[1,2,*] Matteo Barsuglia,[1] Jérôme Degallaix,[3] Laurent Pinard,[3] Nicolas Straniero,[3] Roman Schnabel,[4] Kentaro Somiya,[5] Yoichi Aso,[2] Daisuke Tatsumi,[2] and Raffaele Flaminio[2]



Planning

- End 2016 ➔ filter cavity characterization and losses measurements

- 2017 ➔ frequency independent squeezing production

- 2018 ➔ frequency dependent squeezing measurement

Experimental issues with long filter cavities

PROS

- <u>Reduce the impact of cavity losses</u>

- Relax the requirement on the finesse

$$\gamma_{\rm fc} = \frac{1}{\tau_{\rm storage}} = \frac{\pi c}{2 L_{\rm fc} \mathcal{F}} \simeq 2\pi \cdot 50\,{\rm Hz}$$

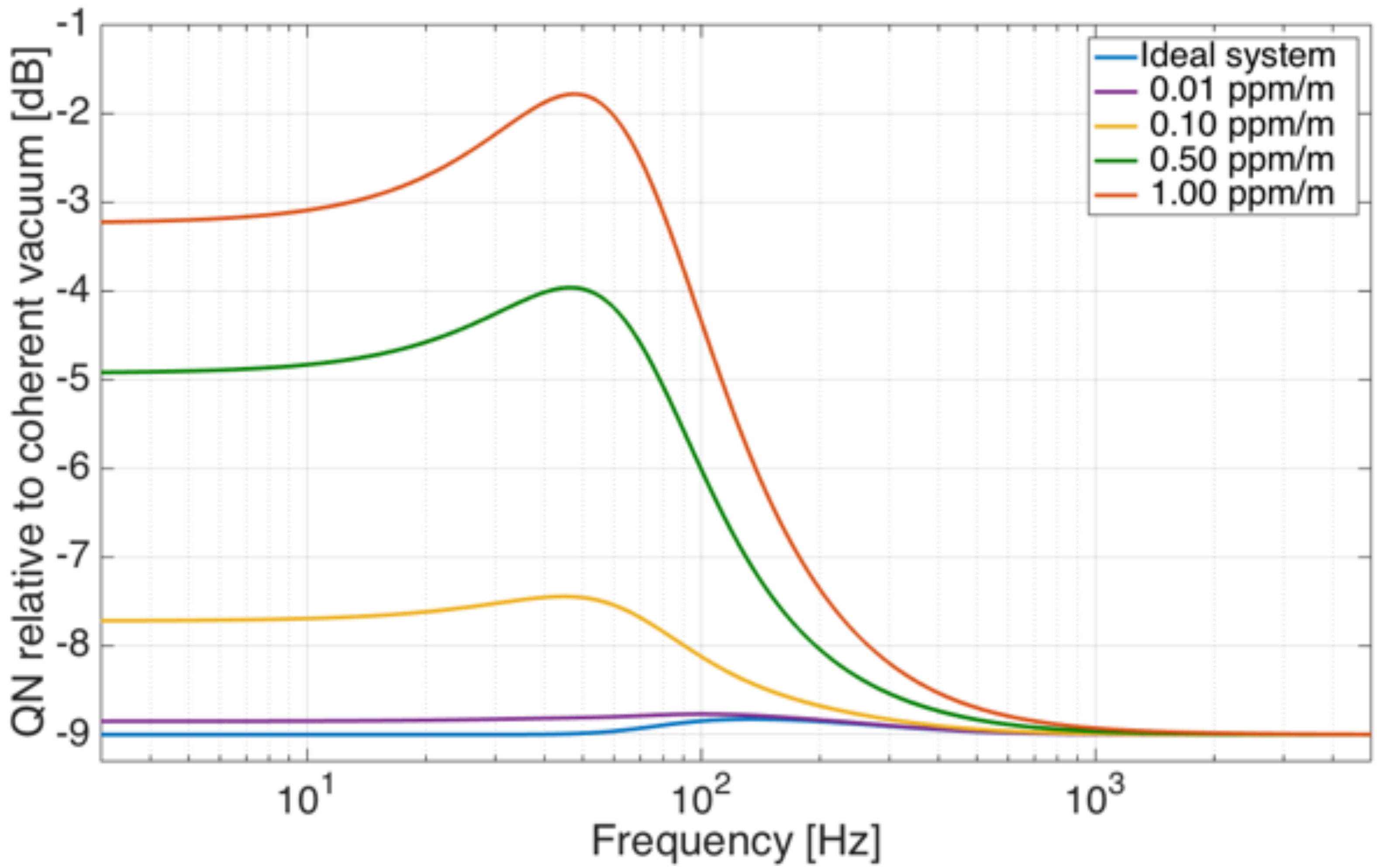
$$L = 16\,m \rightarrow \mathcal{F} \simeq 90000 \qquad\qquad L = 300\,m \rightarrow \mathcal{F} \simeq 5000$$

CONS

- More complex infrastructure

- Cost

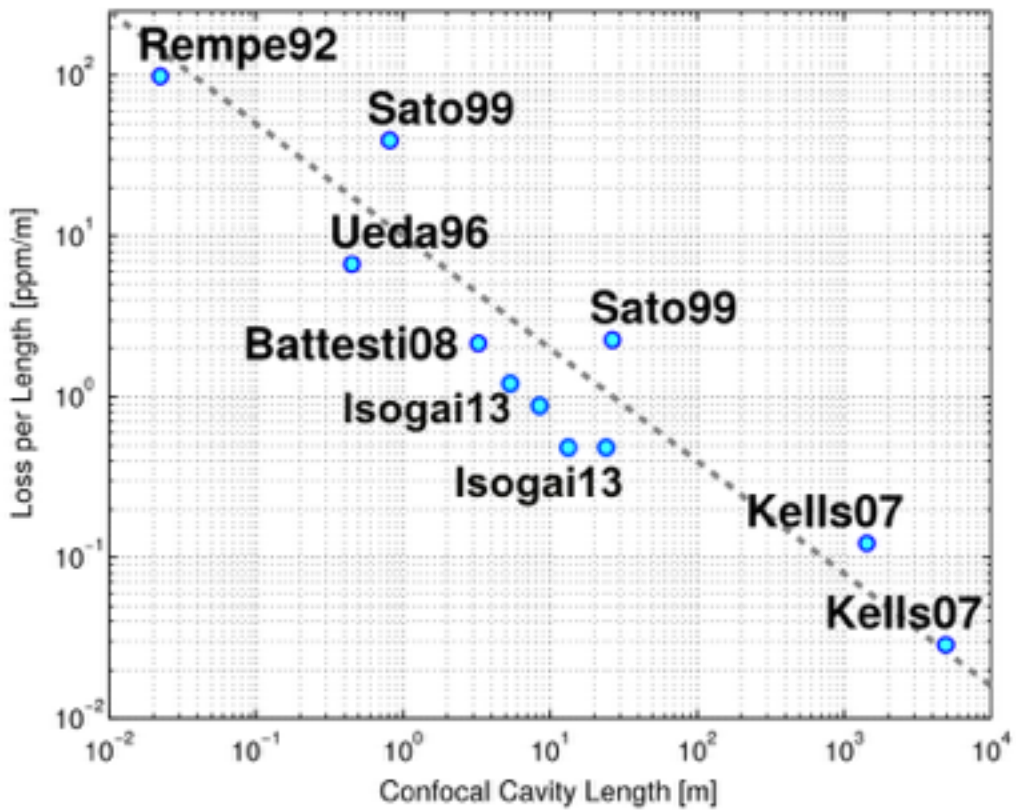
Effect of the filter cavity losses



- Losses are more influent at low frequency where the squeezing experiences the rotation

- The cavity performance depends on the loss per unit length

$$\gamma_{\rm fc} = c\frac{t_{in}^2 + \Lambda_{rt}^2}{4L_{\rm fc}}$$



Loss in long-storage-time optical cavities
T. Isogai, J. Miller,* P. Kwee, L. Barsotti, and M. Evans

The loss per unit length are observed to decrease with cavity length

How to minimise the effect of the losses?

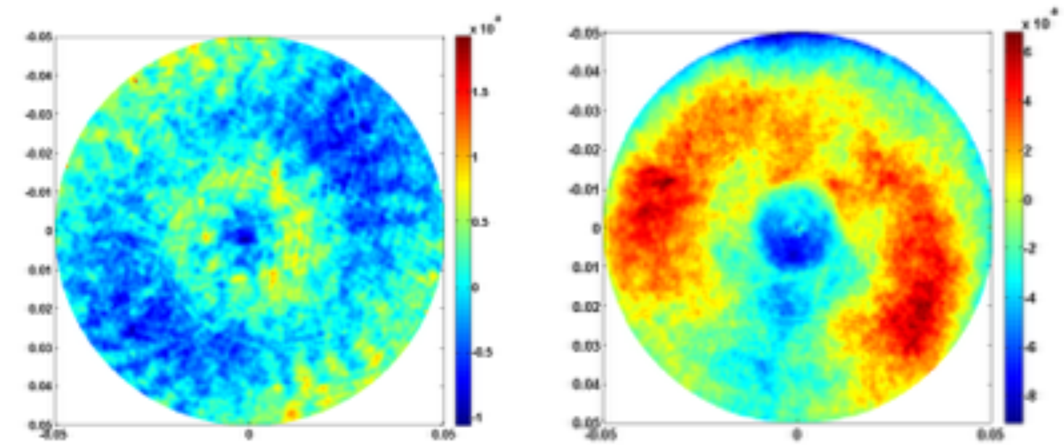
Increasing cavity length

Improve the mirrors quality (which are the limits?)

Intracavity losses mechanisms

We can neglect cavity losses (<1 ppm) caused by

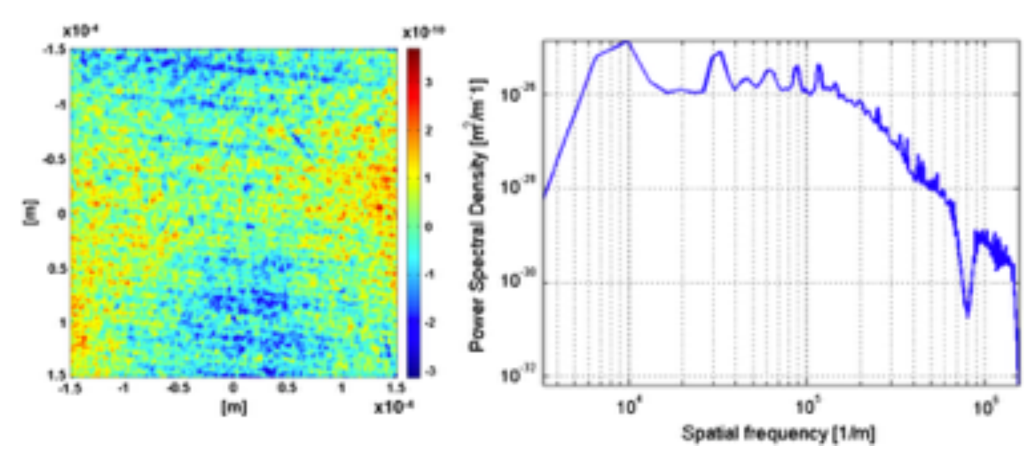
- absorption
- end mirror transmission
- clippling losses (in case of perfect spherical mirrors)



AdVirgo Virgo

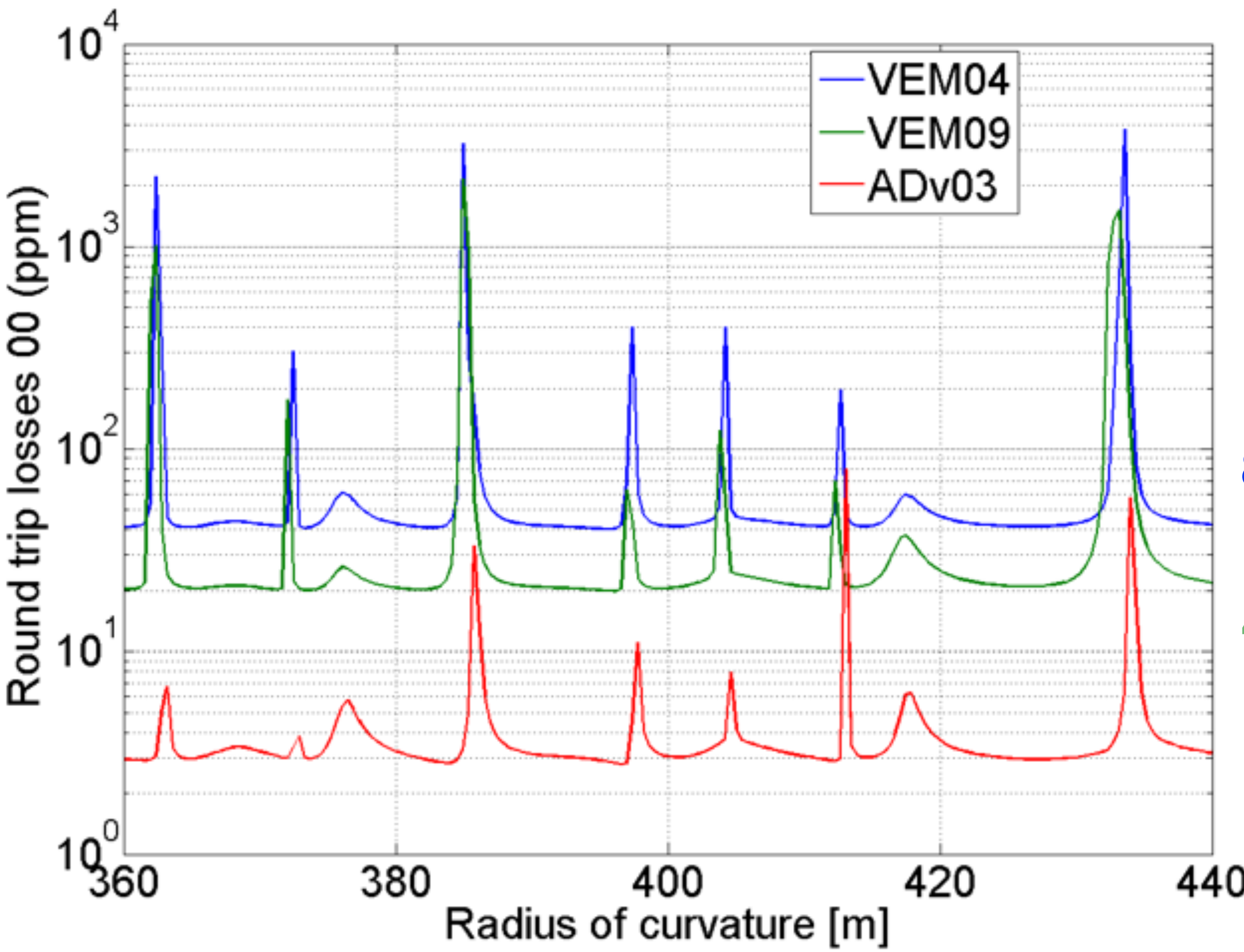
The main losses mechanism is the scattering from the mirrors originated by:

- flatness (up to 1000 m^{-1})
- roughness
- point defects



Simulated losses for different mirror qualities

Simulation performed for a 300 m filter cavity using Virgo and AdVirgo mirror maps



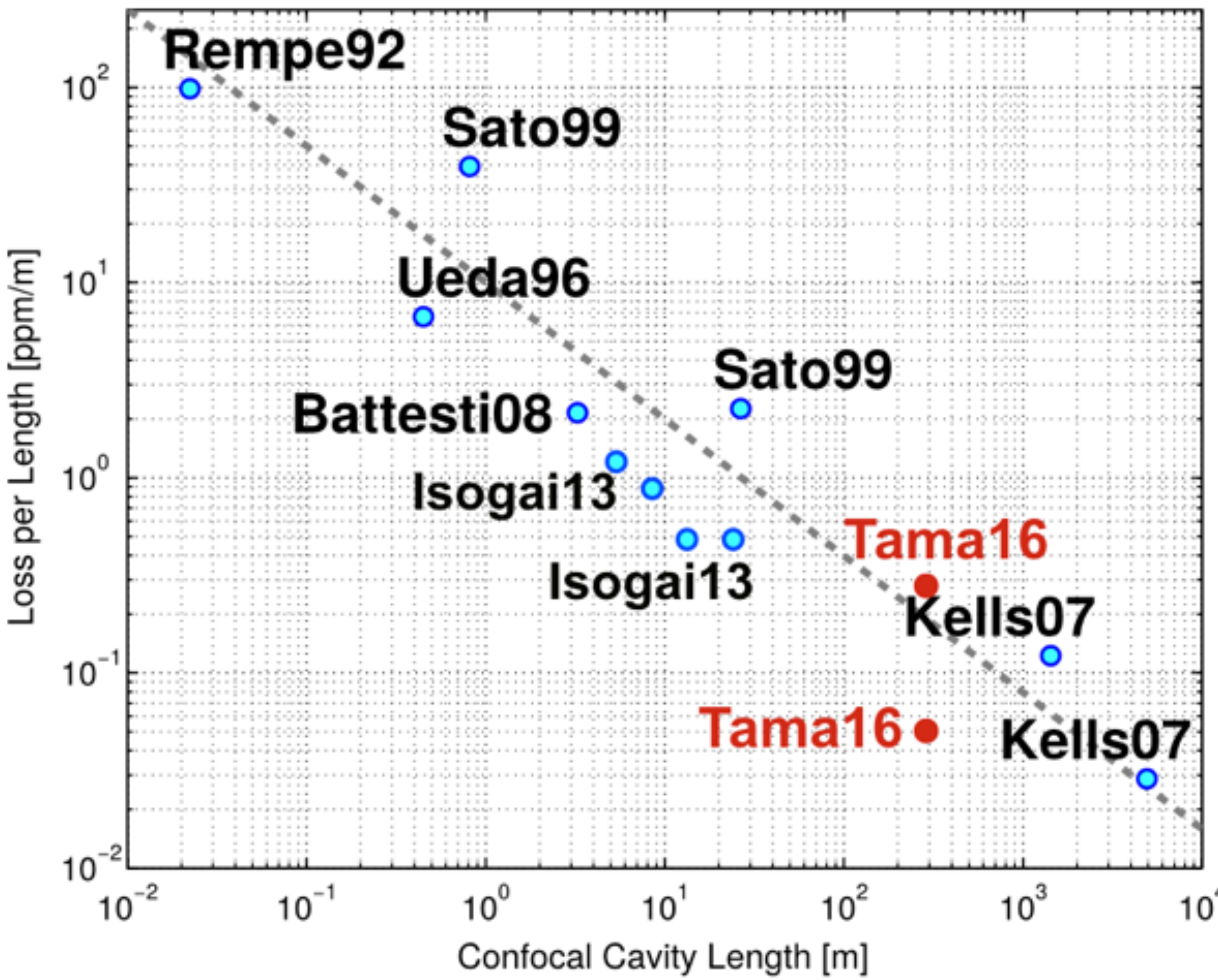
	diameter[m]	0.05	0.01
82 ppm	RMS [nm]	1.23	0.81
42 ppm	RMS [nm]	1.36	0.53
6 ppm	RMS [nm]	0.27	0.18

10 ppm to be added from roughness and point defects contribution

Estimated losses for the 300 m filter cavity

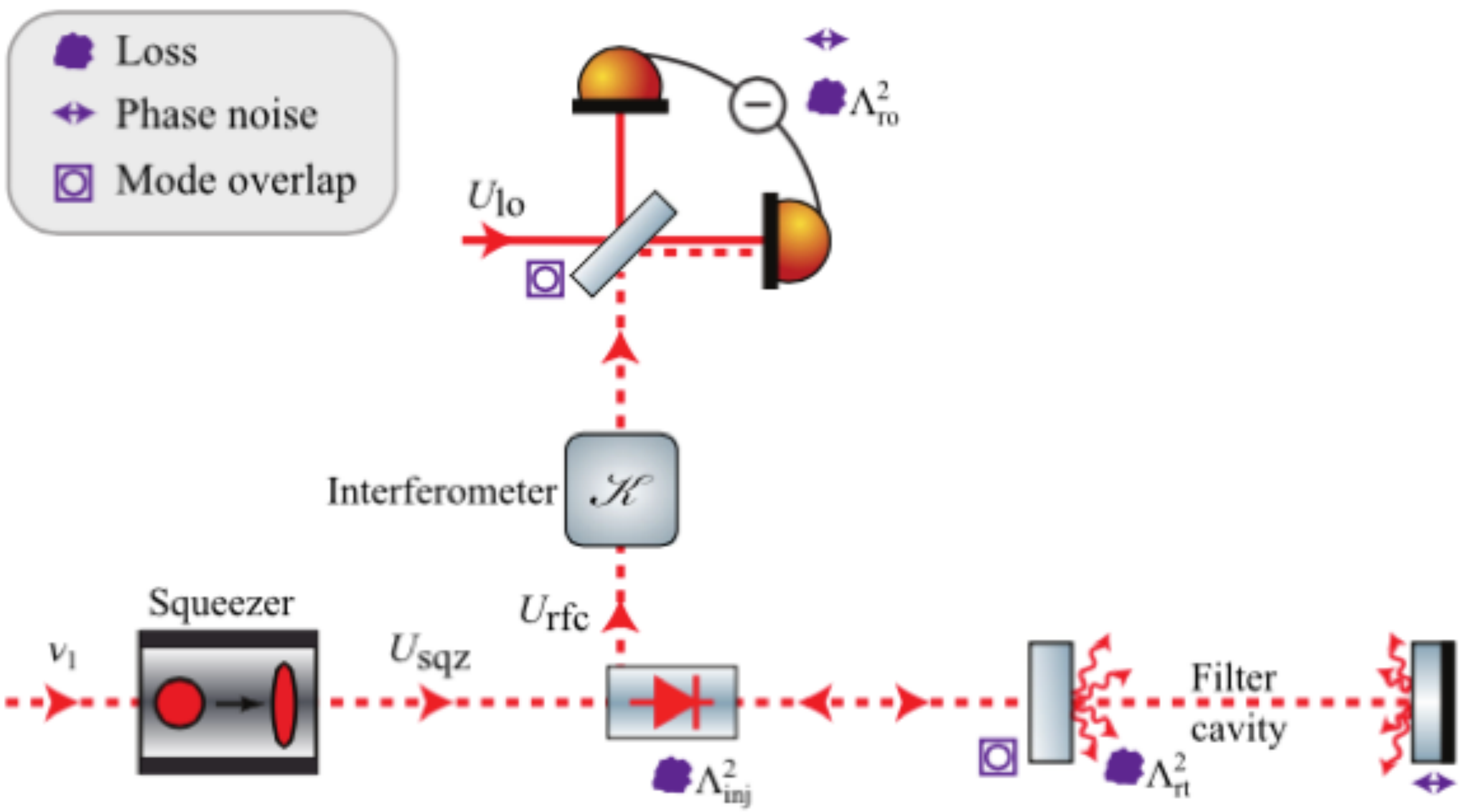
Virgo mirror quality => 70 ppm + 10 ppm = 80 ppm => **0.25 ppm/m**

AdVirgo mirror quality => 6 ppm + 10 ppm = 16 ppm => **0.05 ppm/m**



Squeezing degradation mechanisms

- Some degradation mechanisms that can be reduced by increasing cavity length



- Filter cavity losses
- Injection/readout losses
- Mode mismatch
- Frequency-dependent phase noise
- Frequency-independent phase noise

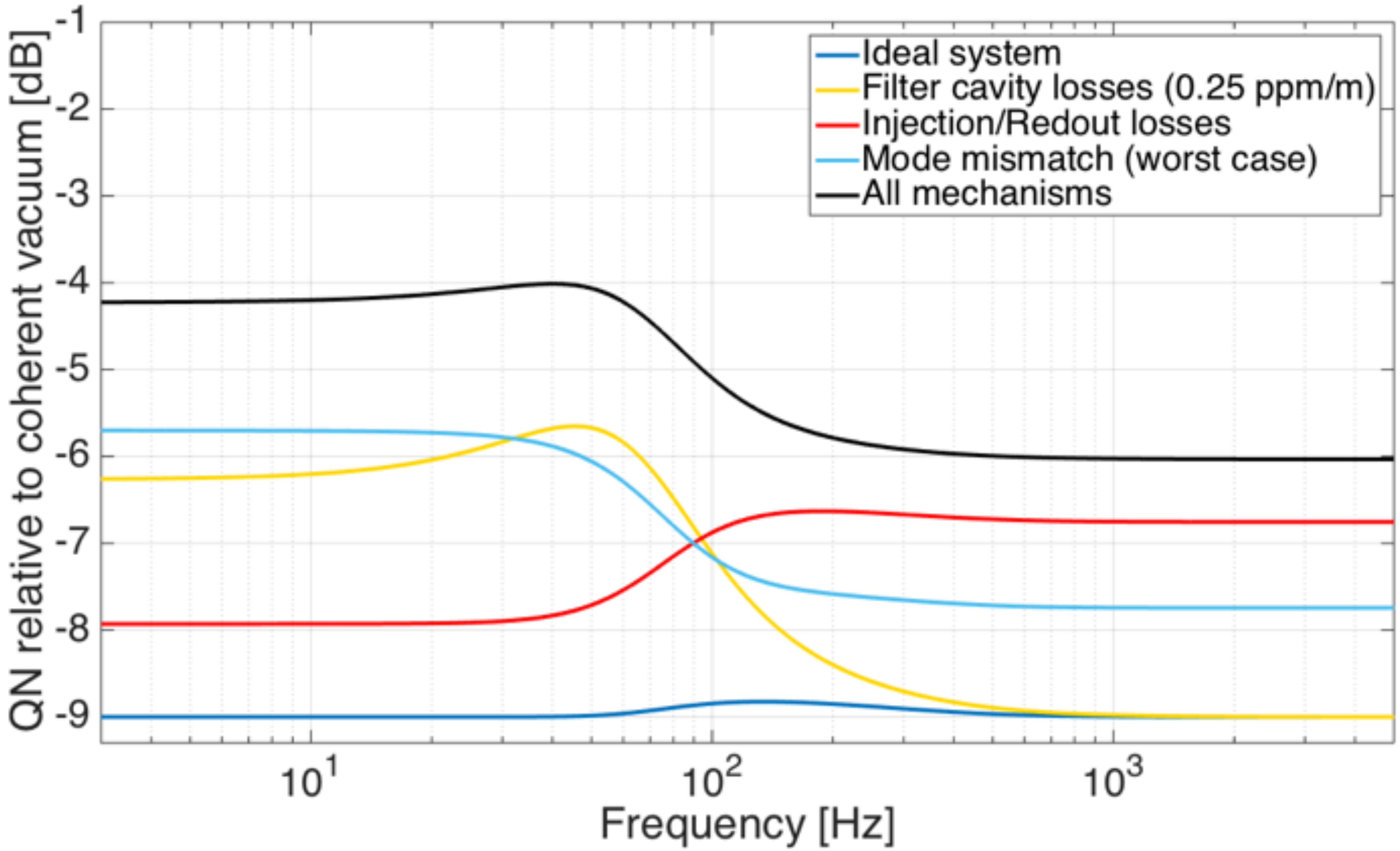
PHYSICAL REVIEW D **90**, 062006 (2014)

Decoherence and degradation of squeezed states in quantum filter cavities

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

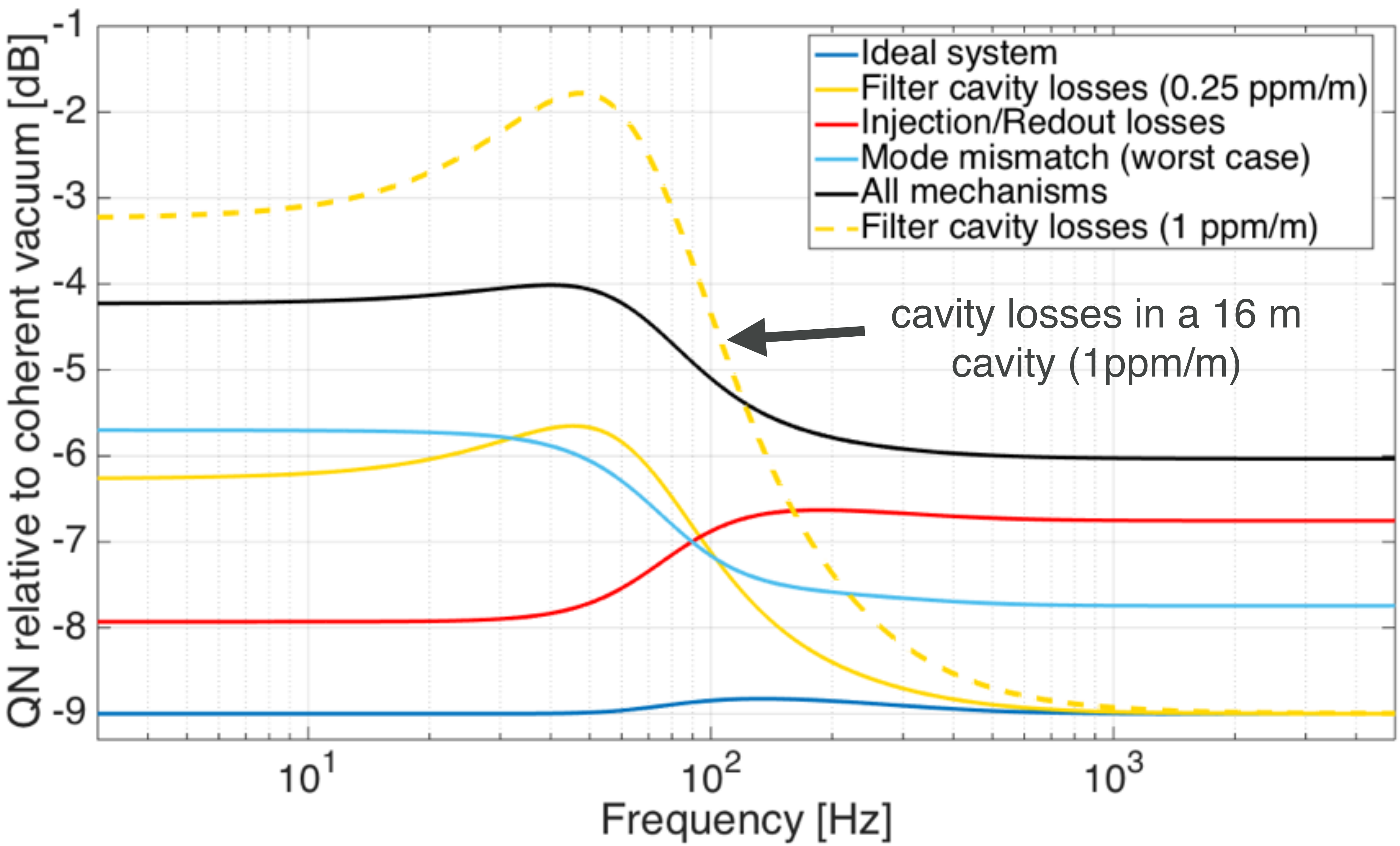
Squeezing degradation budget

for a 300 m filter cavity with losses of 80 ppm (0.25 ppm/m)

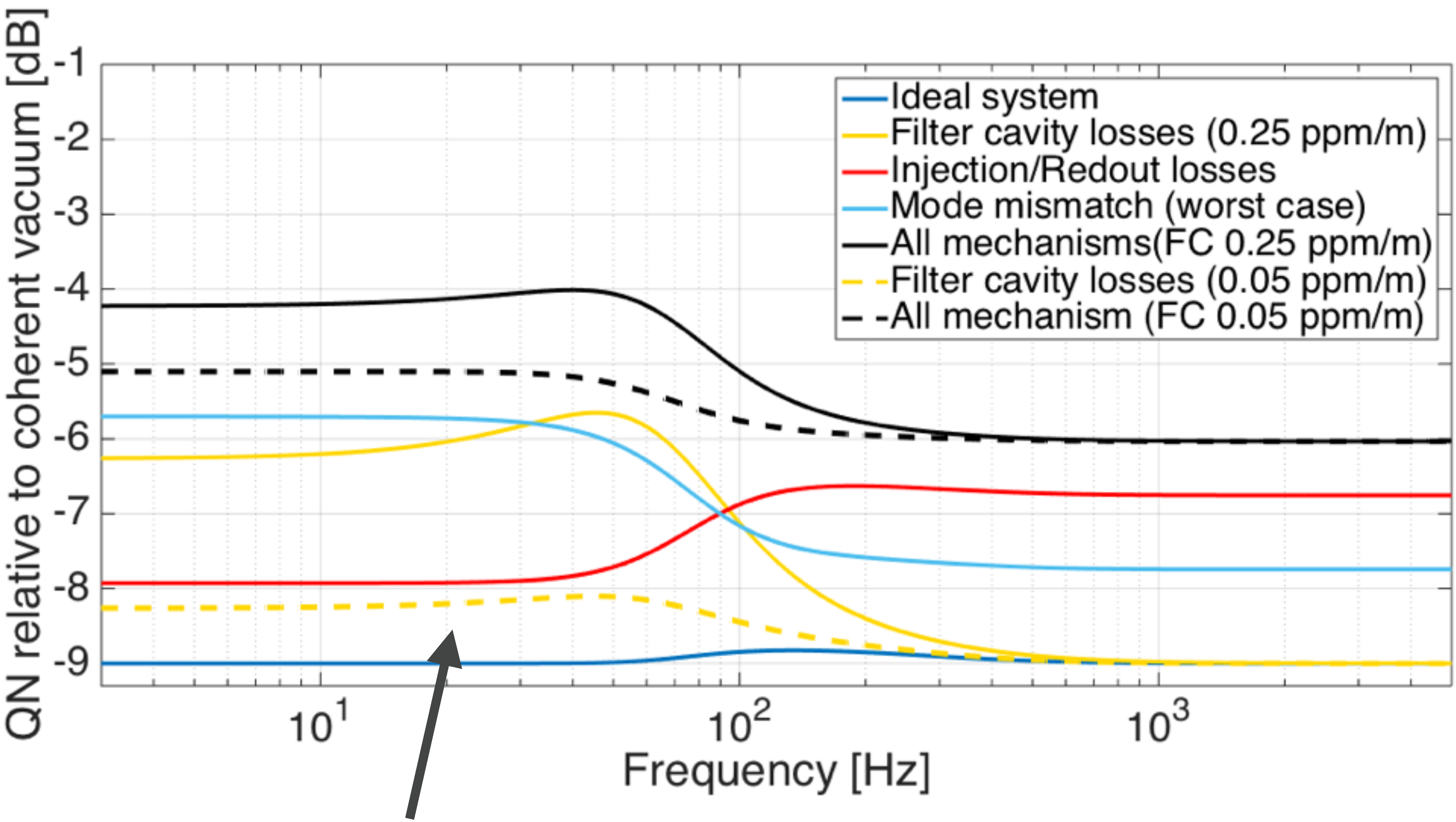


injection losses	5 %
readout losses	5 %
mismatch squeezer-filter cavity	2 %
mismatch squeezer-local oscillator	5 %
δL (rms)	0.3 pm

Squeezing degradation budget



Squeezing degradation budget

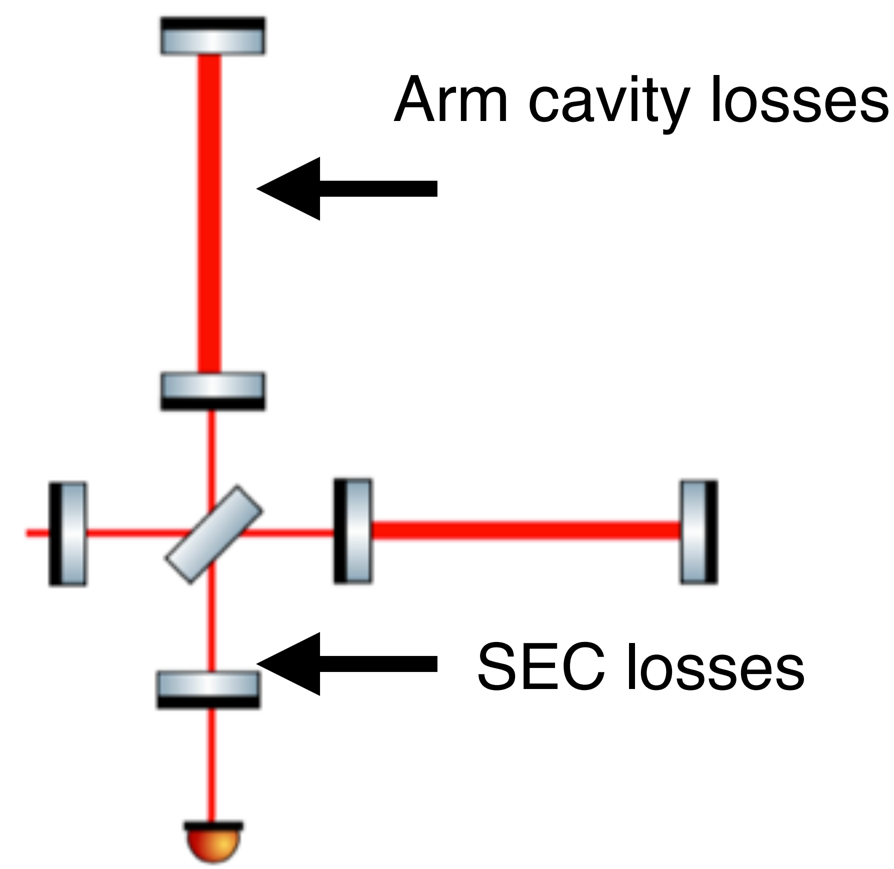


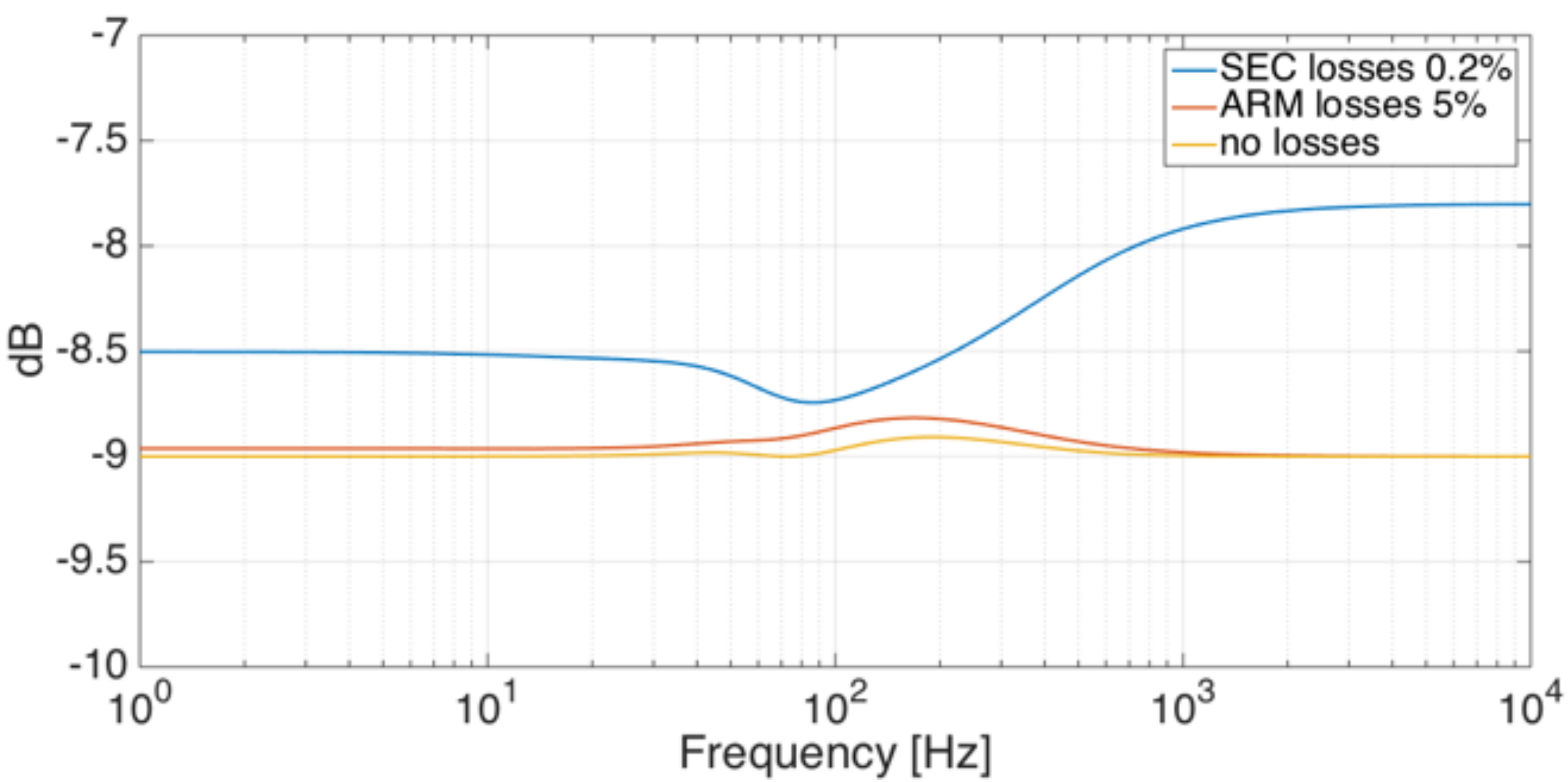
cavity losses with AdVirgo mirror quality (0.05 ppm/m)

Effect of the losses inside the interferometer

- The SR mirror increase the interferometer bandwidth suppressing the effects of arm cavity losses

- SEC losses has a greater impact on squeezing degradation





Conclusions

- The use of long filter cavity will improve the sensitivity of enhanced detectors in the whole bandwidth, in the scenario where quantum noise is dominating also at low frequencies
- Using >100 m filter cavity and best mirror quality available the effects of cavity losses become negligible with respect to the other loss sources
- Further improvement in the squeezing level will require to improve the mode matching and injection/readout losses
- Longer term future: long filter cavity (km scale) necessary for ellipse rotation at few Hz as planned in ET design