Noise and Control Issues for Filter Cavities

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on behalf of ET WG3

GEO Sensing and Control Group Meeting
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Outline

Part I: The need for Filter Cavities and their technical requirements

- The impact of optical loss inside the filter cavities on the
  - required baseline length
  - resulting squeezing spectra
- Robustness of the filter cavity parameters
  - a deviation of the targeted filter cavity bandwidth
    - requirements for the coupling mirror reflectance

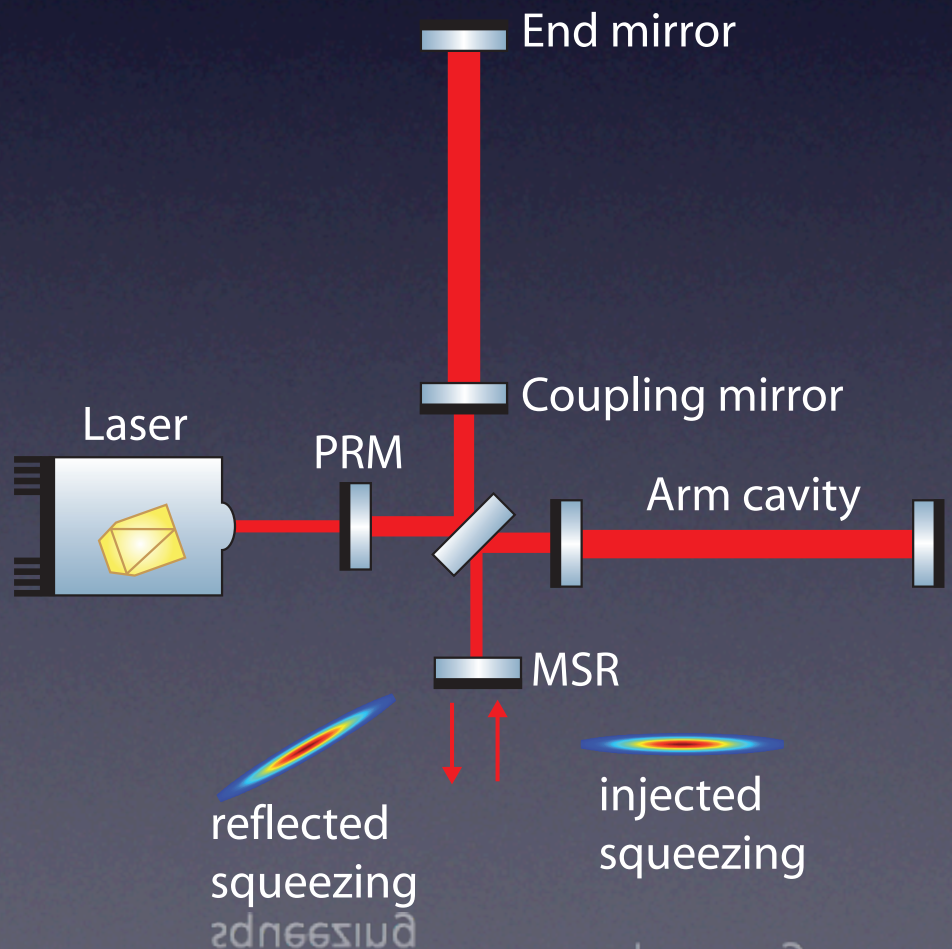
Part II: Noise and control issues

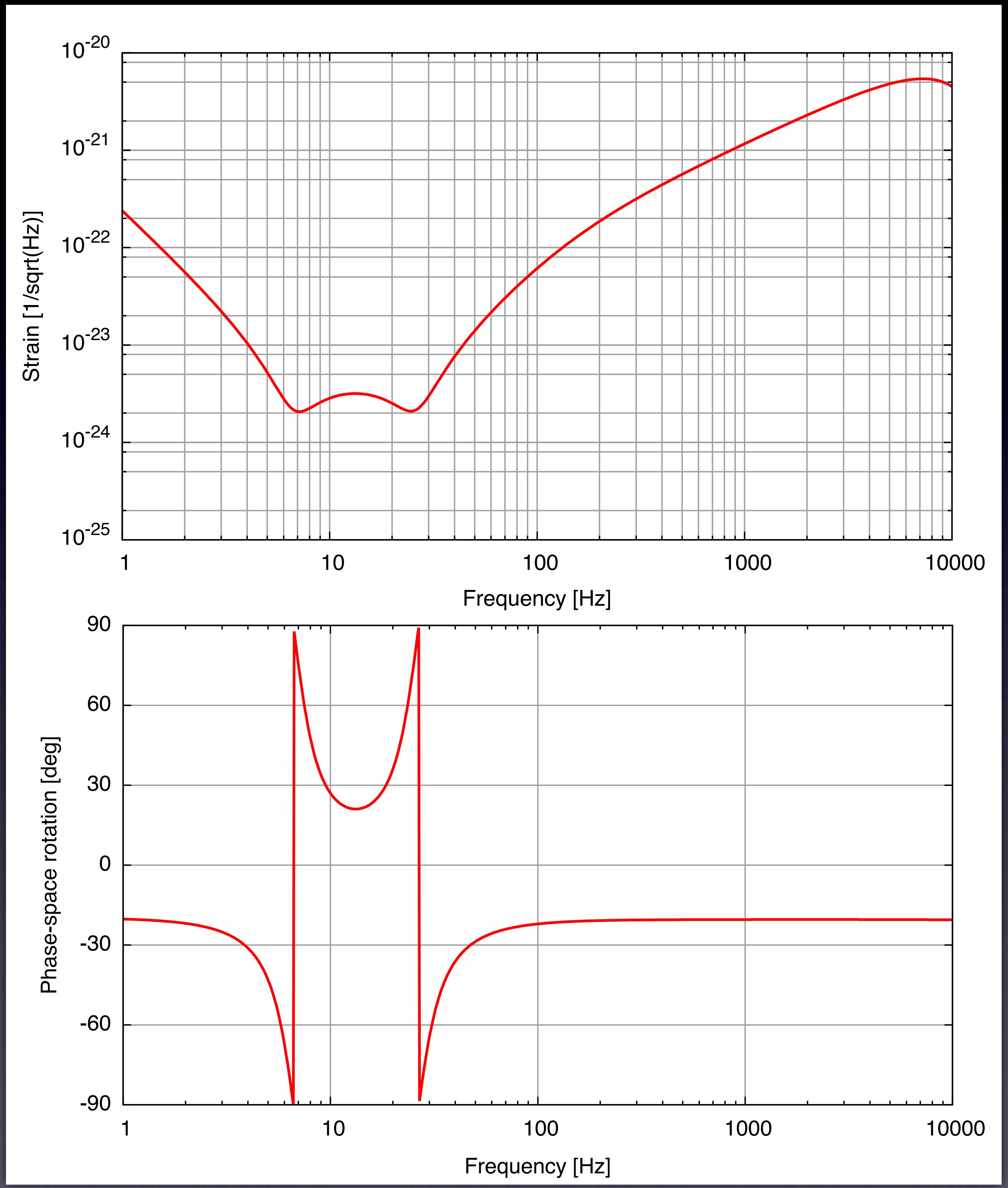
- Consideration of phase noise in the squeezing path
- Ideas and thoughts for the locking scheme

The need for filter cavities

Filter cavities are needed to compensate the phase-space rotation of light fields entering the IFO at the output port.

The rotation is determined by the IFO topology/configuration





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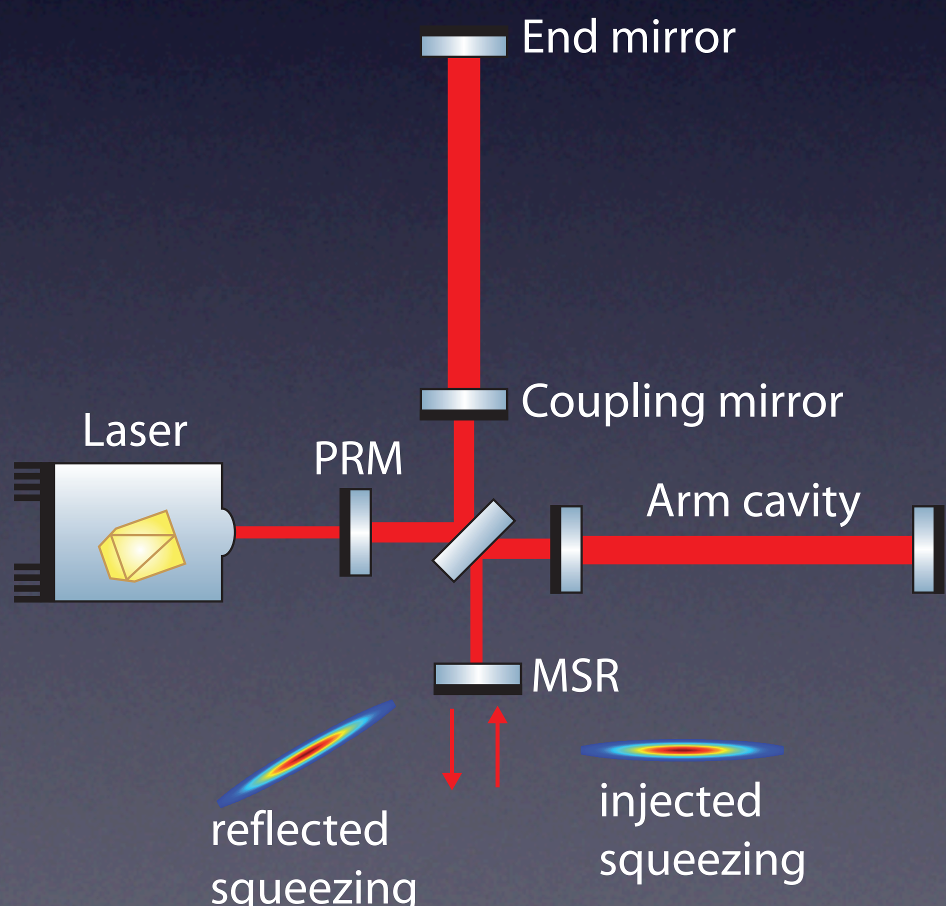

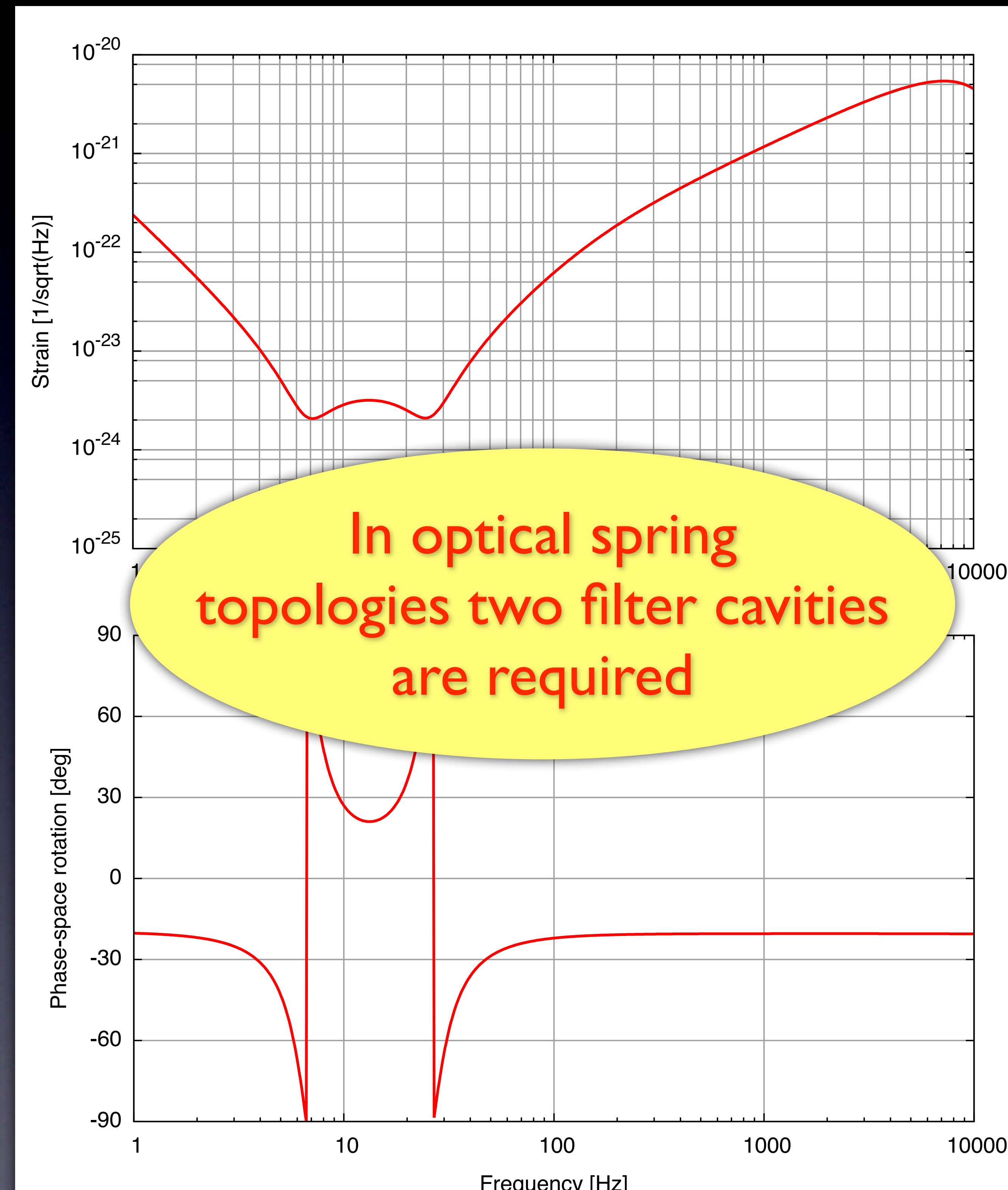

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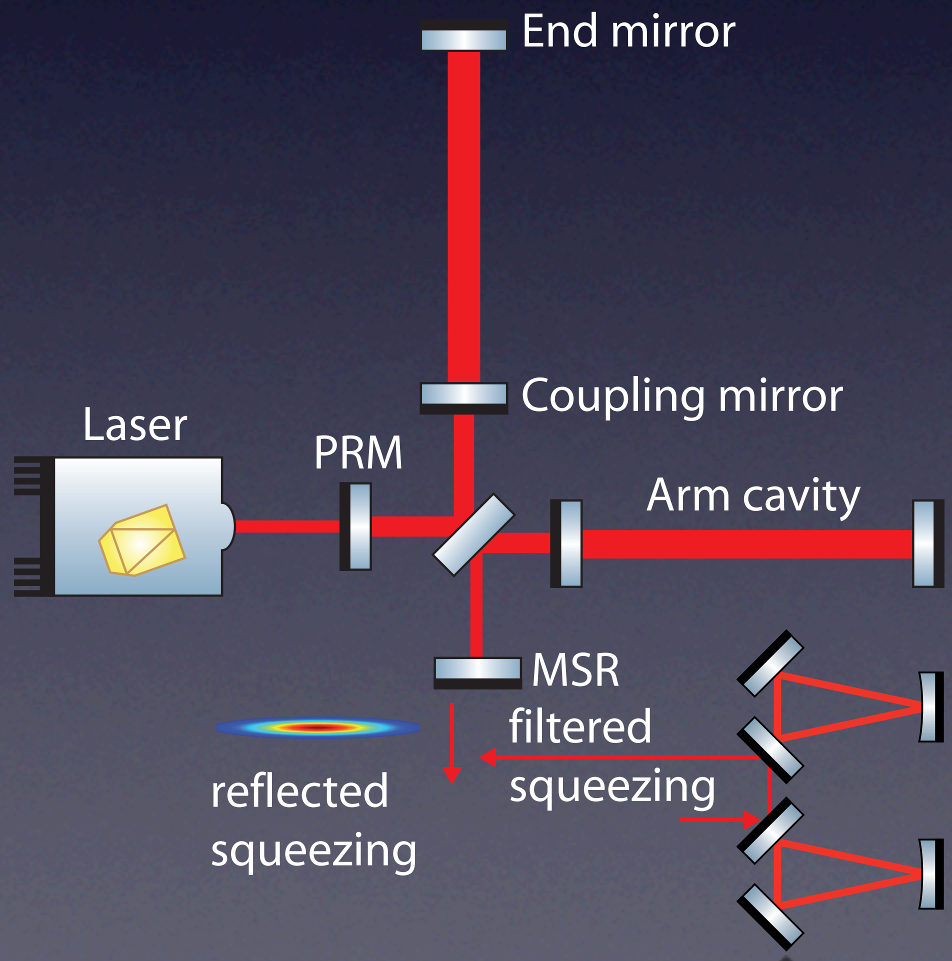

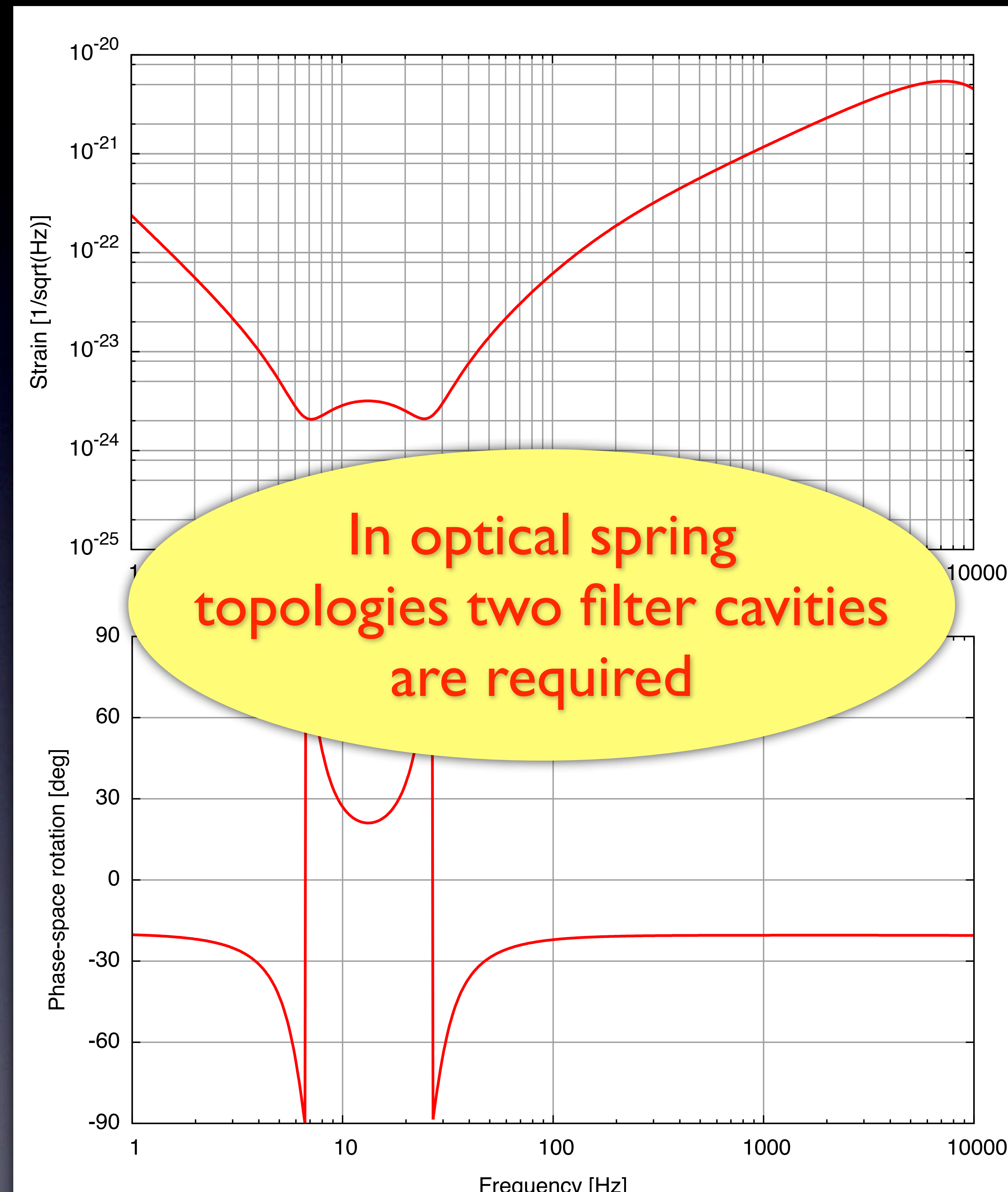

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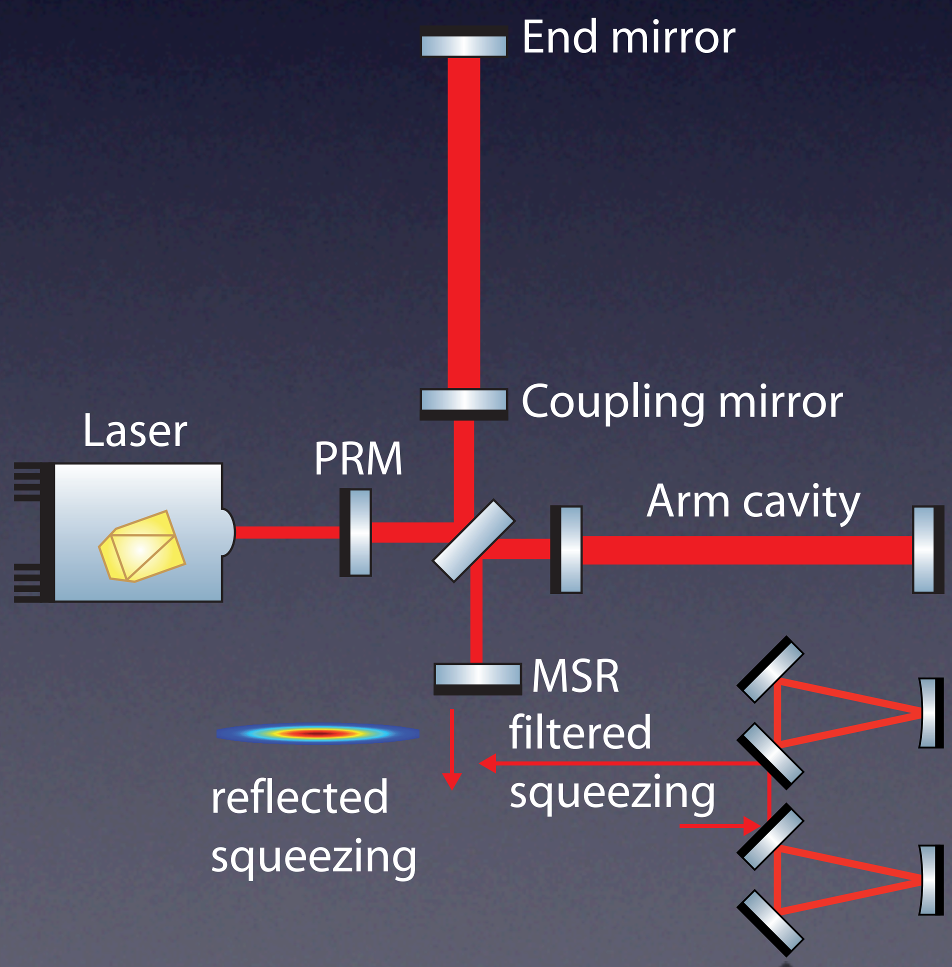

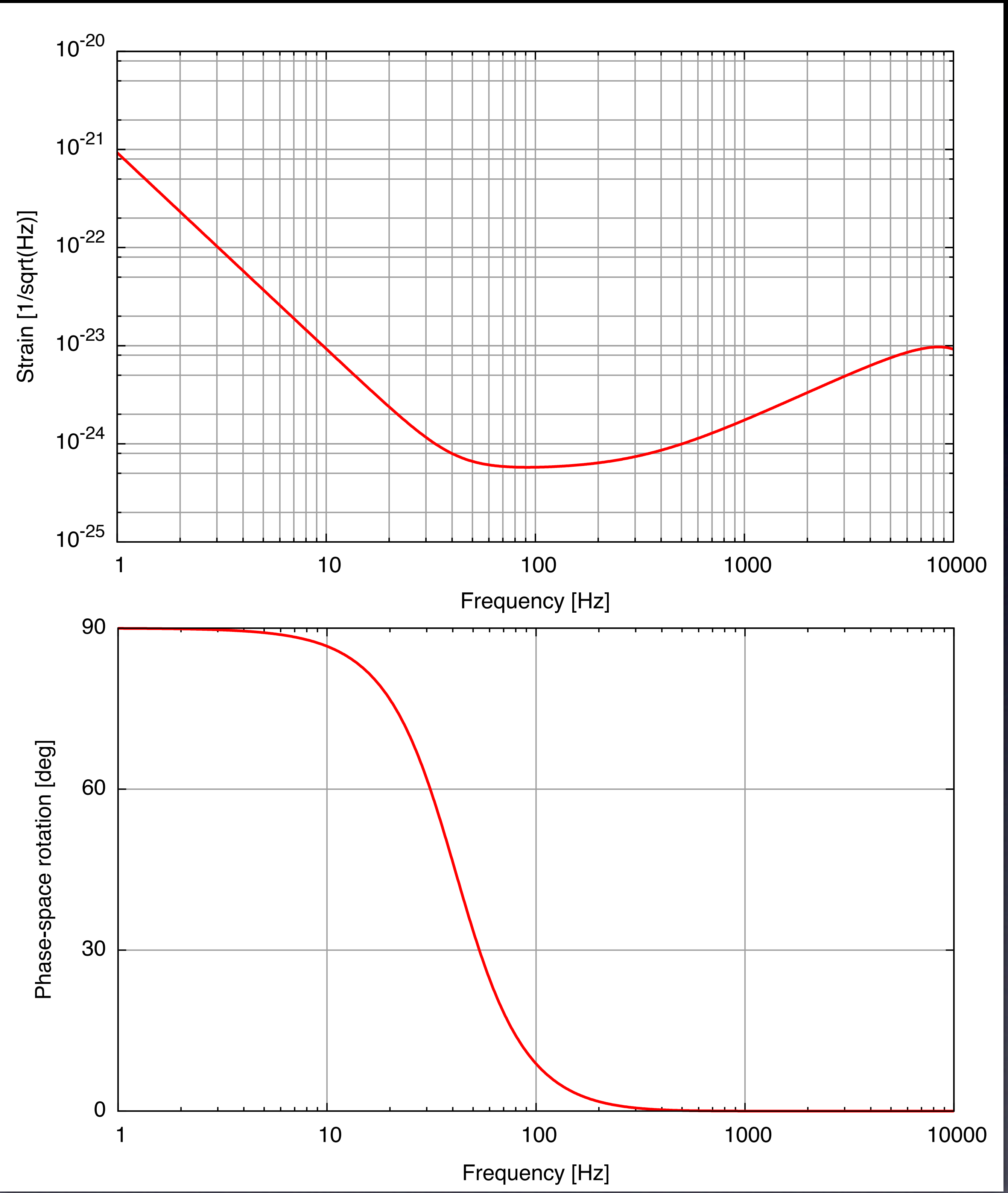

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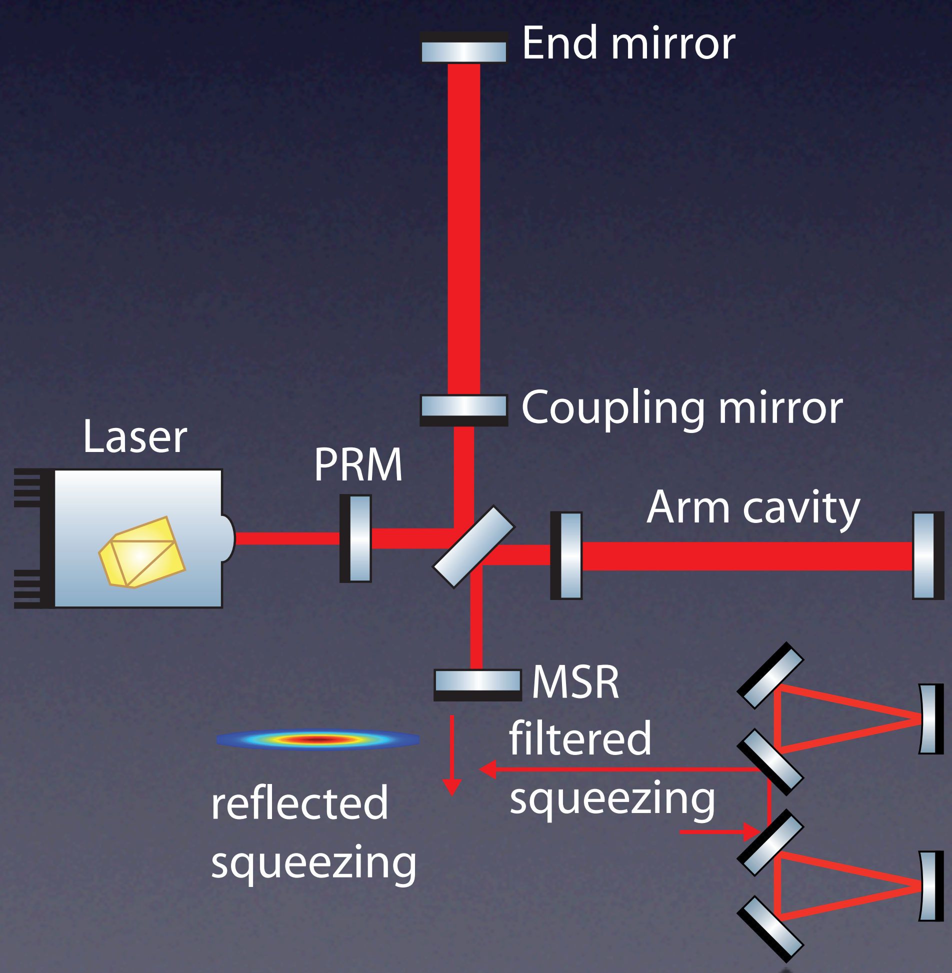

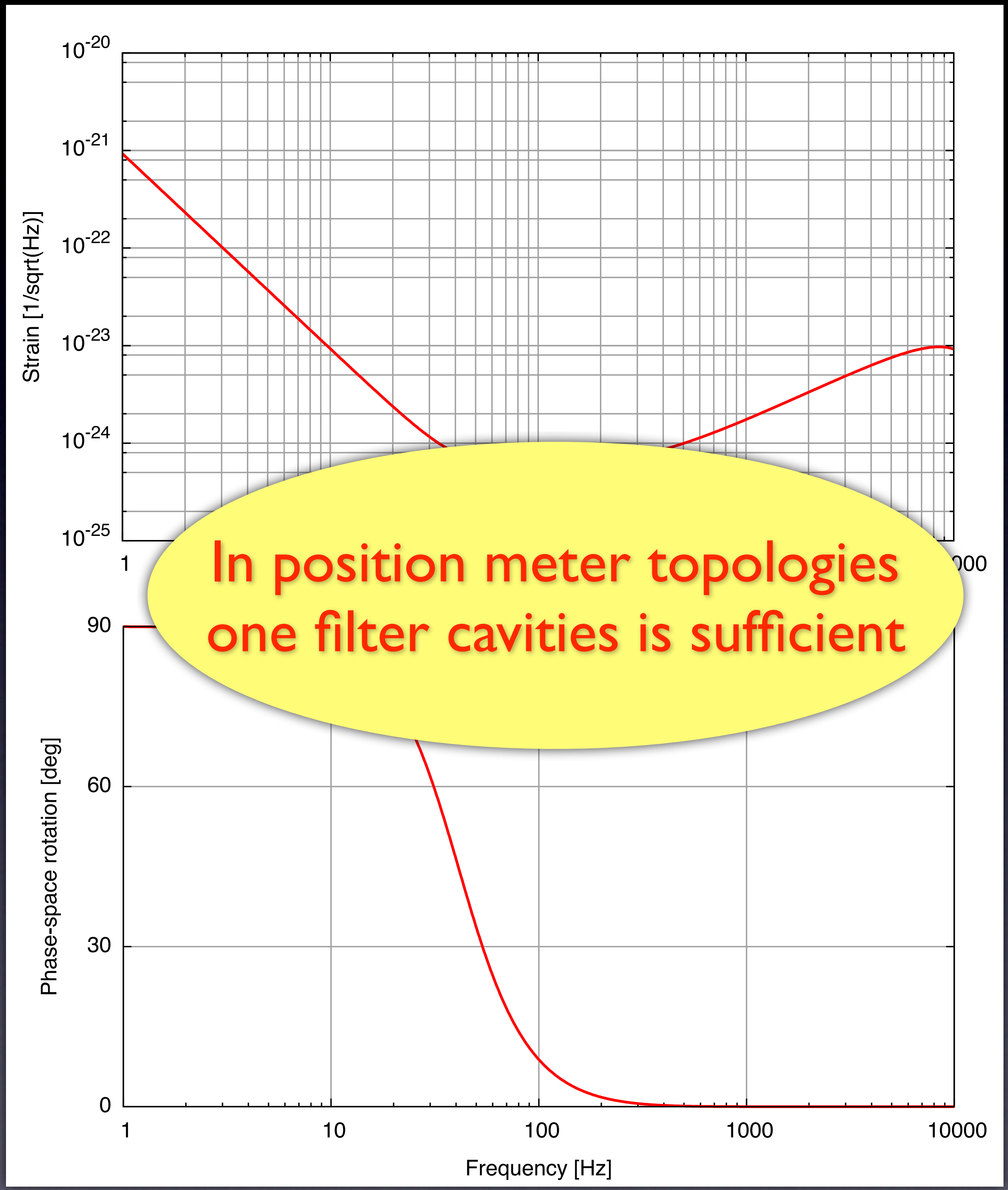

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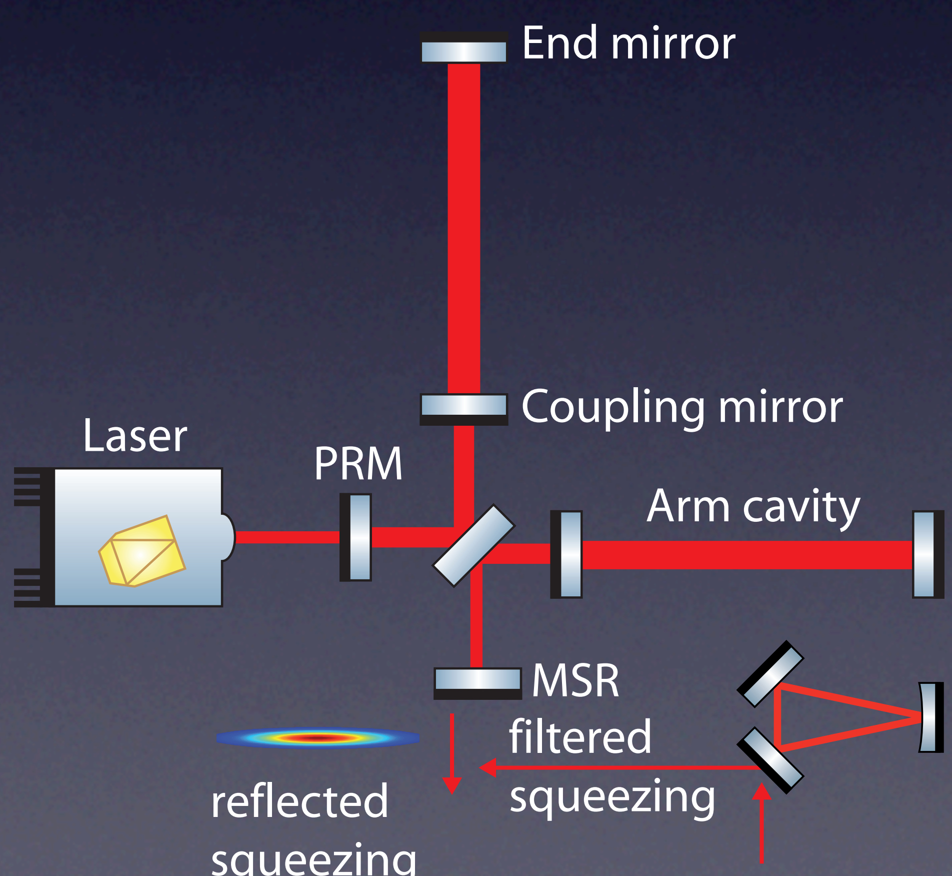
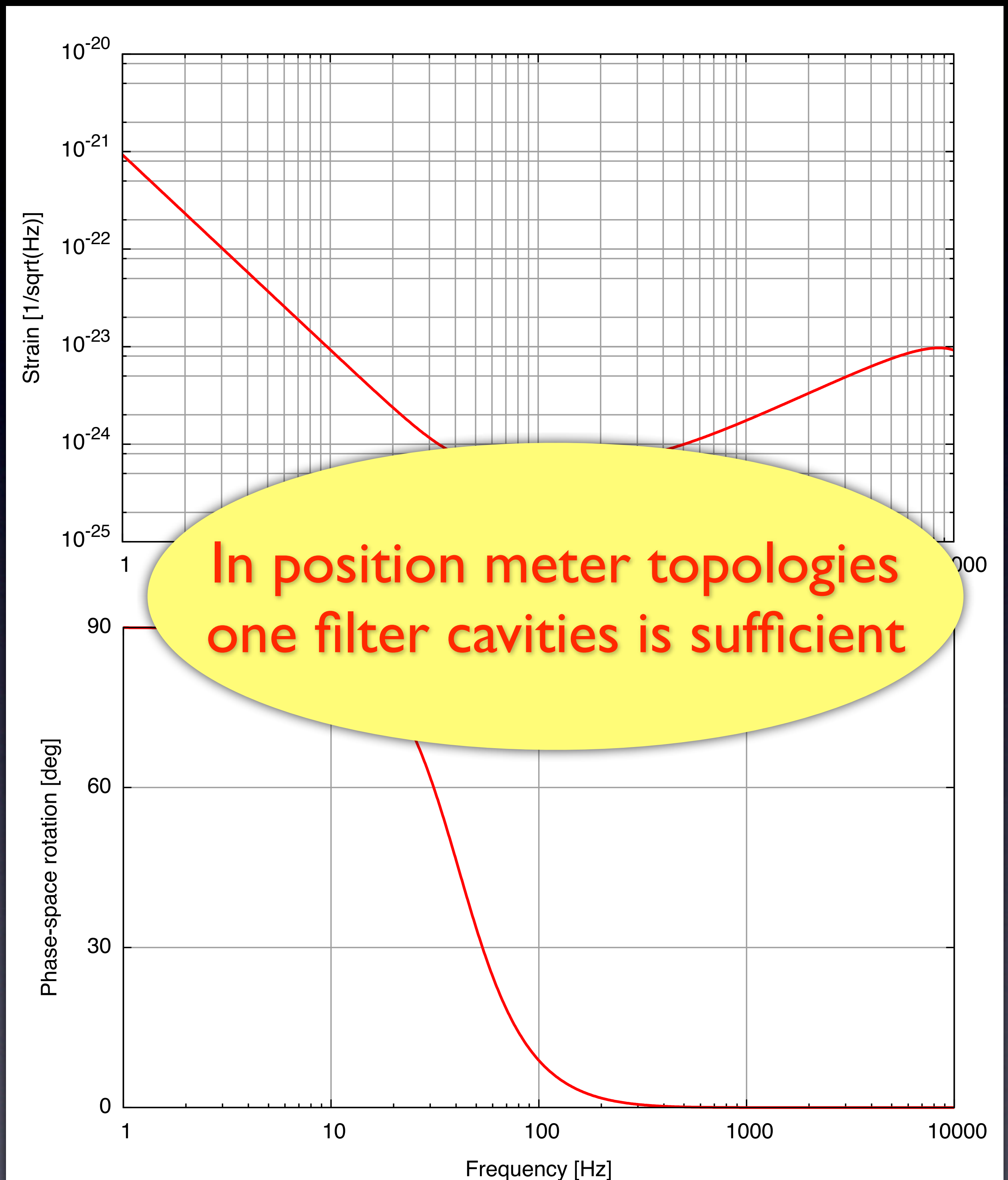
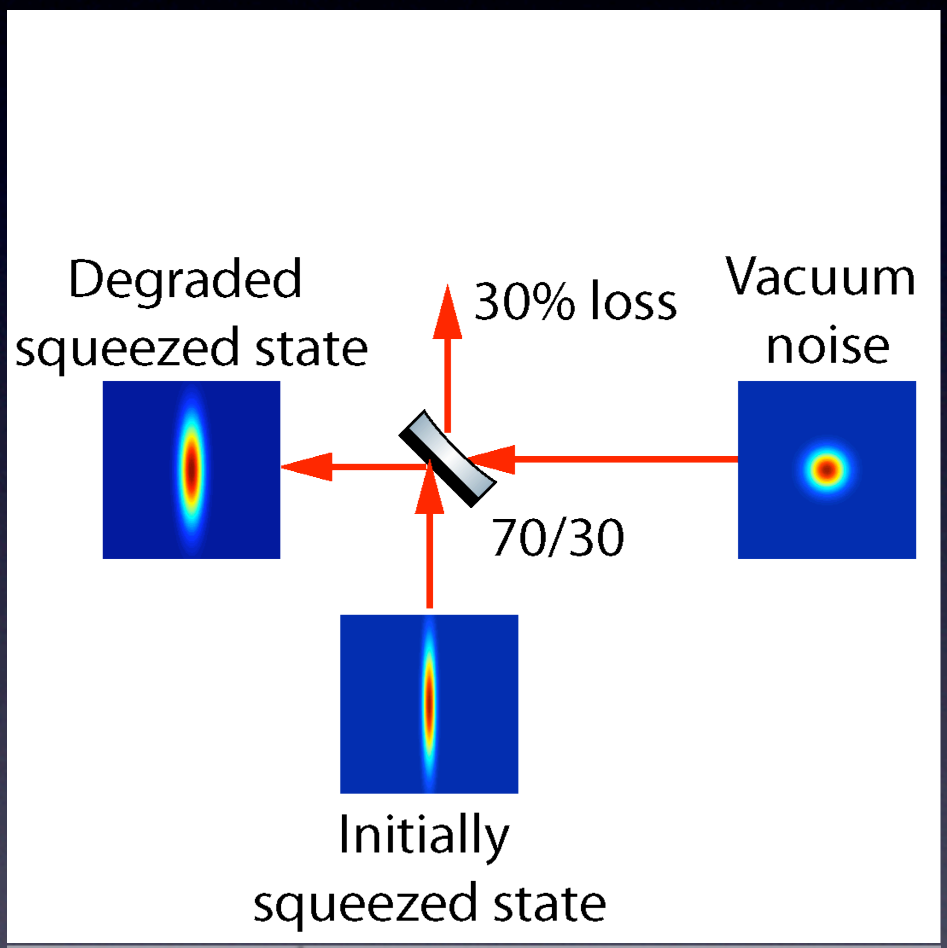
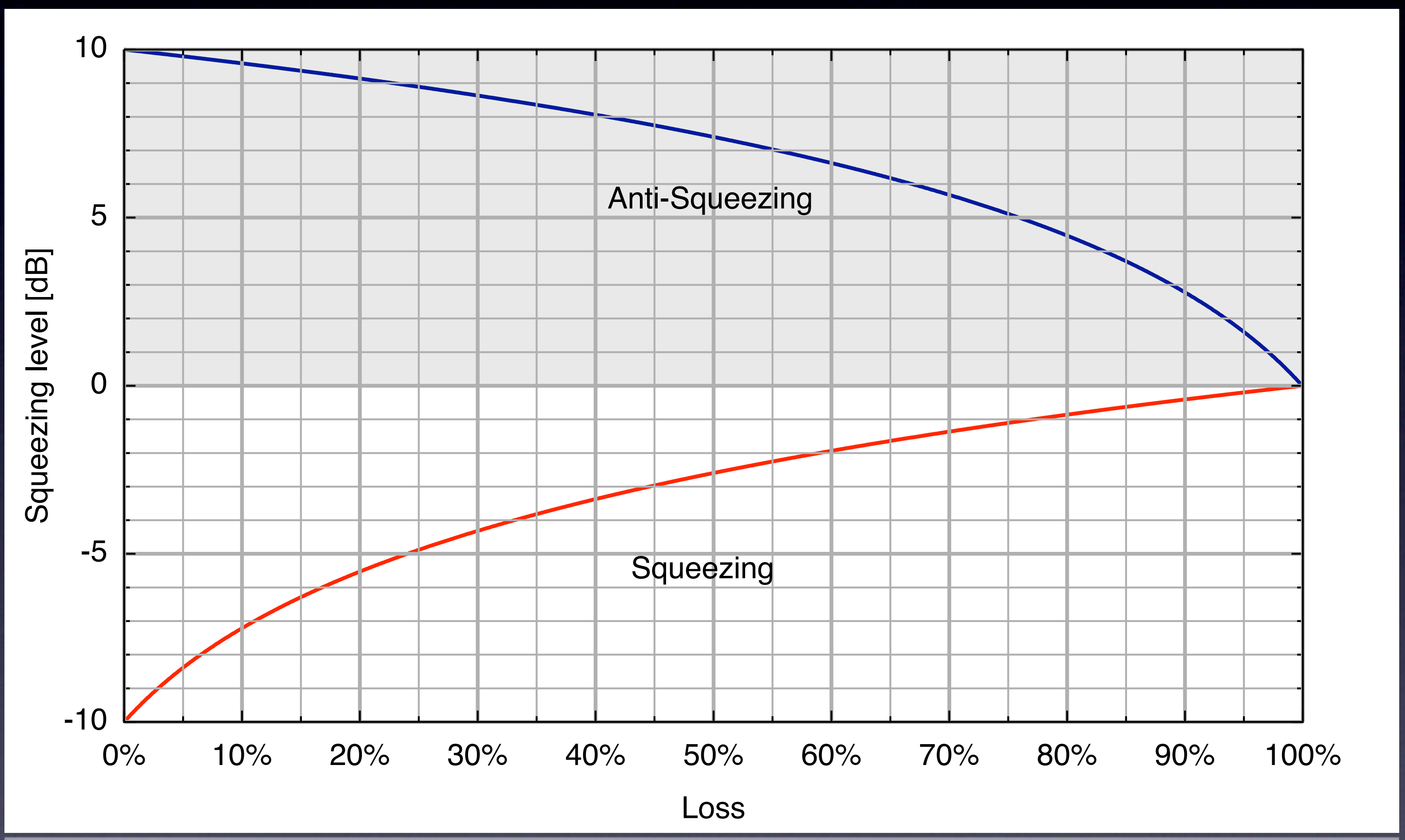




Degrading of squeezing due to optical loss

At every open (lossy) port vacuum noise couples in





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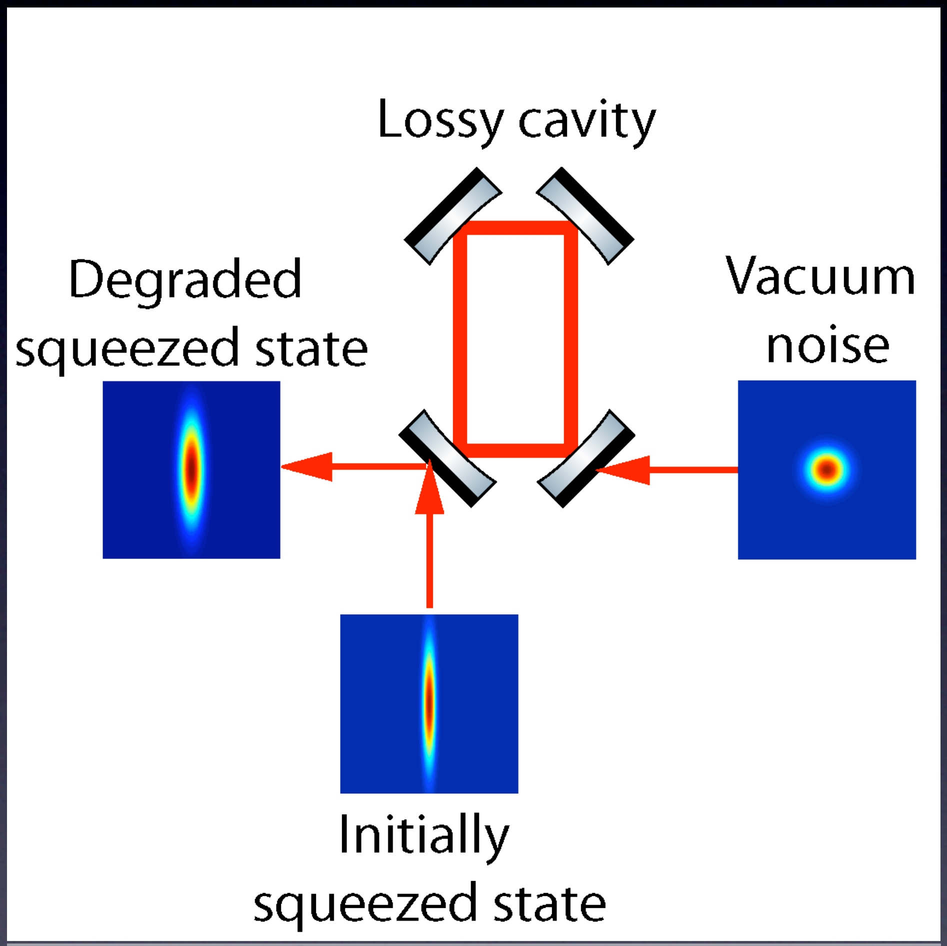

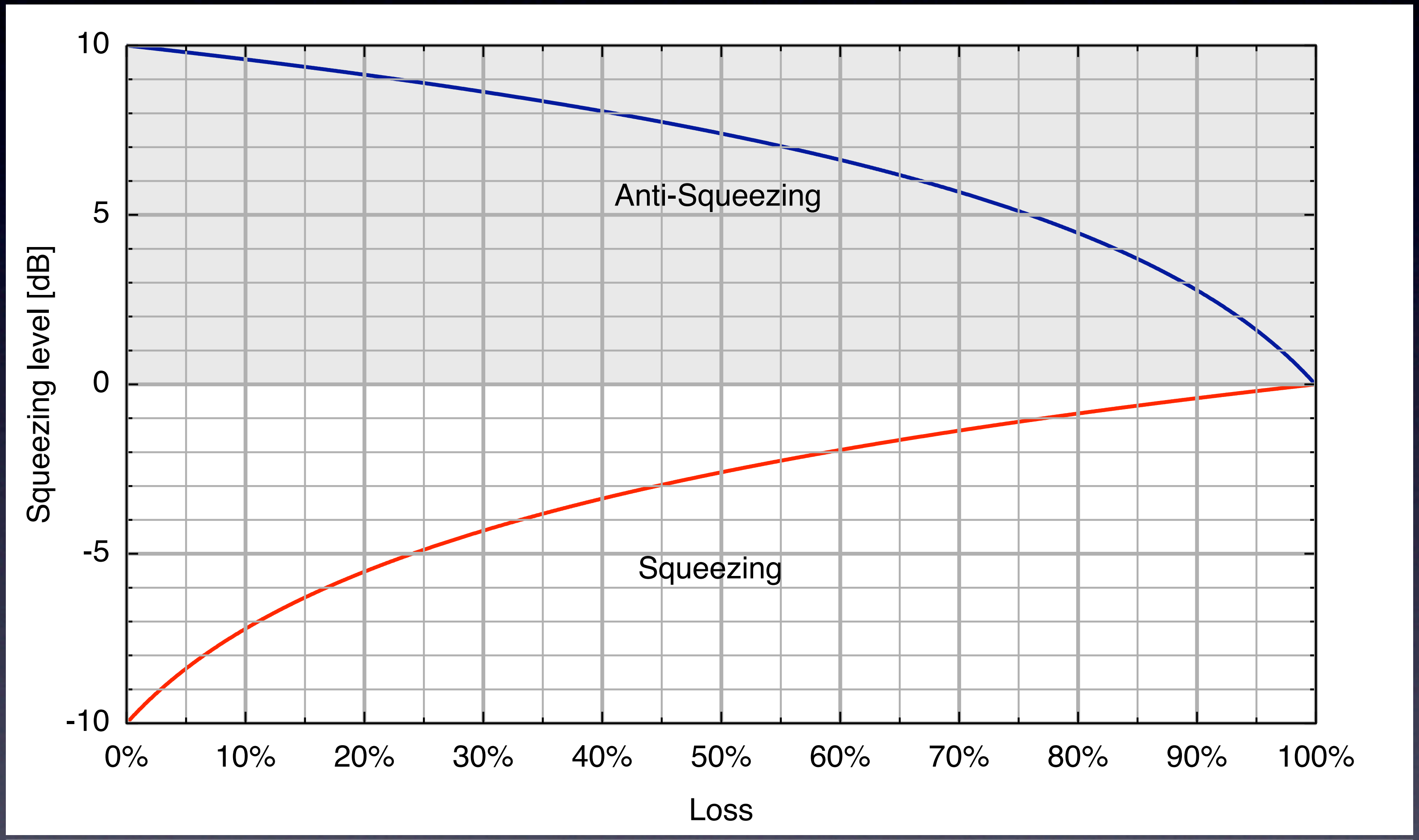

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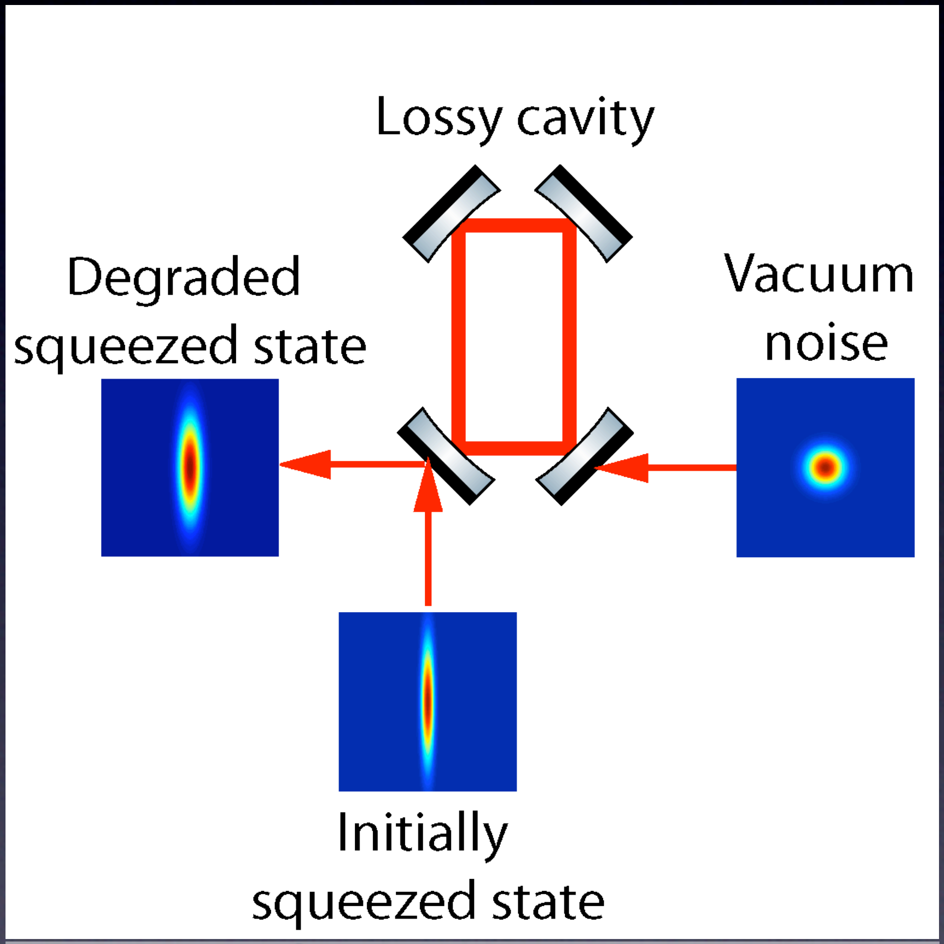

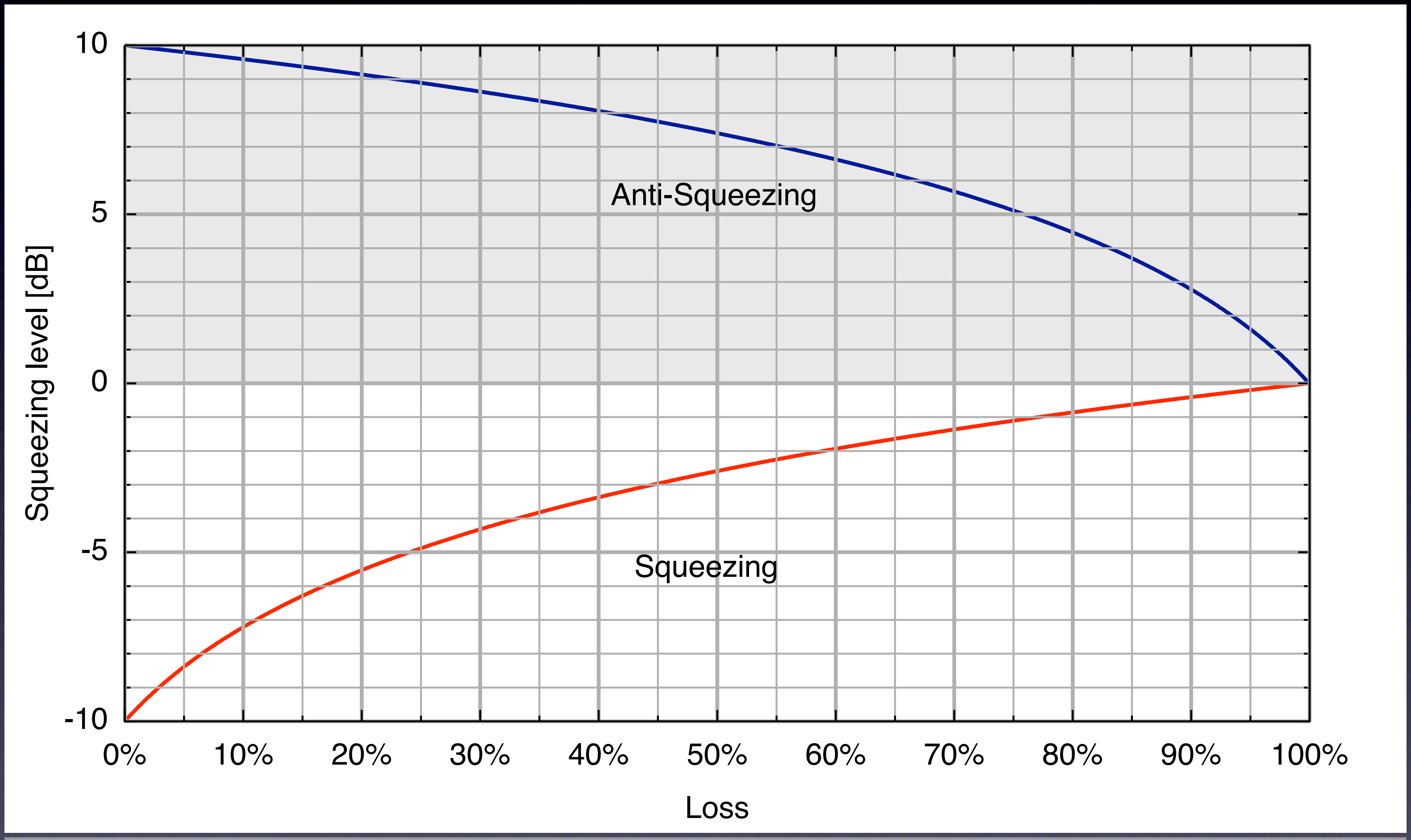

A cavity reflectance R<1 means loss. The degrading of squeezing is then frequency dependent

Restrictions for the baseline length

1. The required coupling mirror reflectance can be calculated from the round-trip loss, the baseline length and the targeted bandwidth

$$\rho_{\mathrm{c}} = \frac{1}{\sqrt{1 - l_{\mathrm{rt,fc}}^2}} \left[2 - \cos(\mathcal{F}') - \sqrt{\cos^2(\mathcal{F}') - 4\cos(\mathcal{F}') + 3} \right] \quad \mathcal{F}' = \frac{2\gamma_{\mathrm{fc}} L_{\mathrm{fc}}}{c} = \frac{\gamma_{\mathrm{fc}}}{\mathrm{FSR}_{\mathrm{fc}}} = \frac{\pi}{\mathcal{F}_{\mathrm{fc}}}$$

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3. There exists a length L_{cc} at which the filter cavity becomes critical coupled.

$$L_{\mathrm{cc}} = \frac{c}{2\gamma_{\mathrm{fc}}} \arccos\left[2 - \frac{1 + (1 - l_{\mathrm{rt,fc}}^2)^2}{2(1 - l_{\mathrm{rt,fc}}^2)}\right]$$

The impact of shortening the Filter Cavity

HBW	1.44 Hz
tuning	6.63 Hz
$l_{rt,fc}^2$	75 ppm
L_{min}	619 m
L_{cc}	1239m
sqz	10 dB
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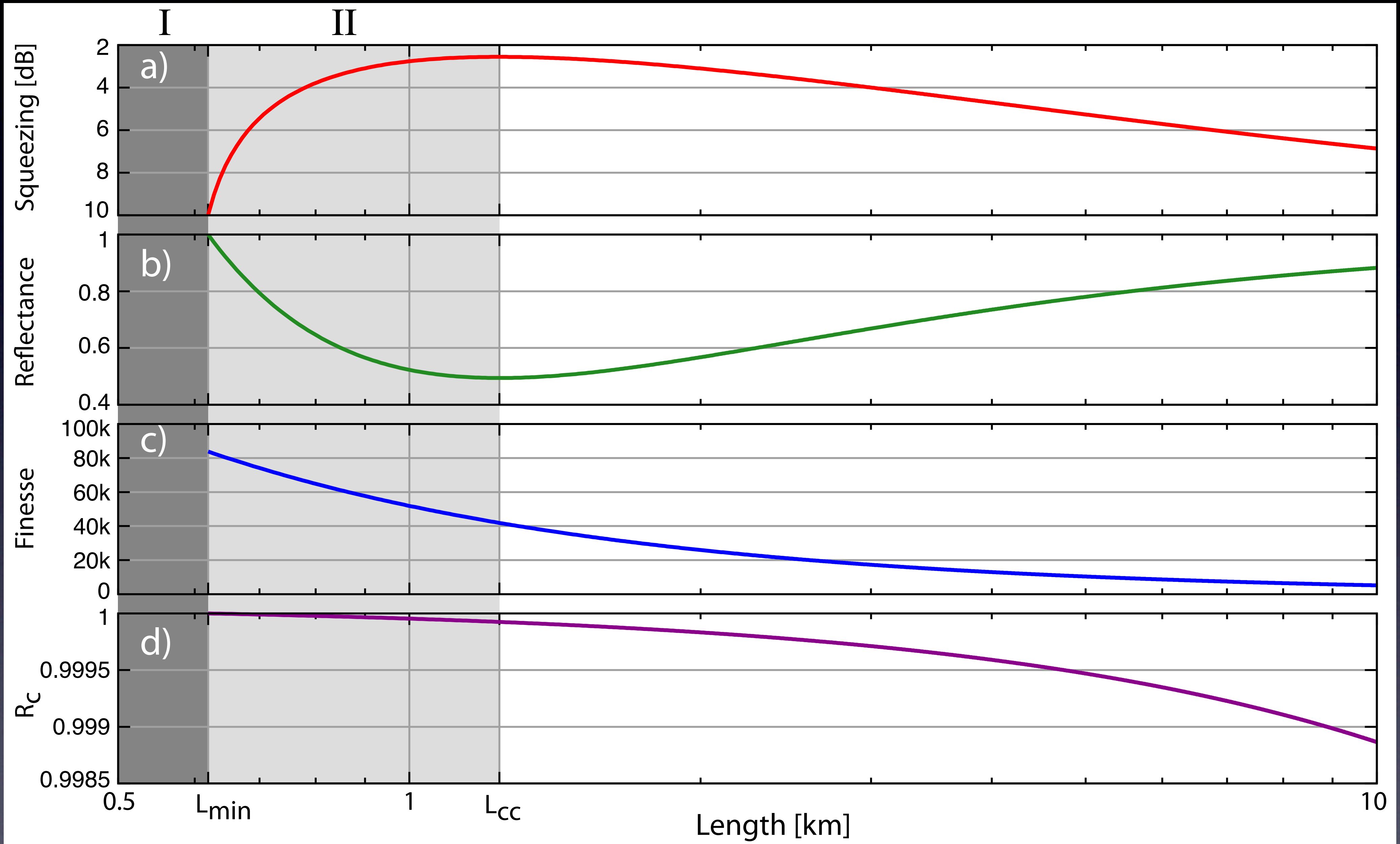

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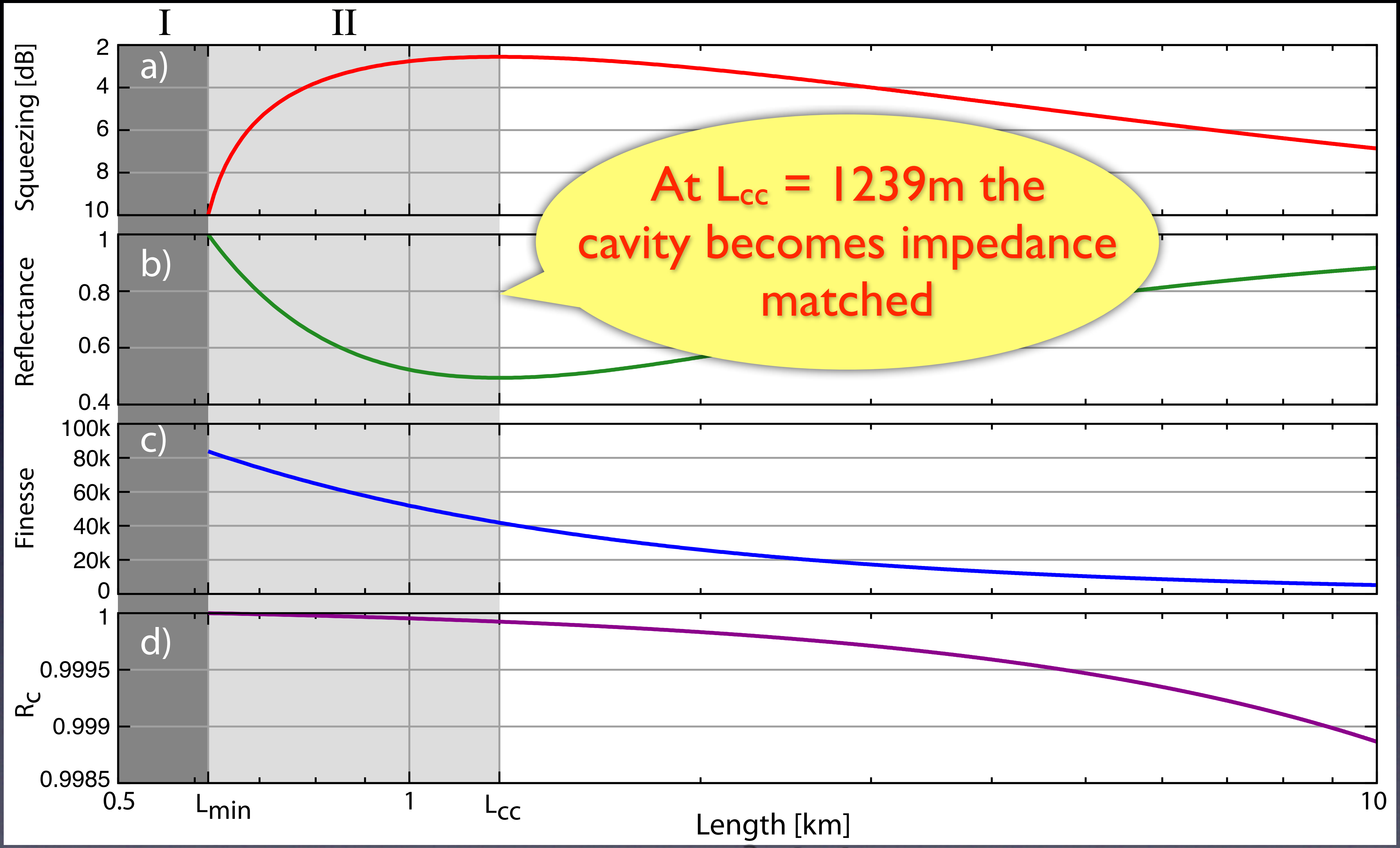

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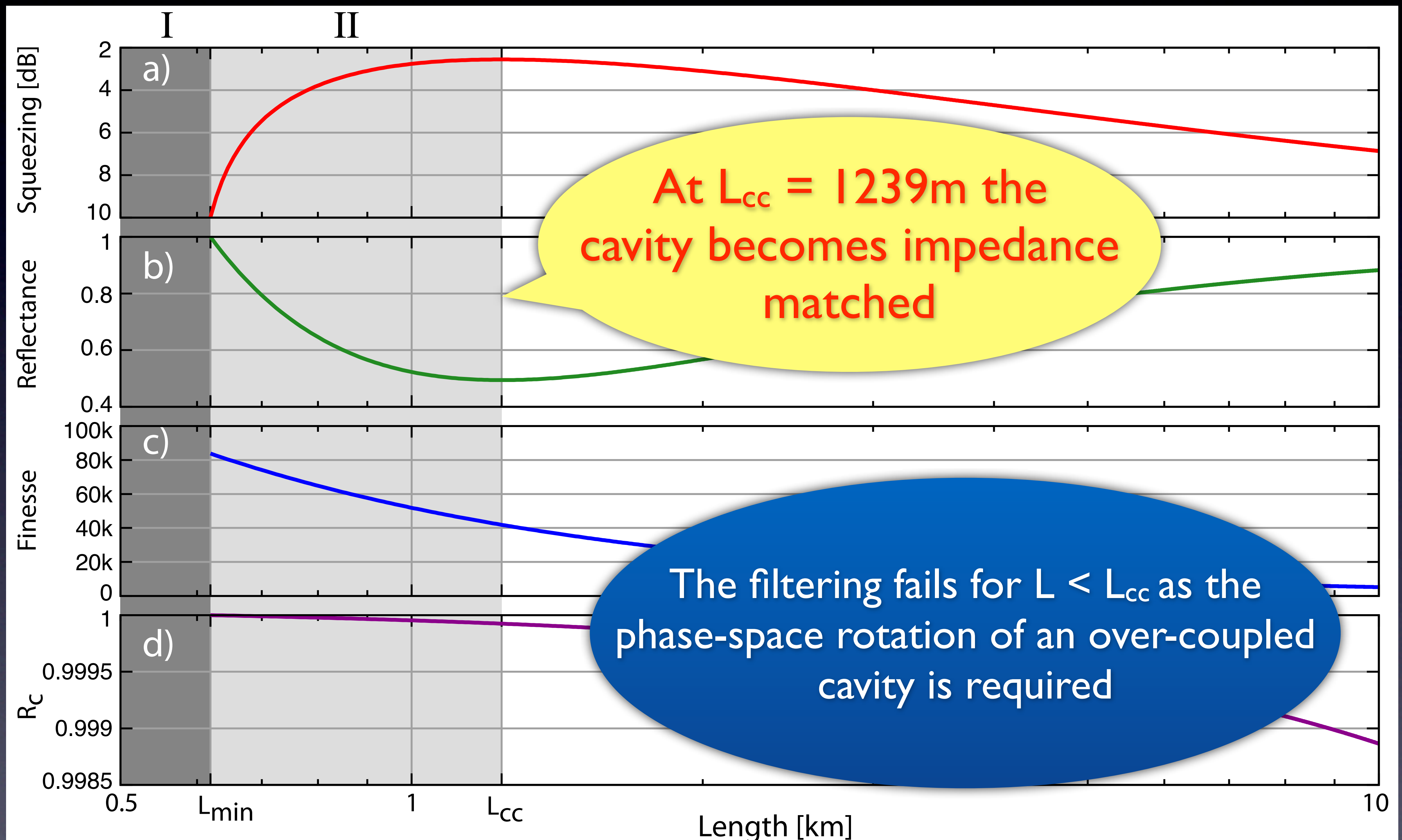

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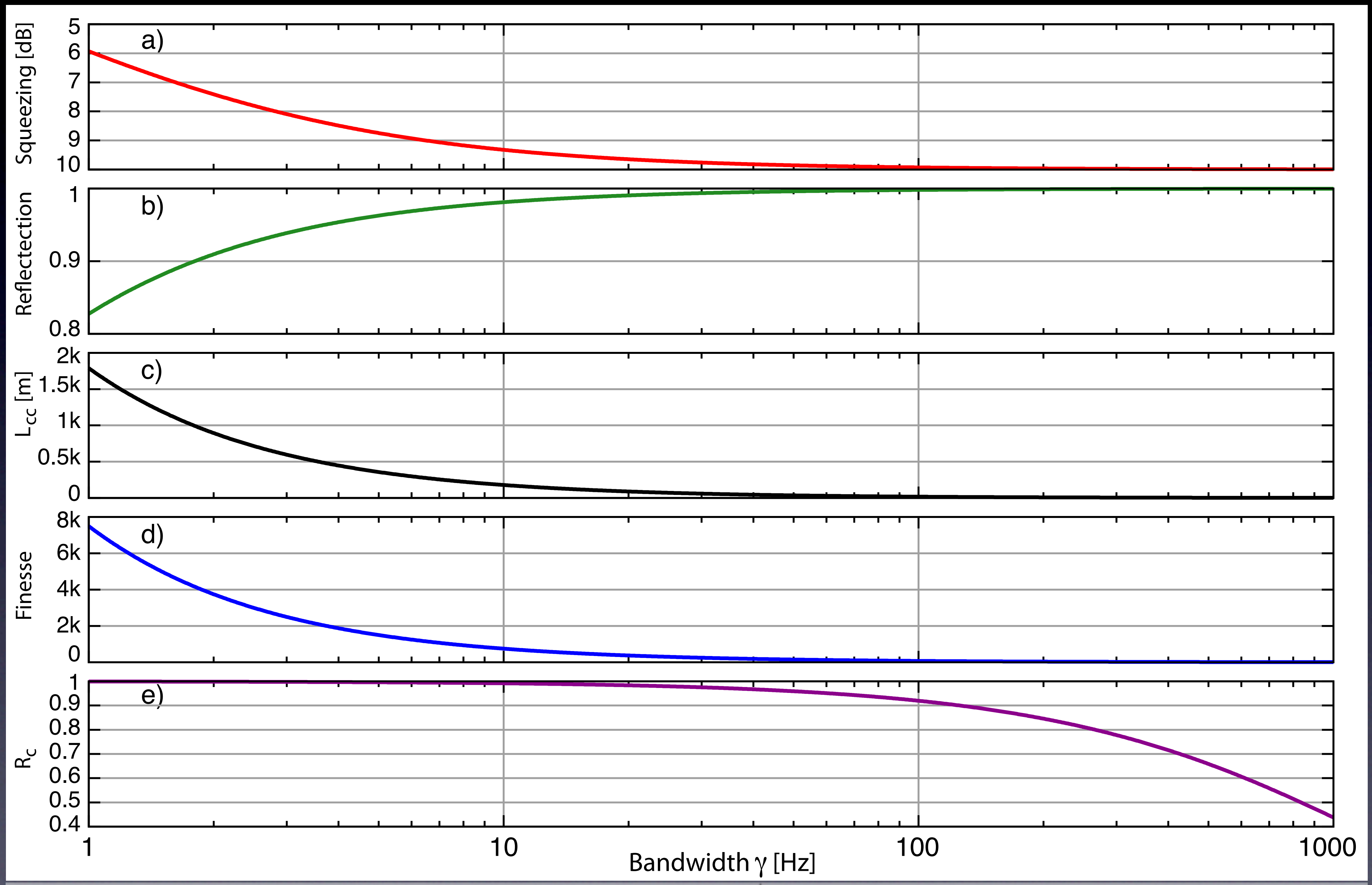

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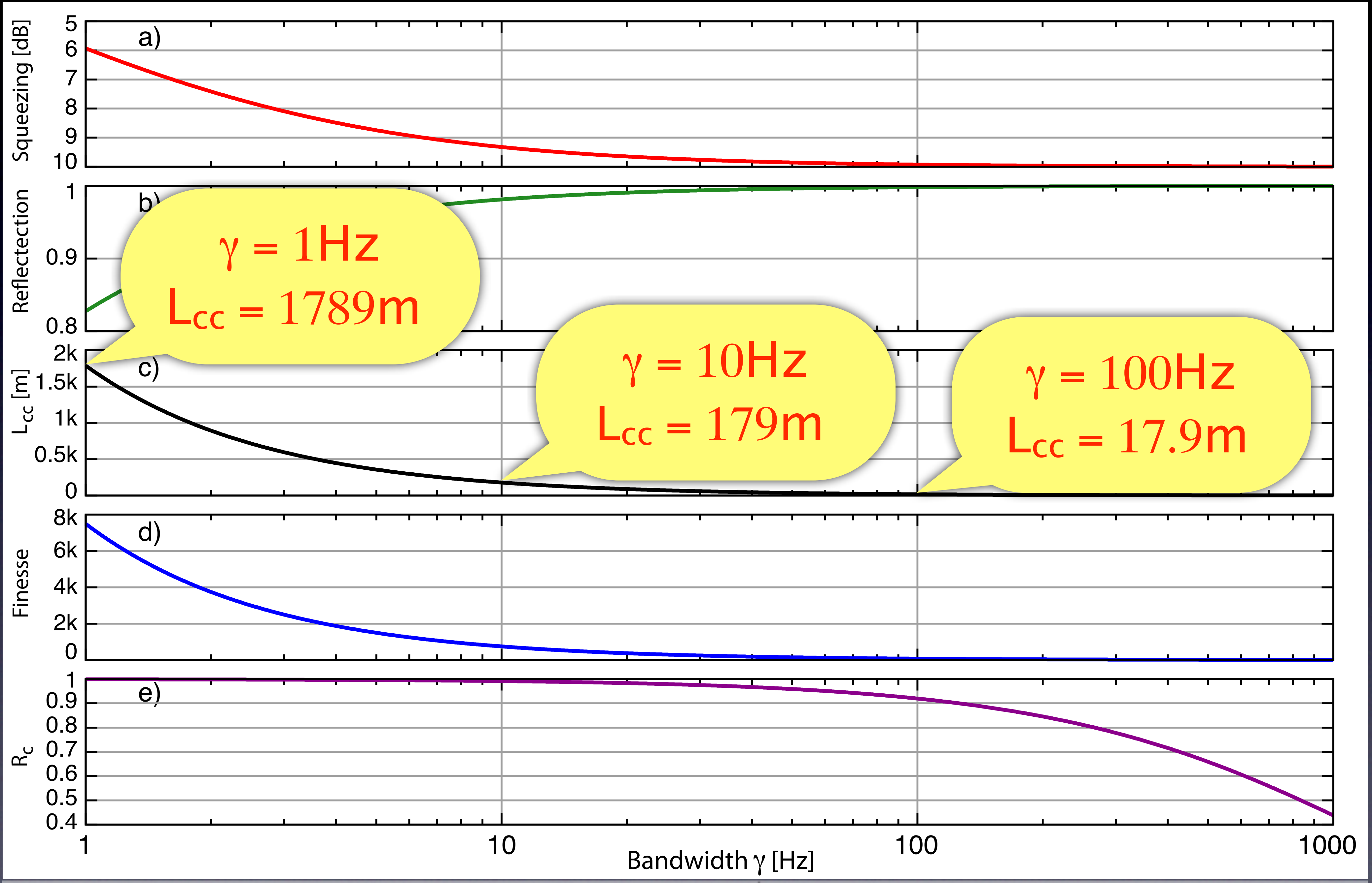

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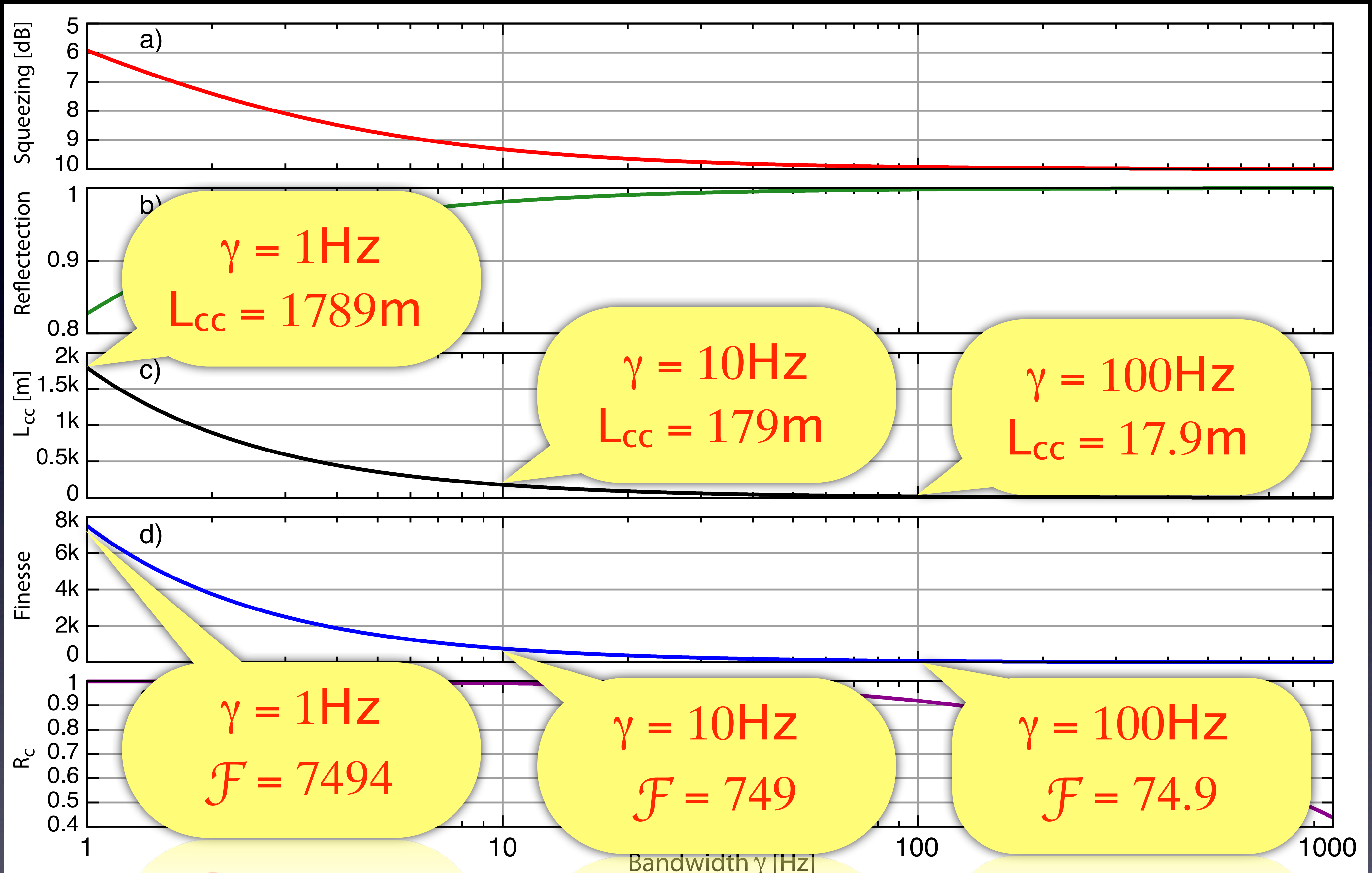
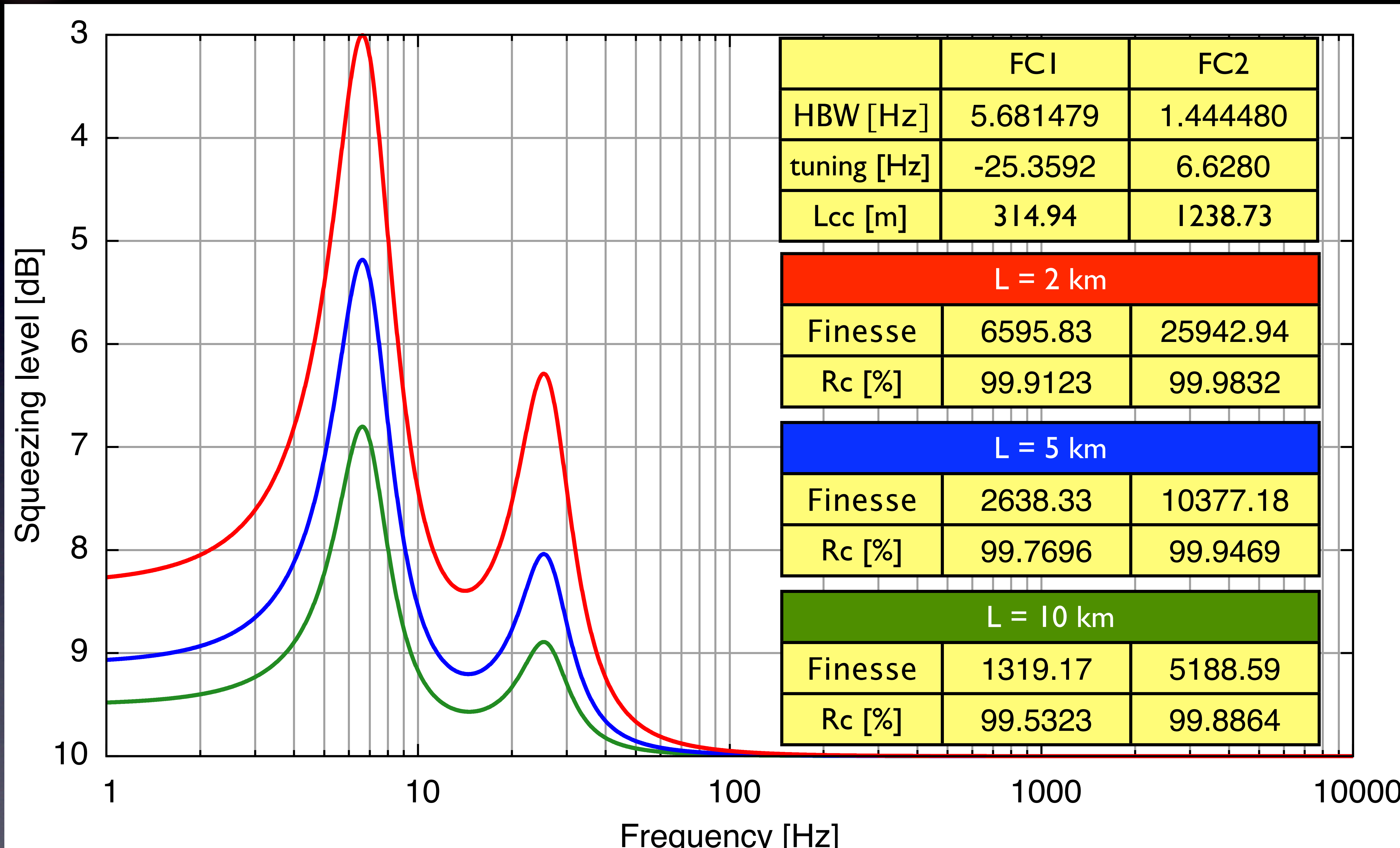
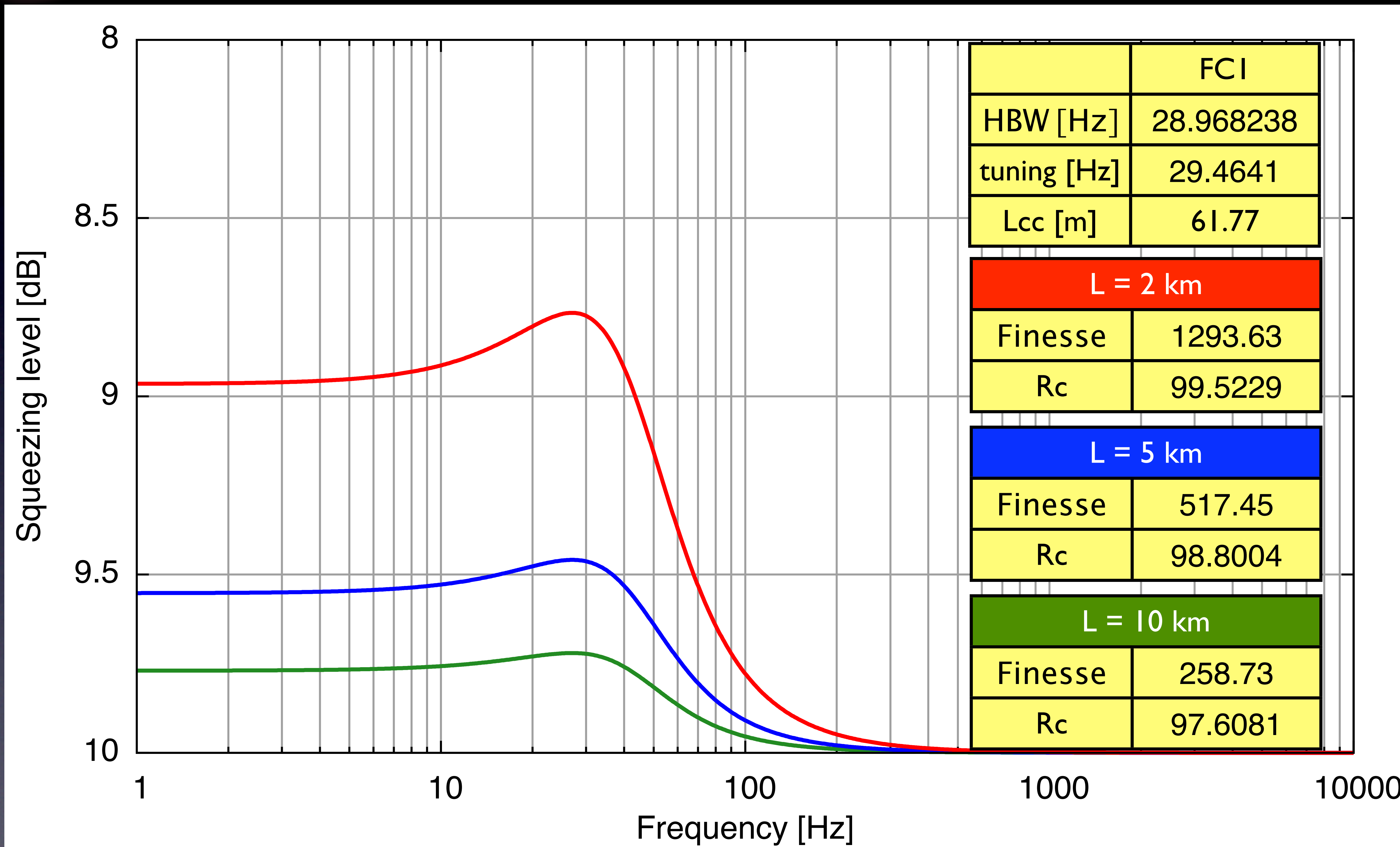


Filters for the ET-C LF part



	FC1	FC2
HBW [Hz]	5.681479	1.444480
tuning [Hz]	-25.3592	6.6280
Lcc [m]	314.94	1238.73
L = 2 km		
Finesse	6595.83	25942.94
Rc [%]	99.9123	99.9832
L = 5 km		
Finesse	2638.33	10377.18
Rc [%]	99.7696	99.9469
L = 10 km		
Finesse	1319.17	5188.59
Rc [%]	99.5323	99.8864

Filters for the ET-C HF part



Robustness of the design parameters

What are the tolerances of the design parameters?

Consider a deviation of the

- round-trip loss
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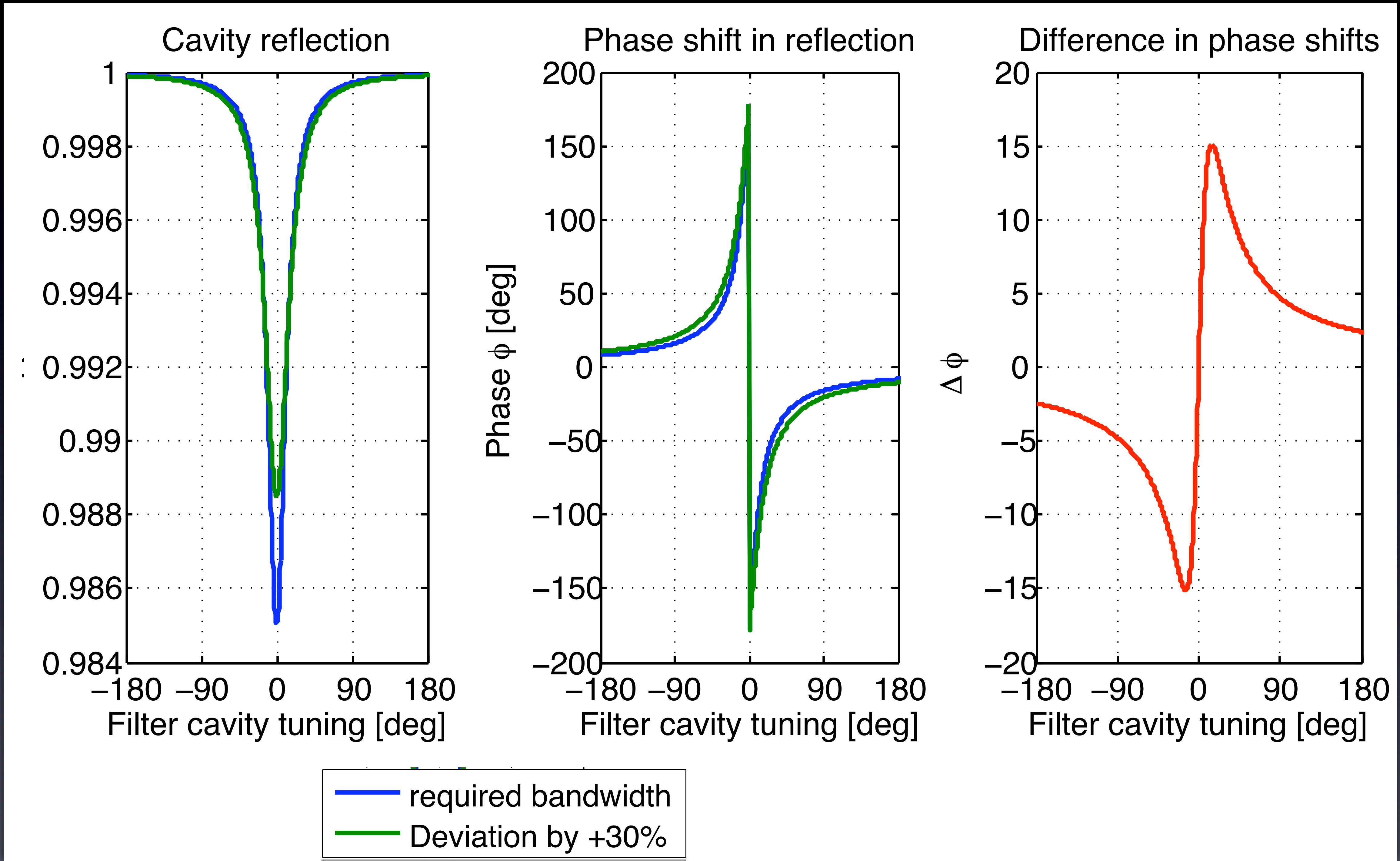
Investigating the impact of a mismatched bandtwidth → Deduce the tolerances for the round-trip loss, coupling mirror and the baseline length

The impact of a mismatched bandwidth



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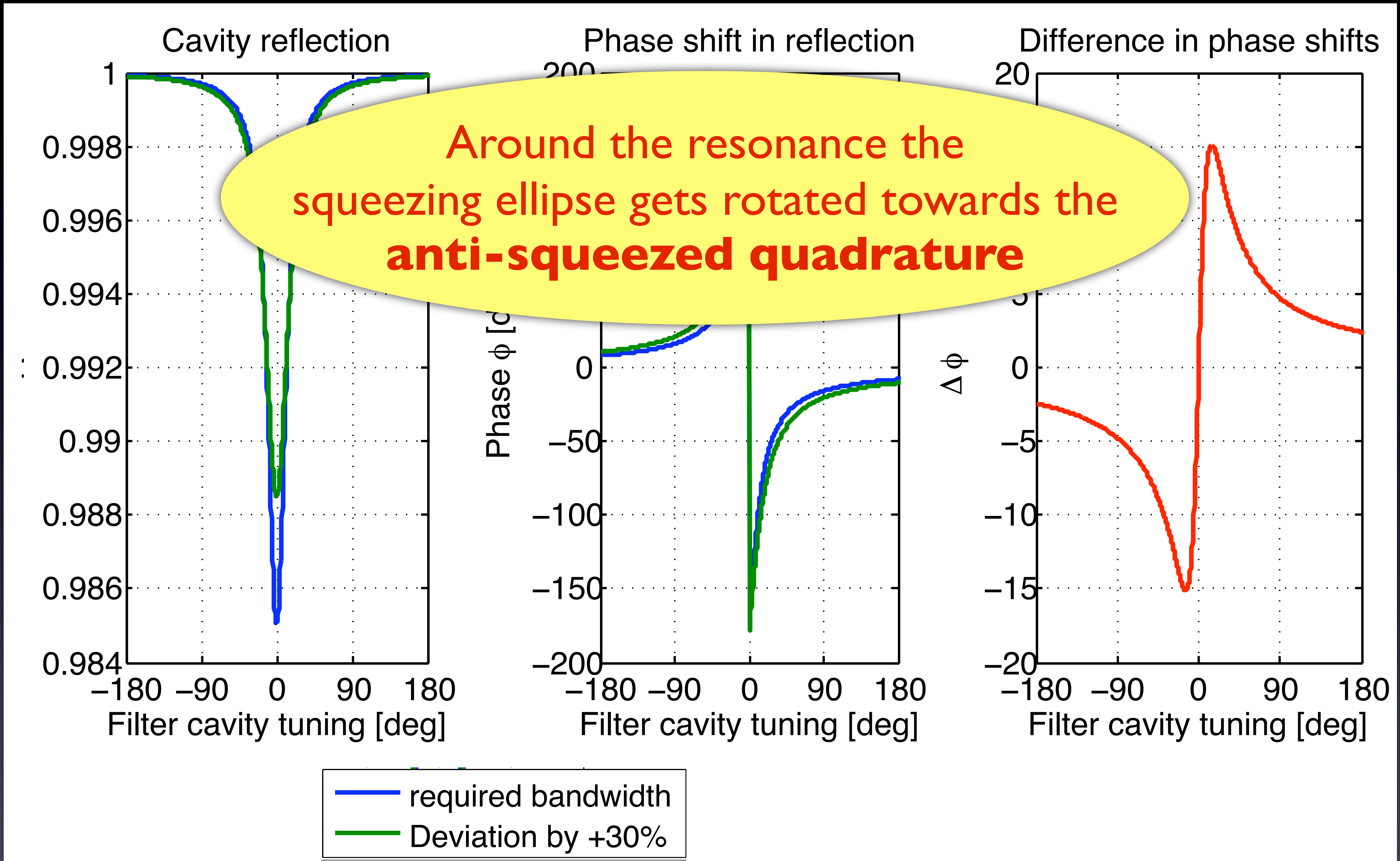
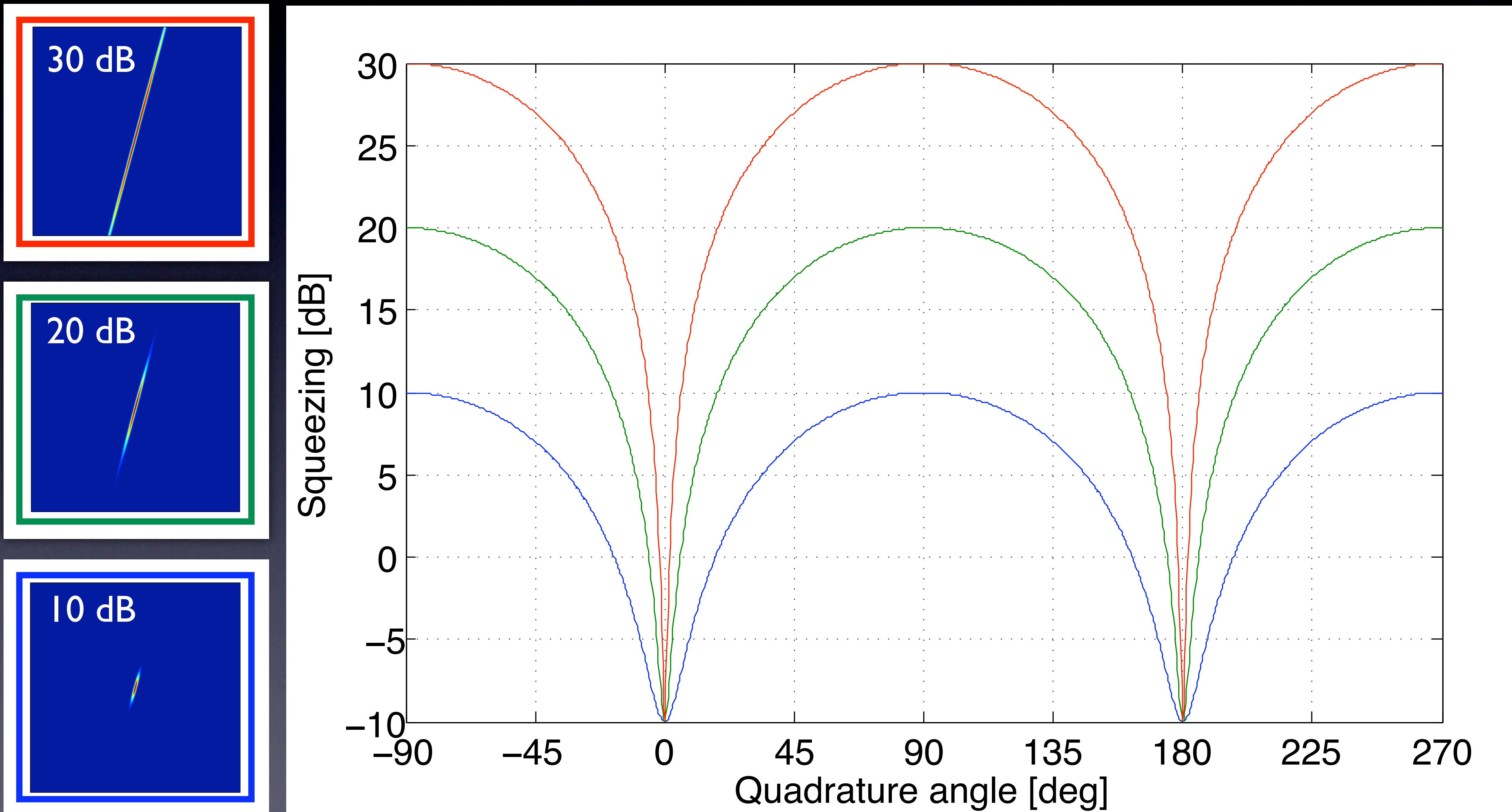


Around the resonance the squeezing ellipse gets rotated towards the **anti-squeezed quadrature**

Quadrature dependent squeezing levels

Assume 10 dB squeezing, but different anti-squeezing levels (10 dB, 20 dB, 30 dB)



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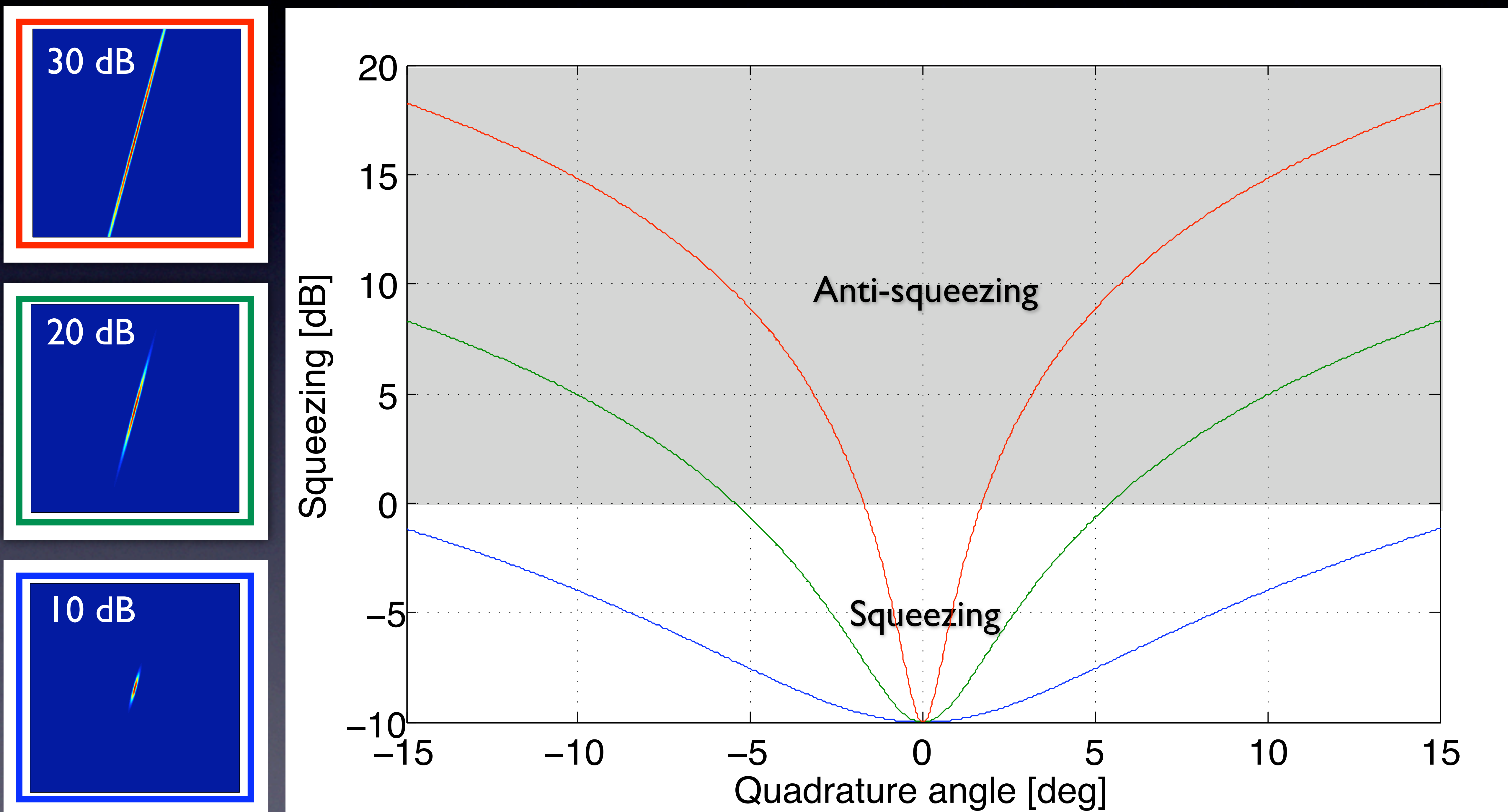


Squeezing spectra for a mismatched bandwidth

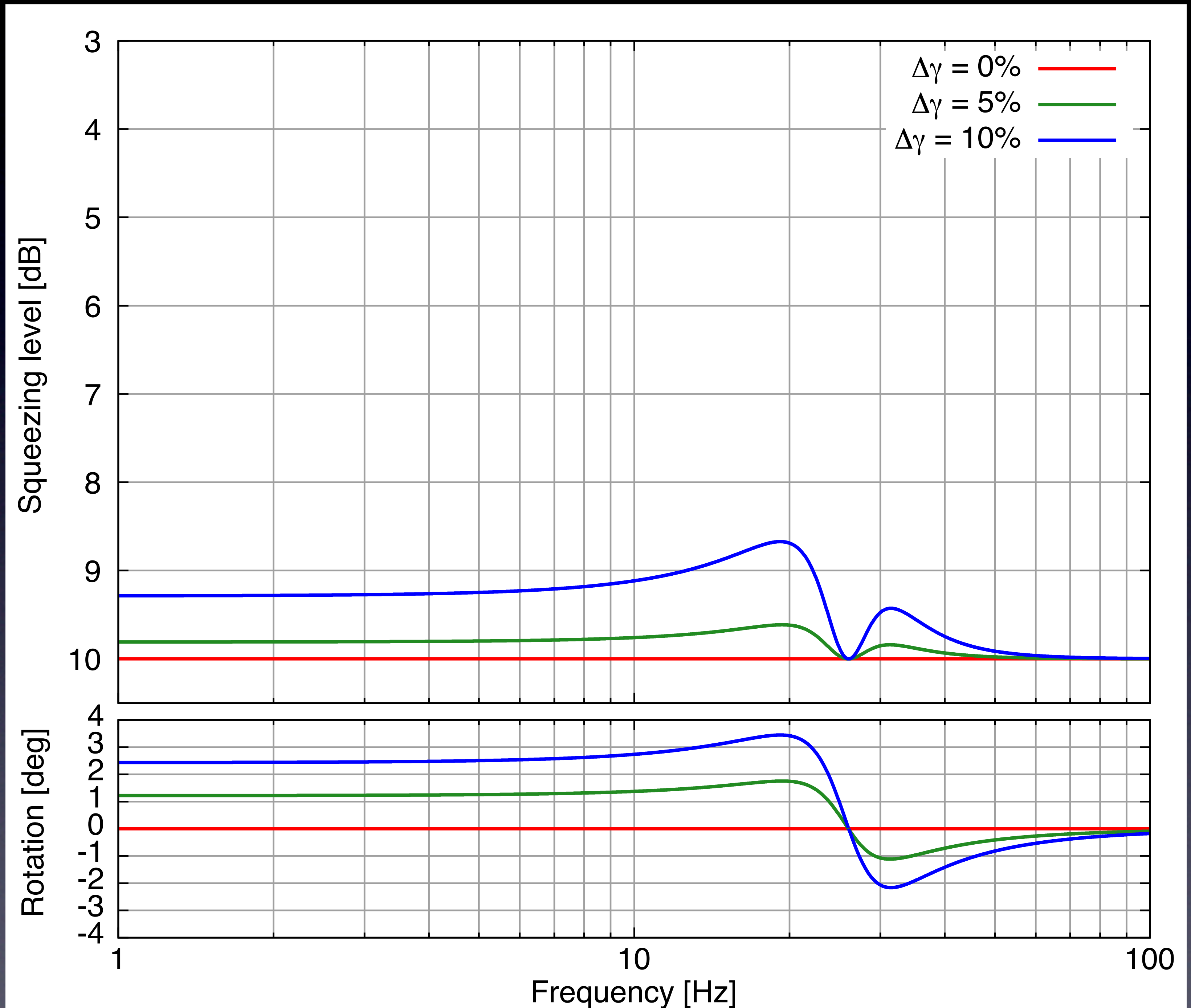
<u>Consider FC1 for ET-C LF:</u>

Required bandwidth 5.68 Hz

Required detuning -25.36 Hz

NO OPTICAL LOSS!

A pure squeezed state with 10dB (anti-)squeezing looks unproblemetic



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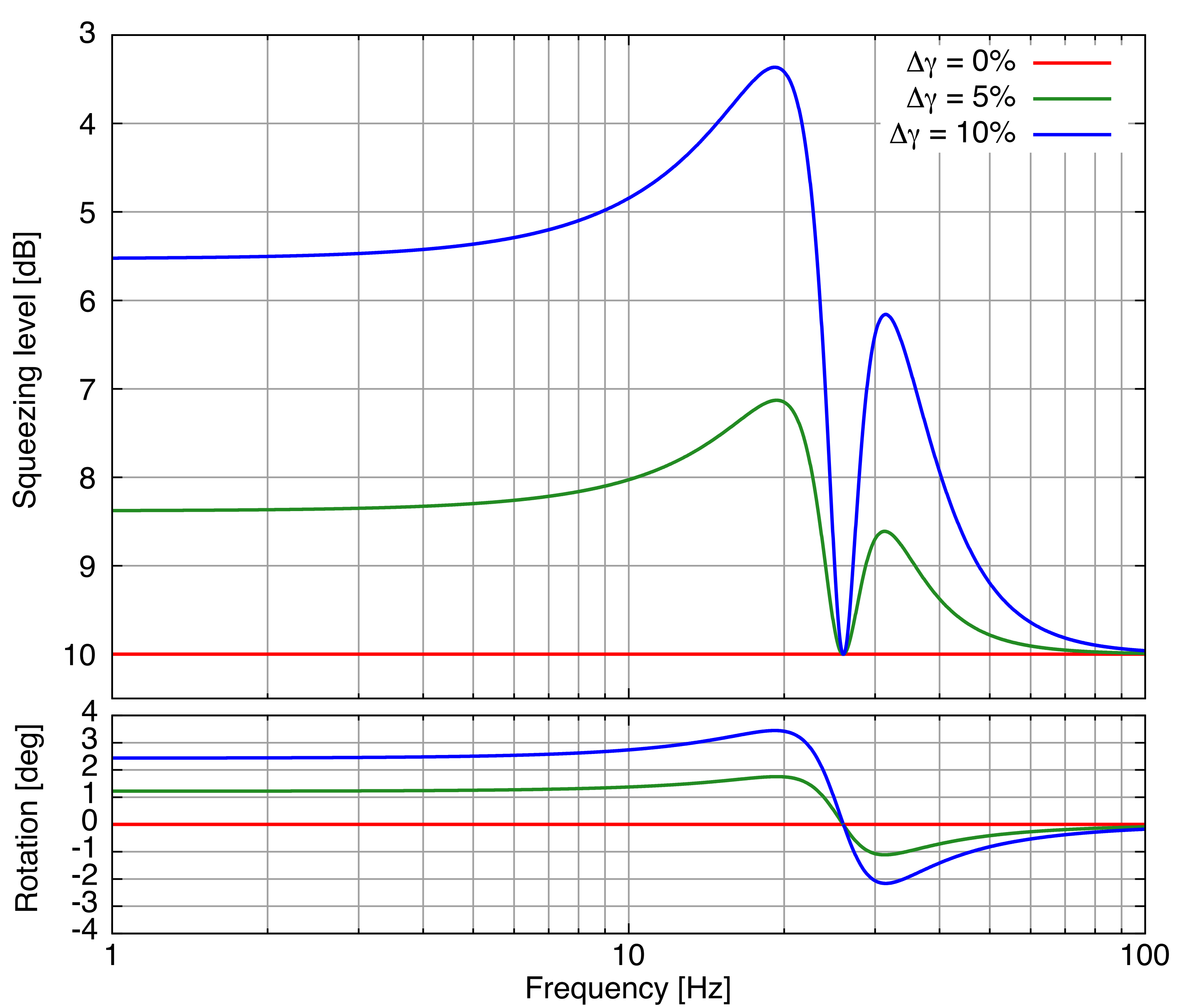
A realistic squeezed state with **10dB squeezing** and **20dB anti-squeezing** makes the problem more obvious.



Deduced parameter tolerances

Assume 10dB squeezing and 20dB anti-squeezing

Account for 75 ppm rt-loss

ET-C LF with 10 km FCs:
A mismatched HBW less than 5 % requires:

R_c = 0.995323 ± 237ppm
l_{rt}^2 = 75ppm ± 300ppm
for FC 1

R_c = 0.998865 ± 60ppm
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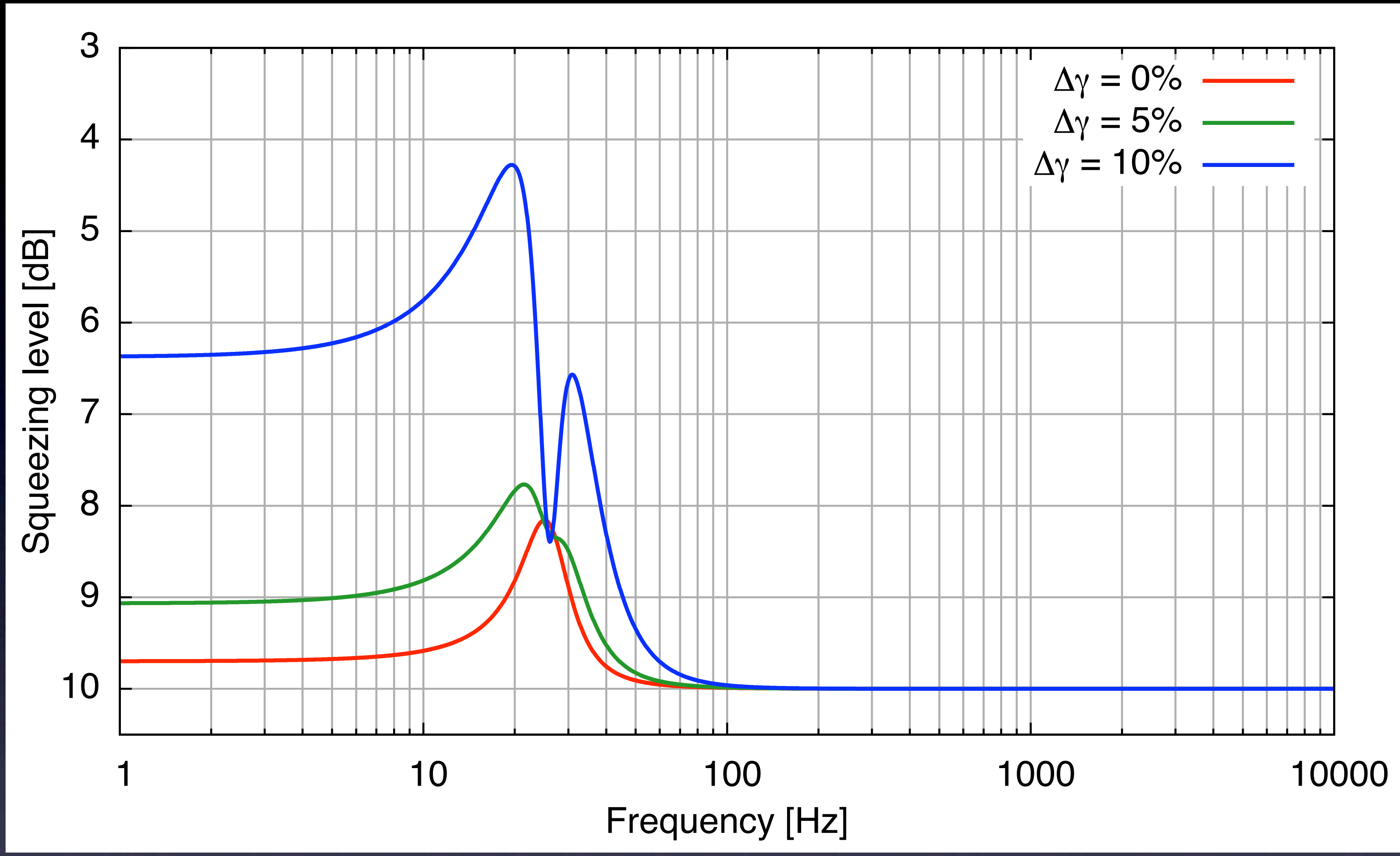
Tolerance for L ~500m



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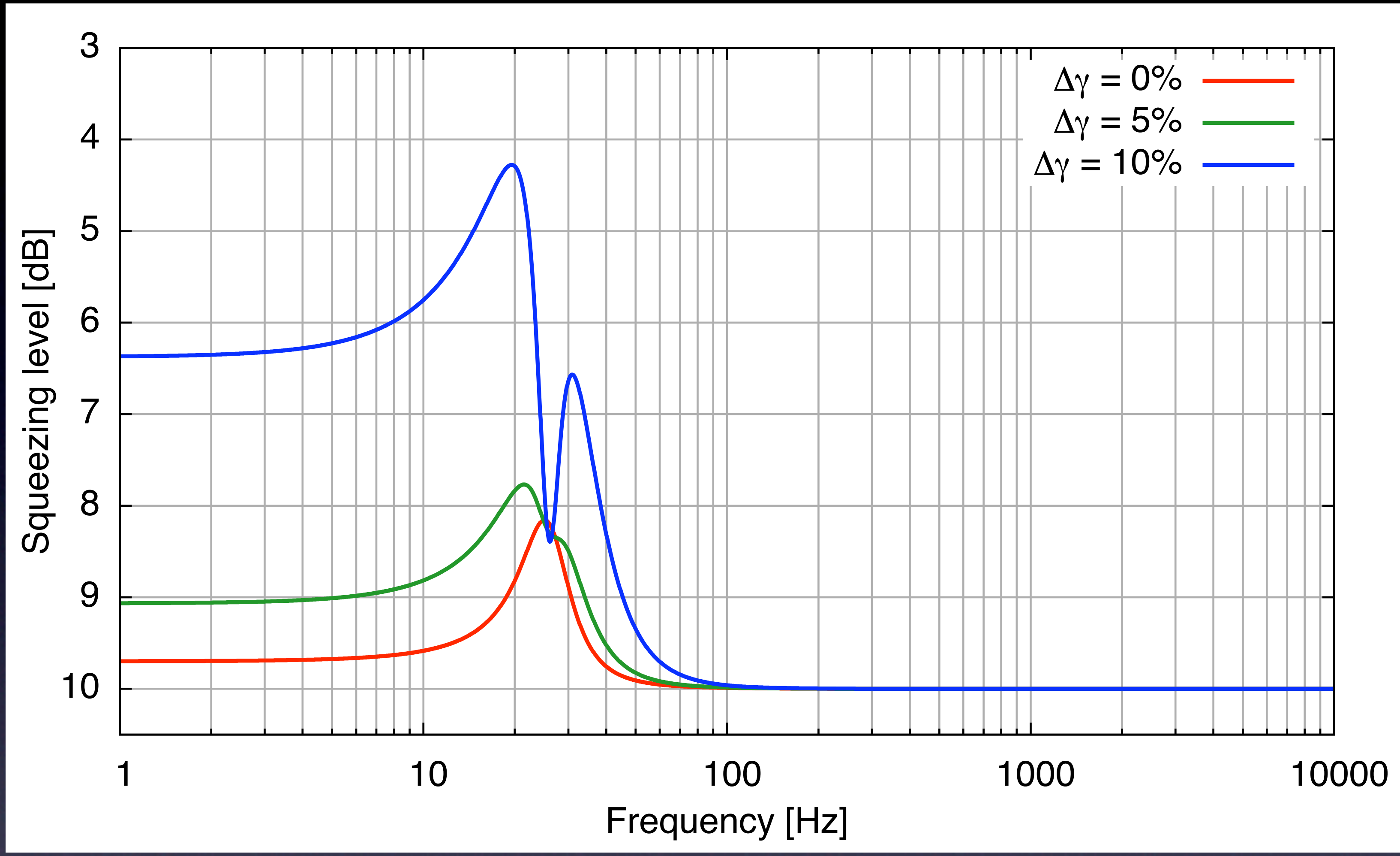

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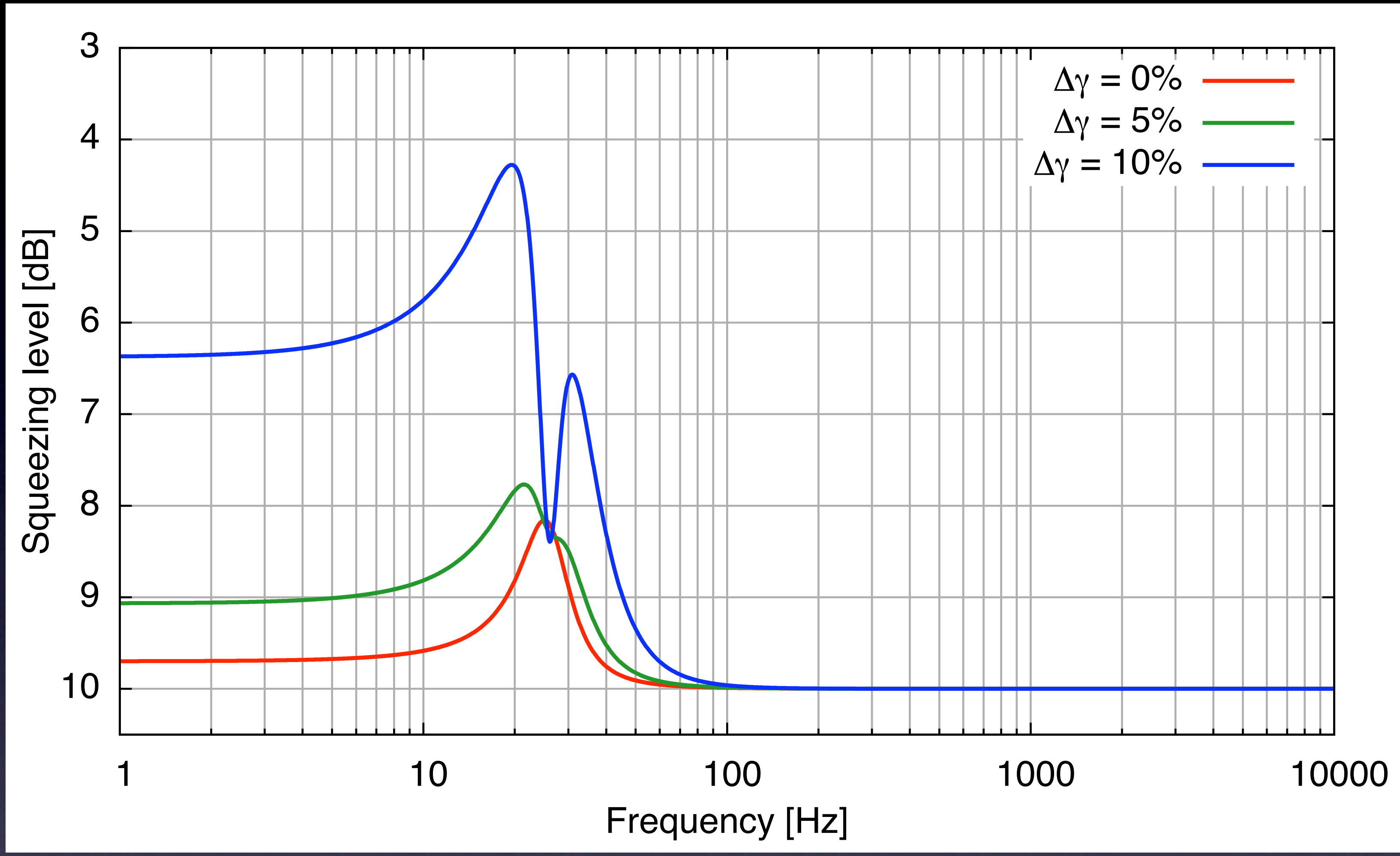

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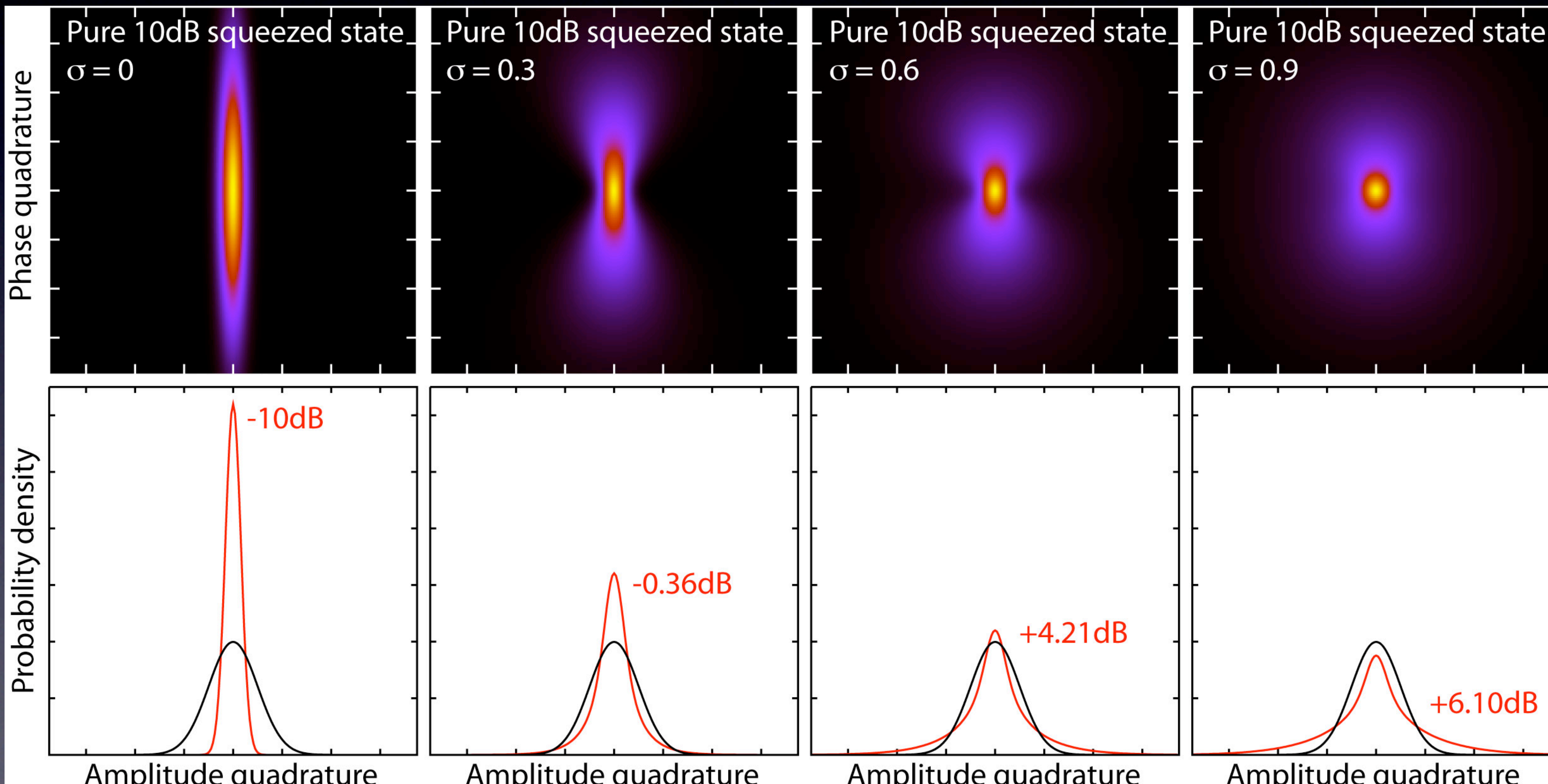
But what is the maximal achievable accuracy of these requirements determined by measurements?

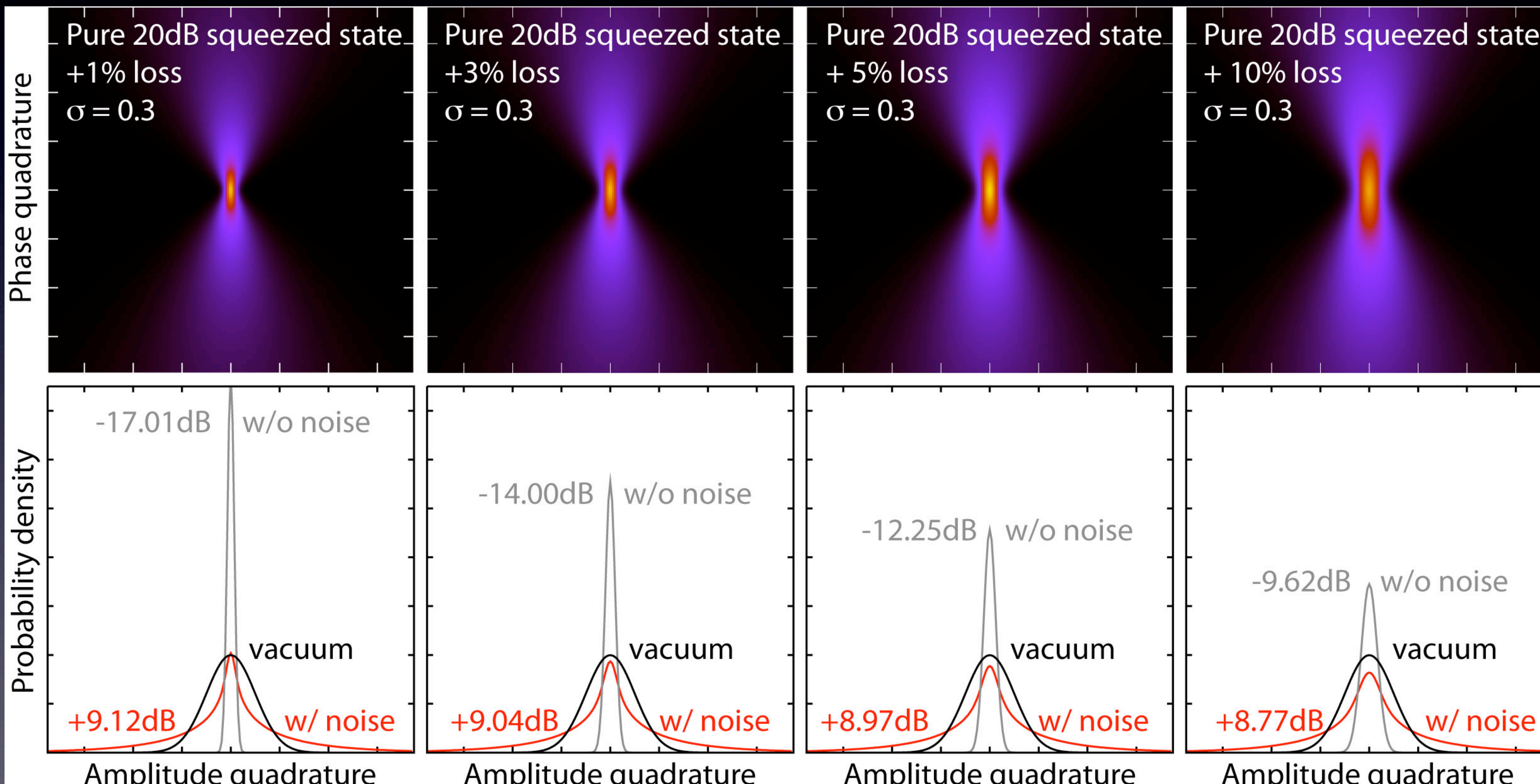
Effect of phase noise in the squeezing path

Due to phase noise a fraction of the noise in the anti-squeezed quadrature is mixed into the initially squeezed quadrature



Effect of phase noise in the squeezing path

The higher the anti-squeezing level, the higher the impact of phase noise



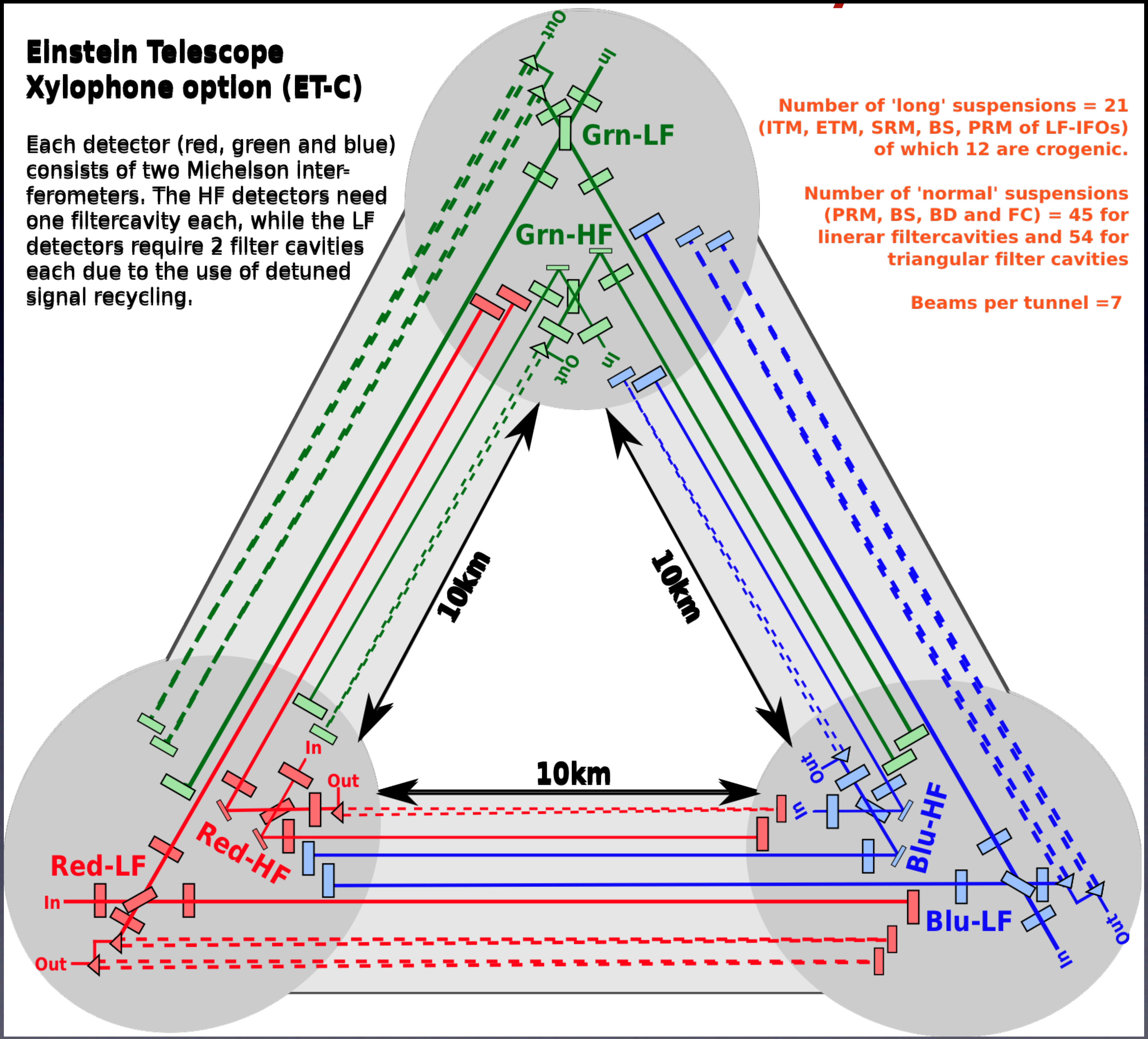
Estimates for the allowed phase noise

Estimates for different values of optical loss in the squeezing path

optical loss [%]	initial squeezing [dB]	squeezing [dB]	anti-squeezing [dB]	$\sigma_{\max}$
1	-10.41	-10	10.37	0.049
3	-11.41	-10	11.29	0.044
5	-12.79	-10	12.58	0.038
9	-19.59	-10	19.19	0.018
10	$-\infty$	-10	∞	0
20	$-\infty$	-6.99	∞	0

If **10dB of quantum-noise reduction** by squeezed light injection is targeted, the ultimate **upper limit for the overall optical loss is 10%**. Additionally, no phase noise is allowed.

DOFs to be controlled in the squeezing path



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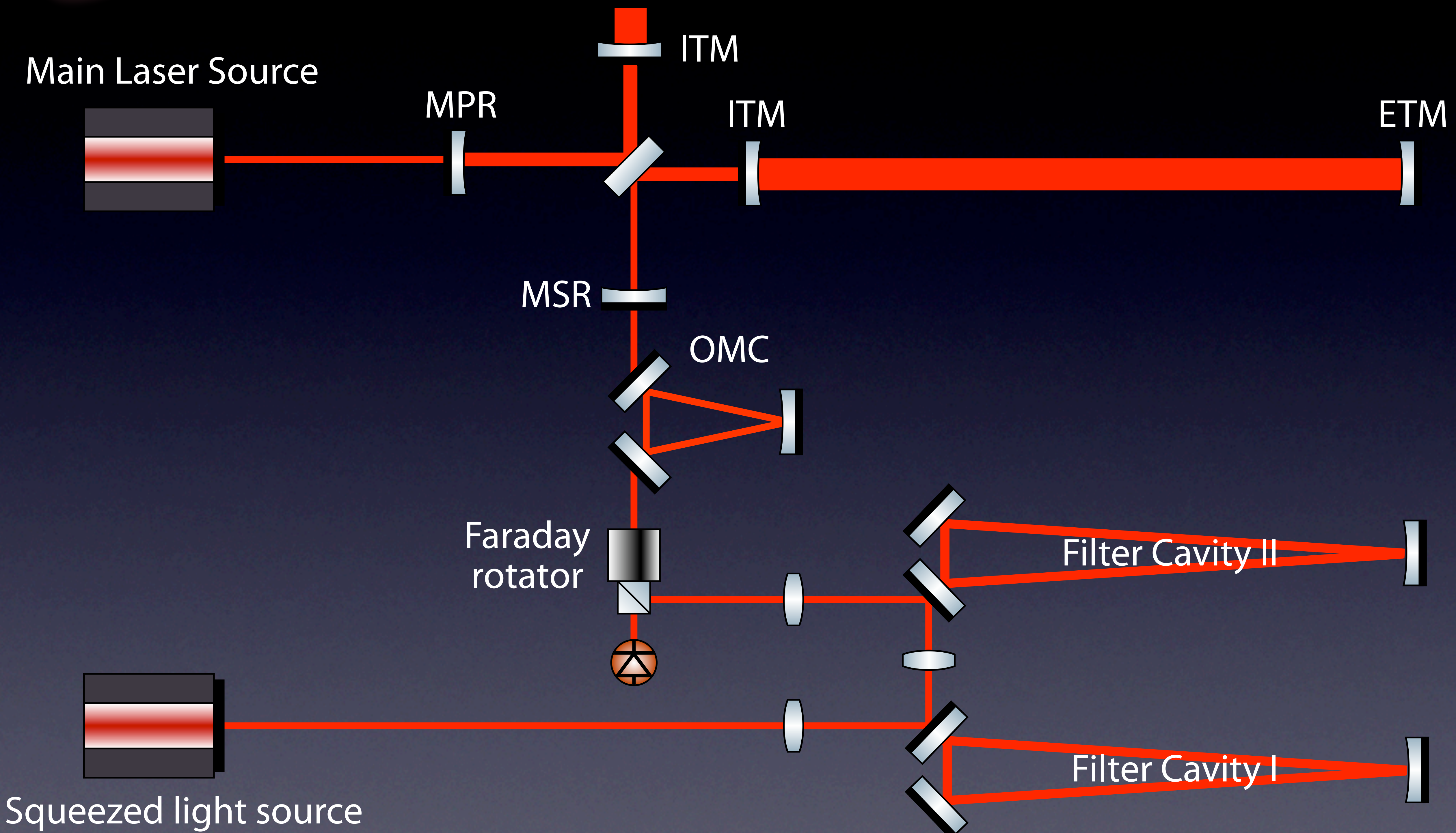

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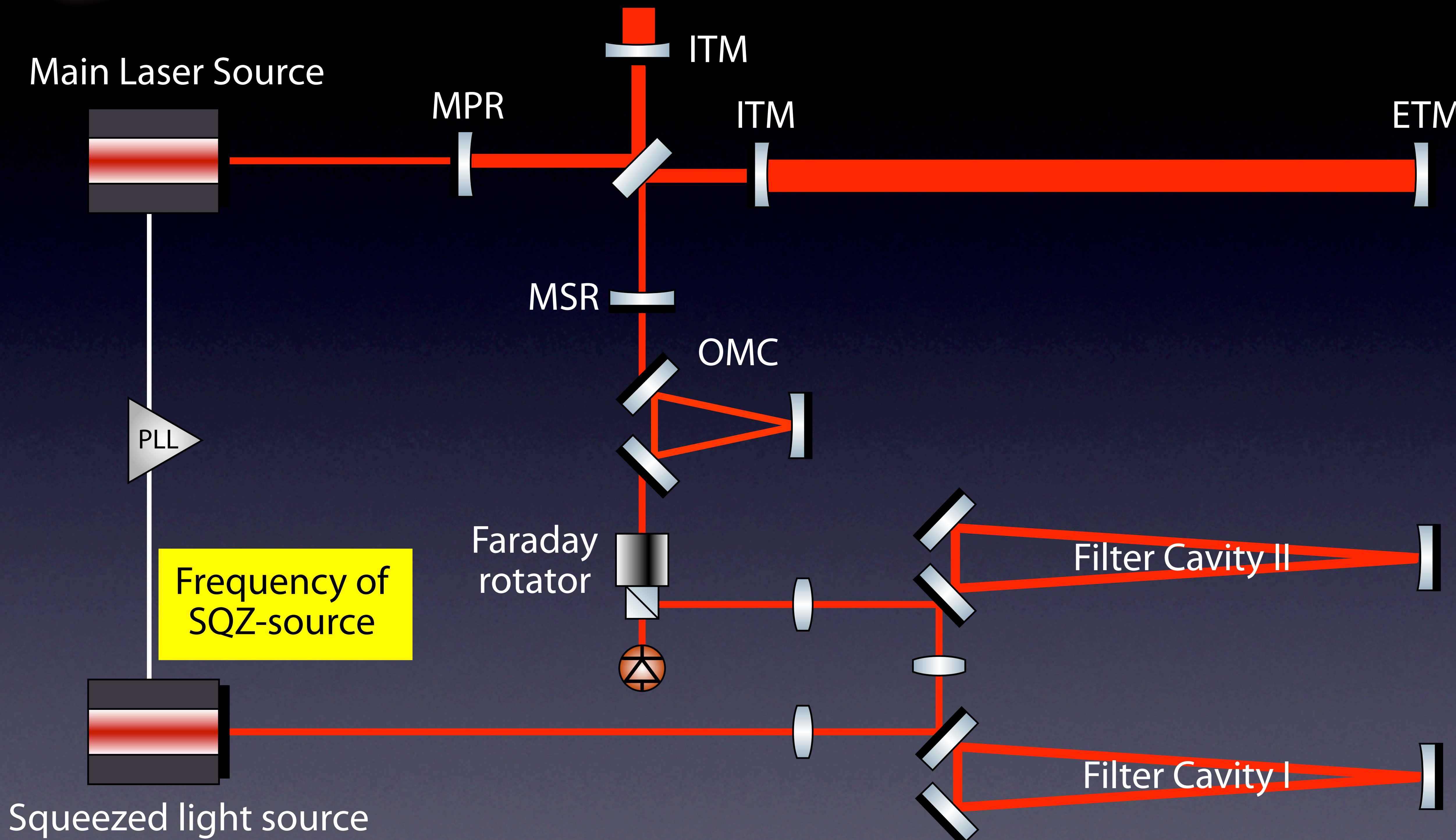

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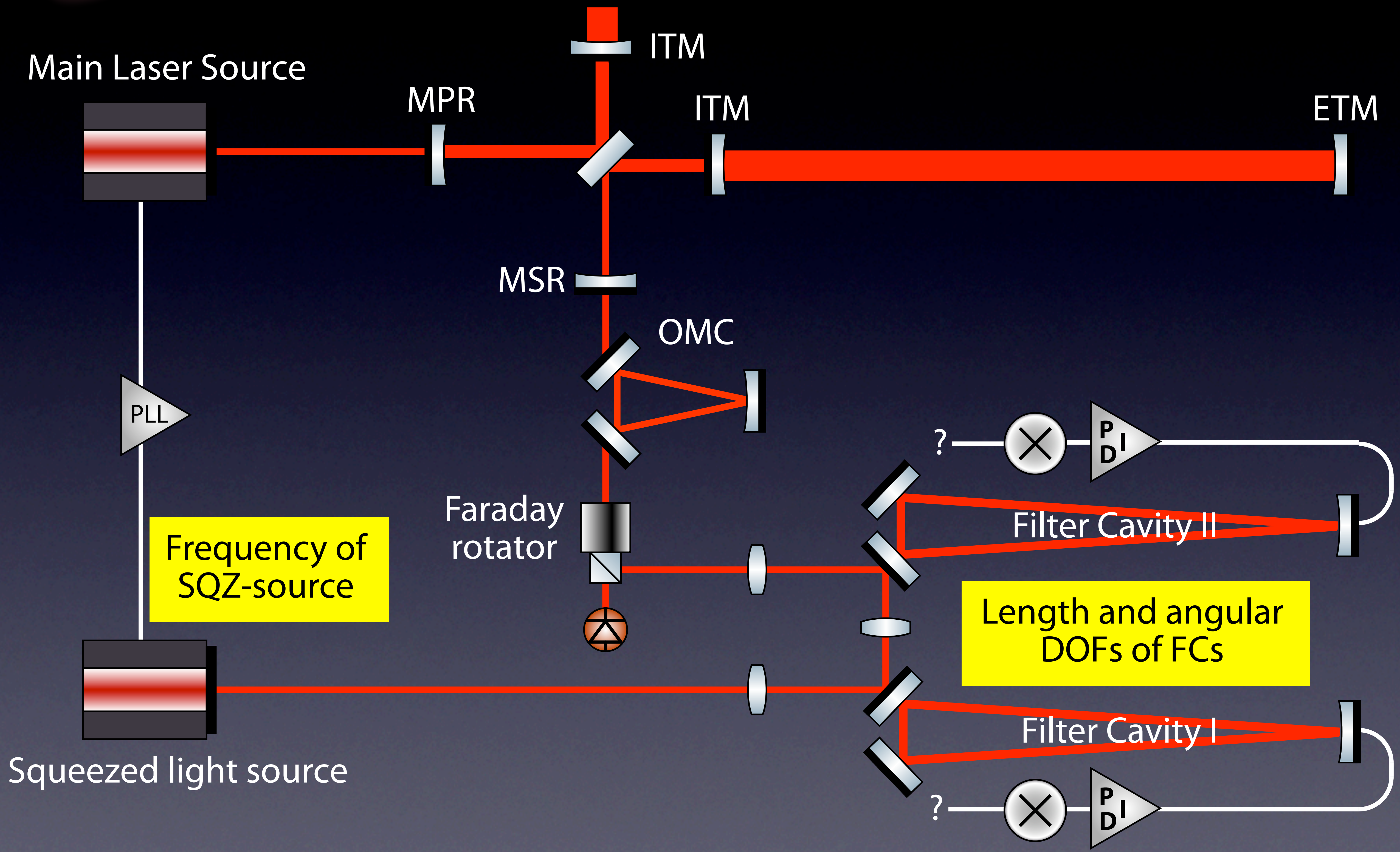

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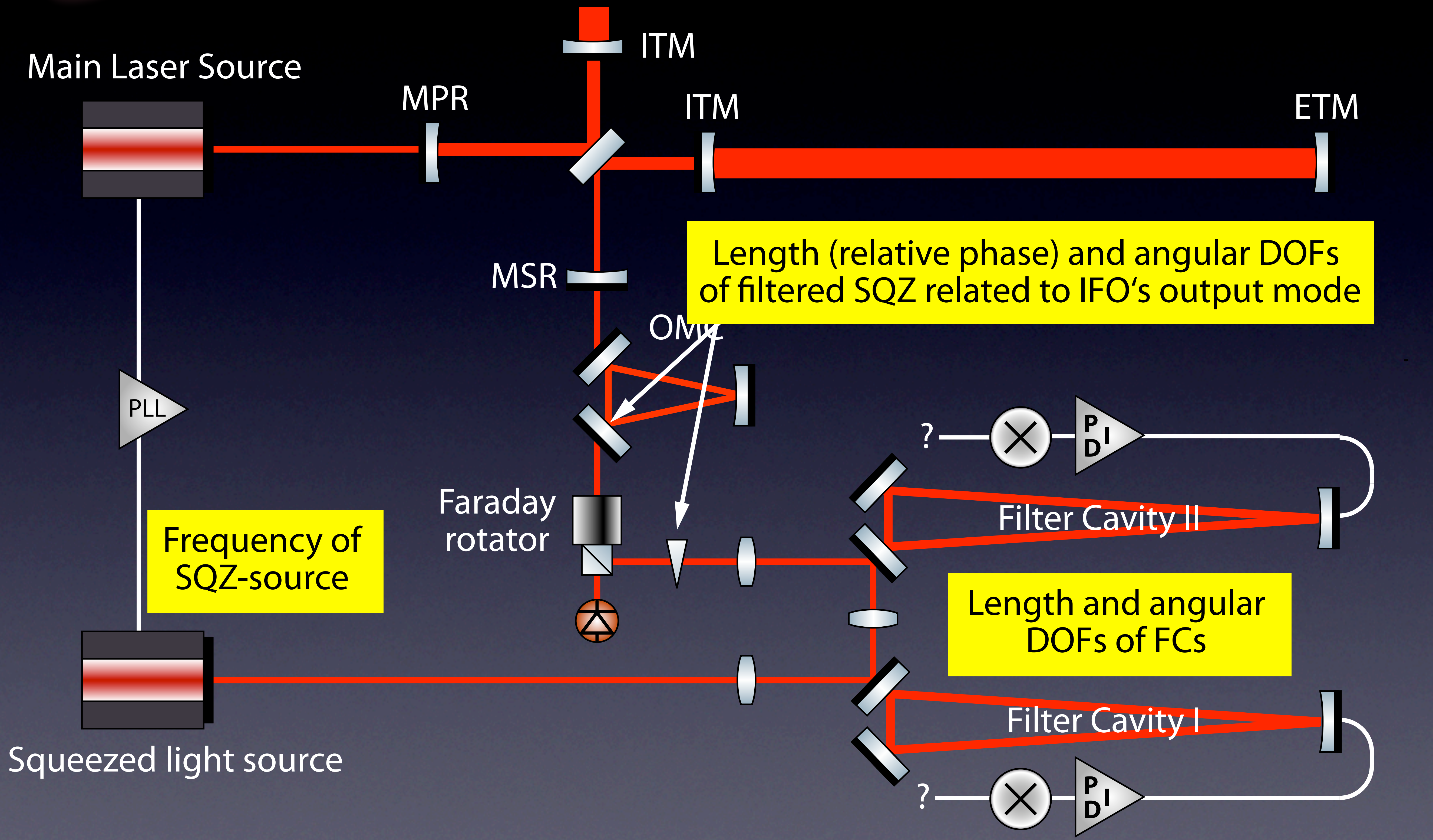

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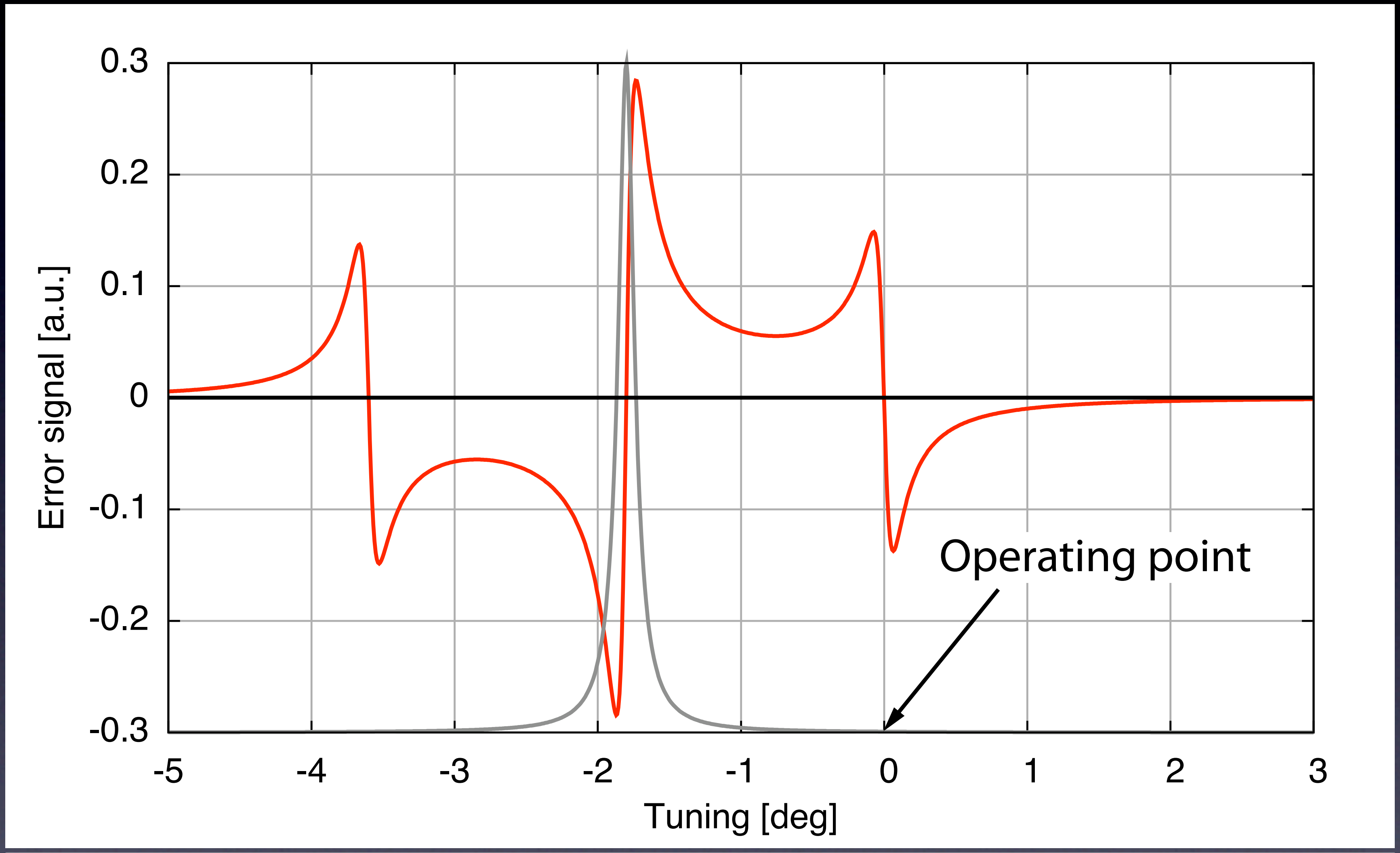
The displacement noise requirements in the FCs and the squeezing path needs to be matched

Take care of the strength of phase-modulation sidebands needed for error-signal generation

How to lock a carrier-detuned cavity?

A common procedure is to realize a PDH-locking scheme with $f_{mod} = f_{res}$



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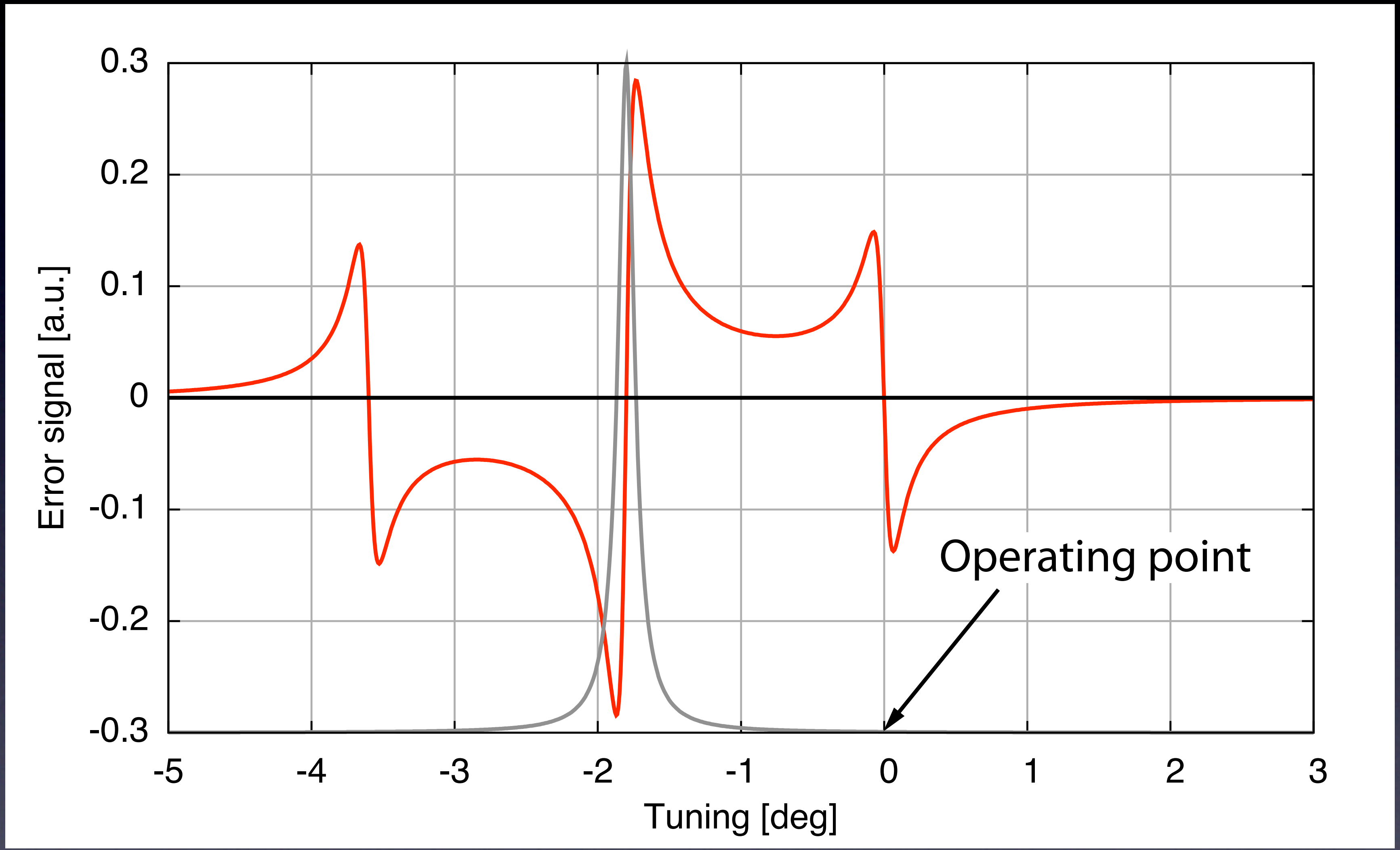
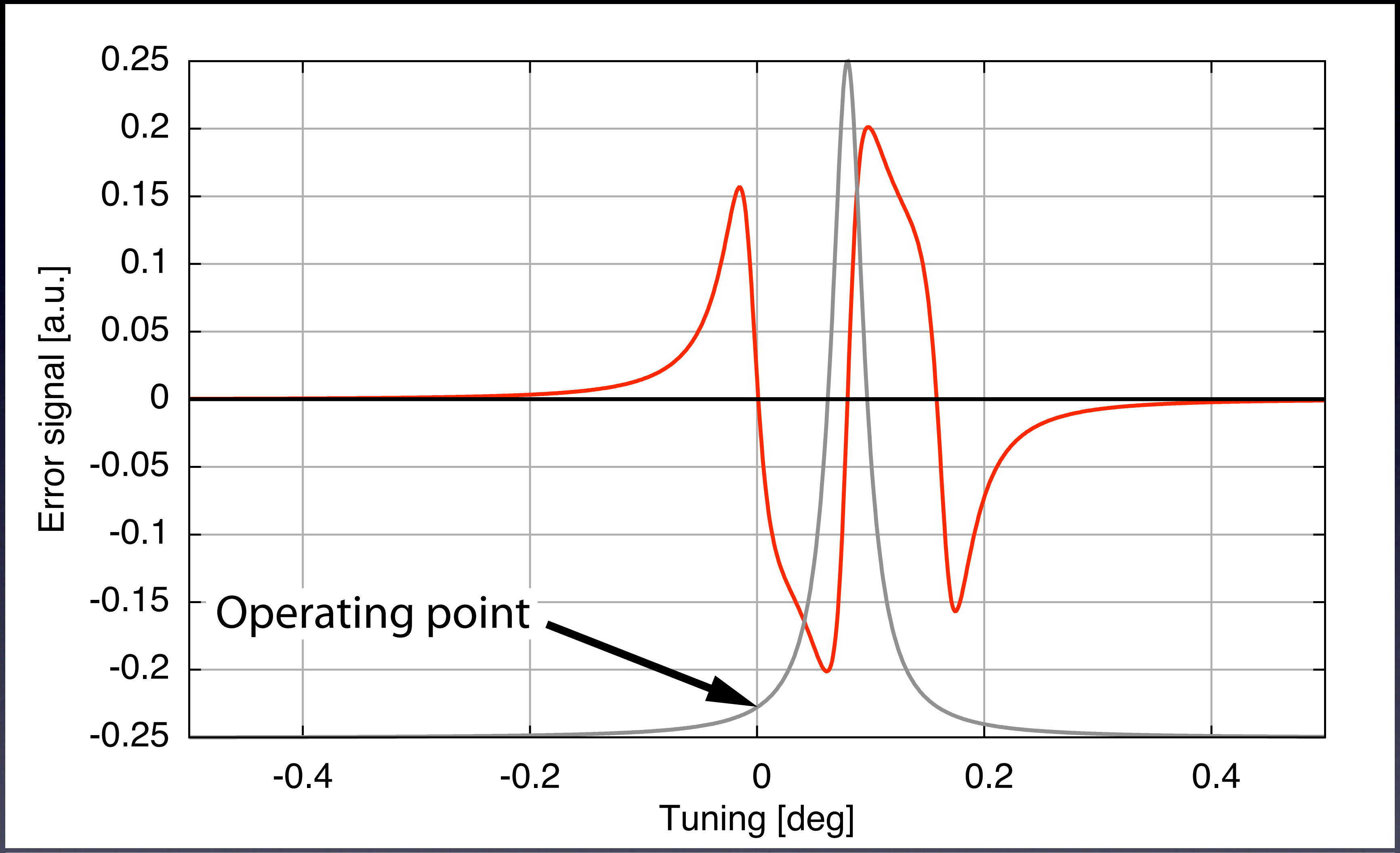


Lock on the zero-crossing corresponding to the resonance of one sideband. This works if f_{res} is much bigger than the cavity‘s half-bandwidth

„Classical“ PDH-scheme for FC_I of ET-LF

Target resonance frequency f_{res} = 6.628Hz
Half-band-width is HBW = 1.444Hz



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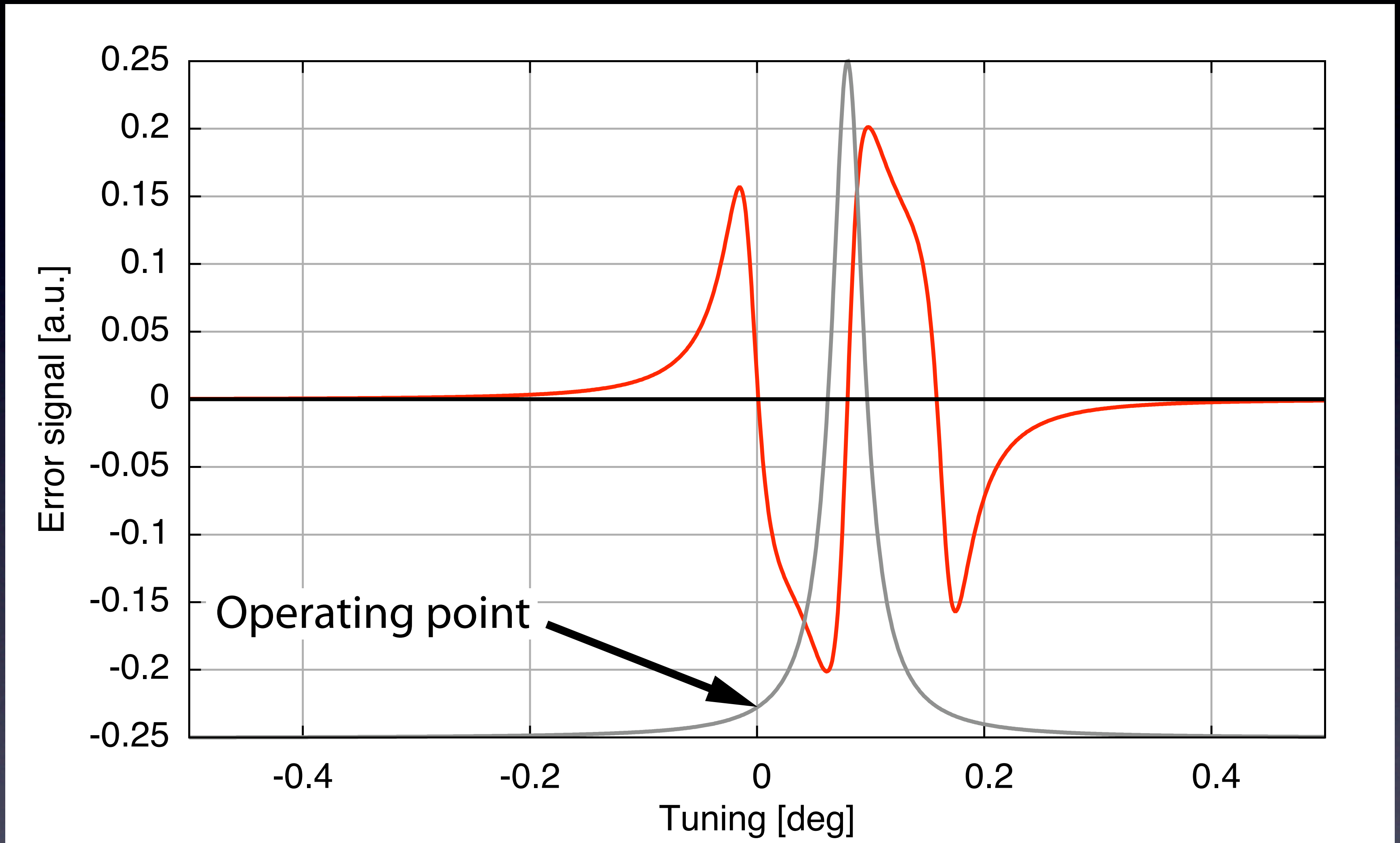
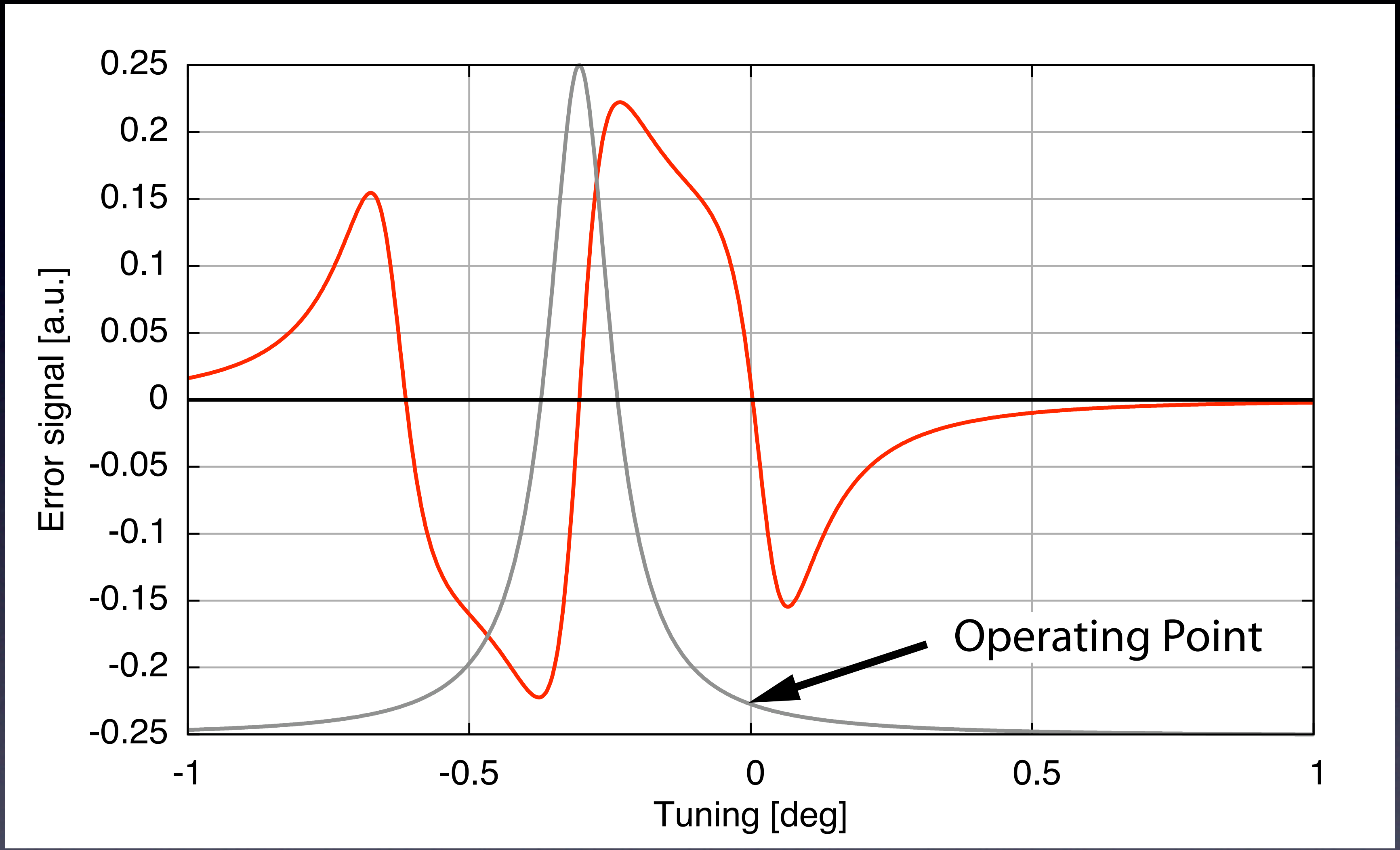


The error signal requires an adaption of the modulation frequency (f_{mod} > f_{res}) and demodulation phase

„Classical“ PDH-scheme for FC_2 of ET-LF

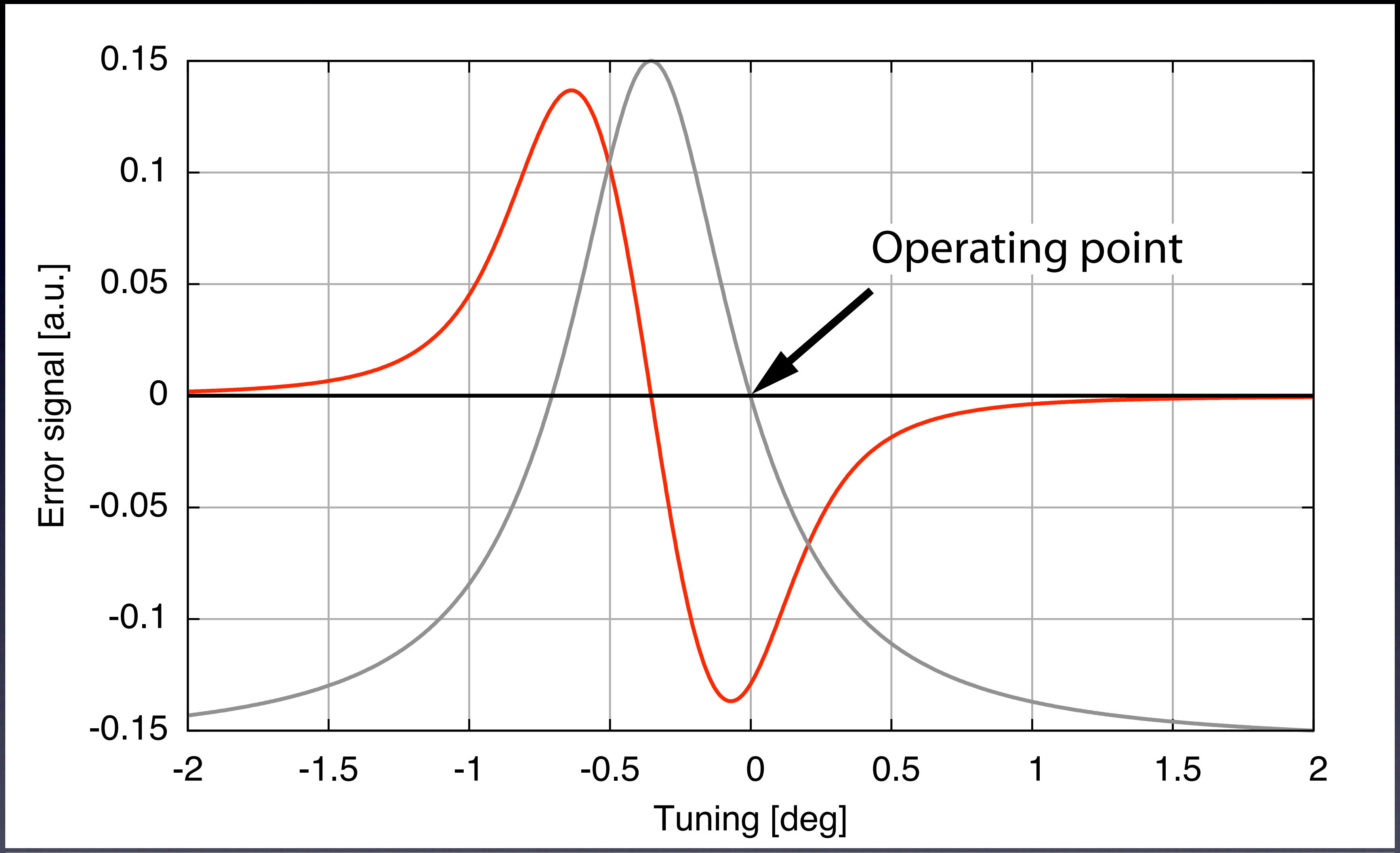
Target resonance frequency f_{res} = -25.359Hz
Half-band-width is HBW = 5.681Hz



The error signal requires an adaption of the modulation frequency ($f_{mod} > f_{res}$) and demodulation phase

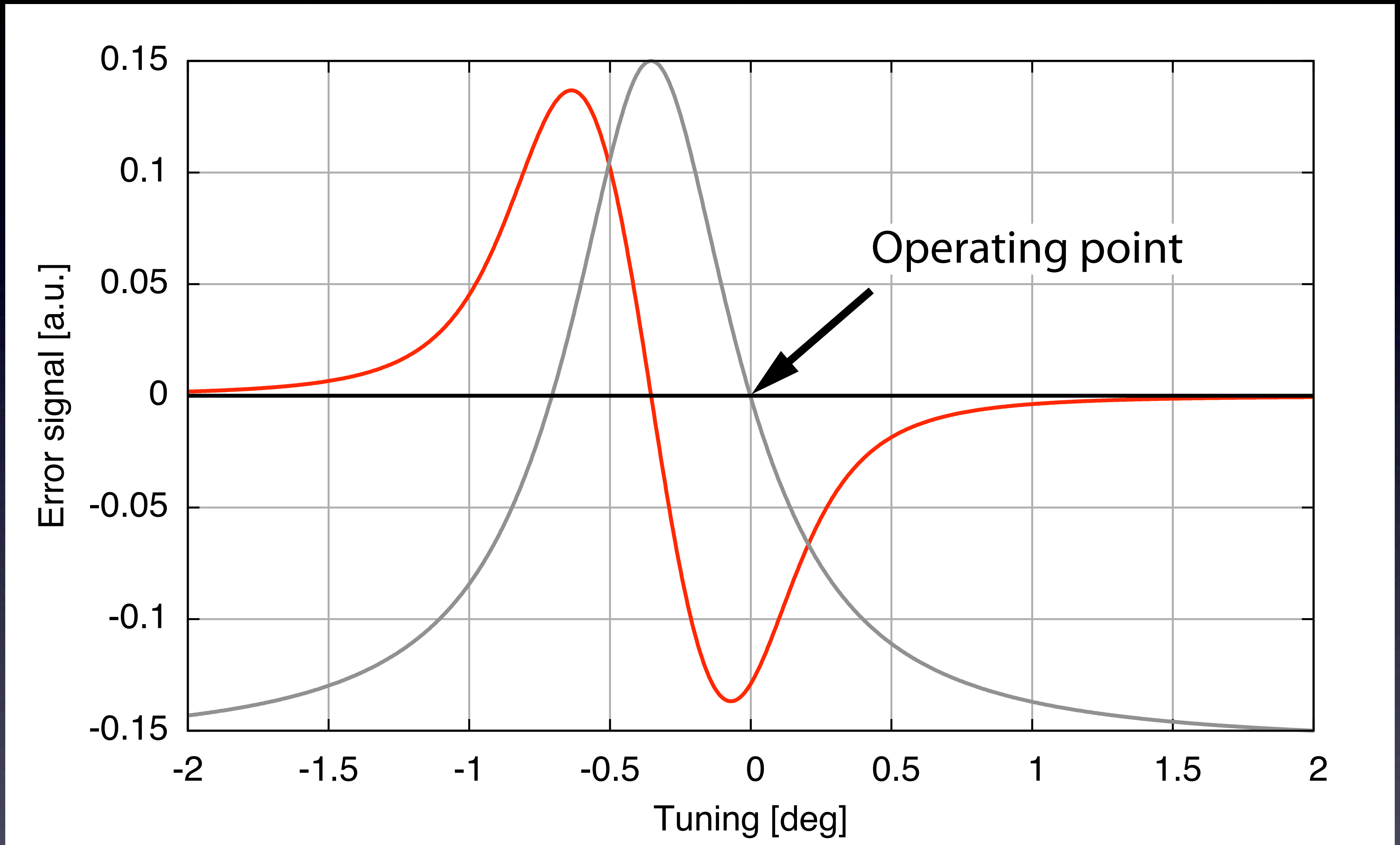
„Classical“ PDH-scheme for FC_I of ET-HF

Target resonance frequency f_{res} = 29.464Hz
Half-band-width is HBW = 28.968Hz



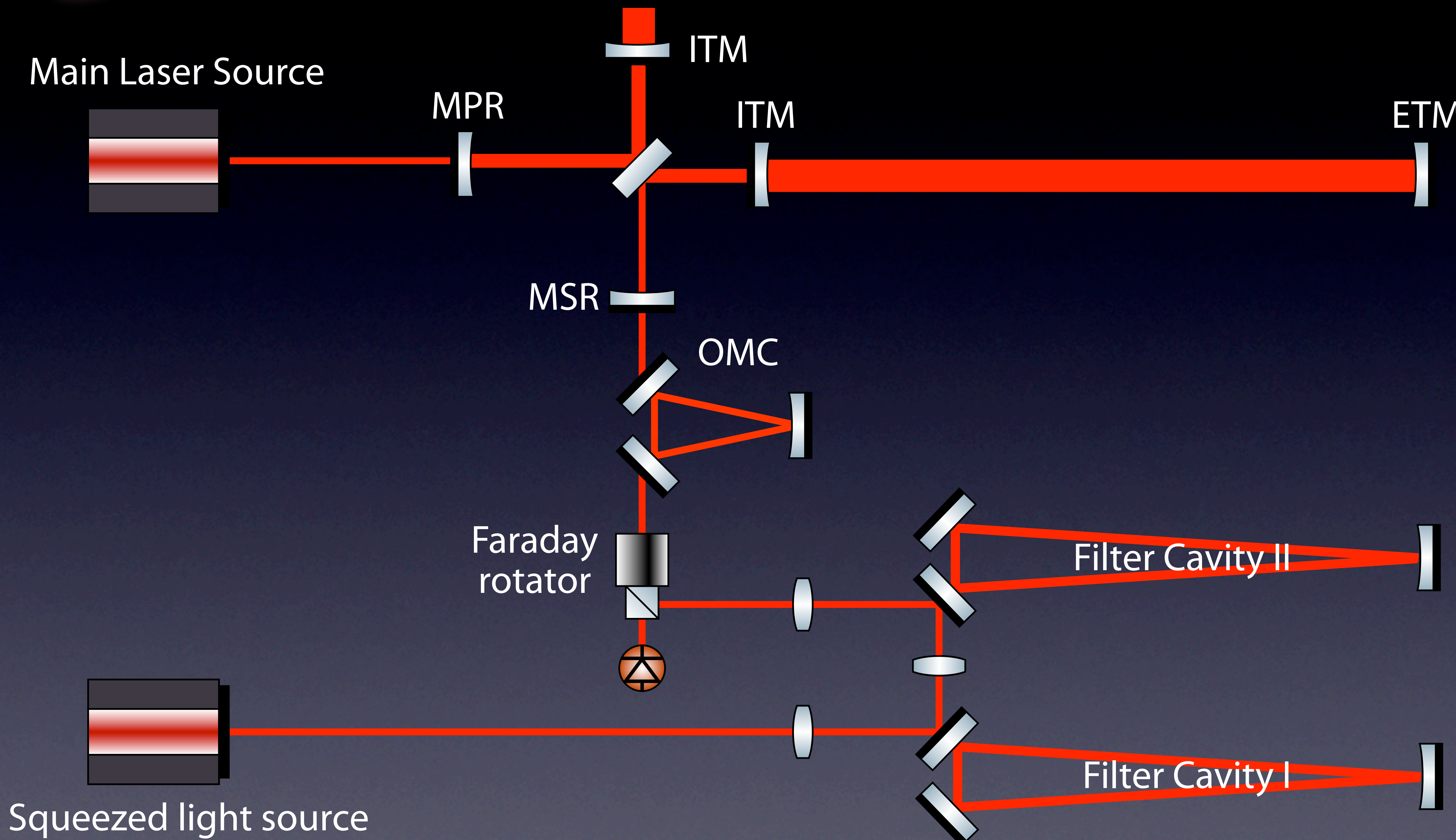
„Classical“ PDH-scheme for FC_I of ET-HF

Target resonance frequency f_{res} = 29.464Hz
Half-band-width is HBW = 28.968Hz

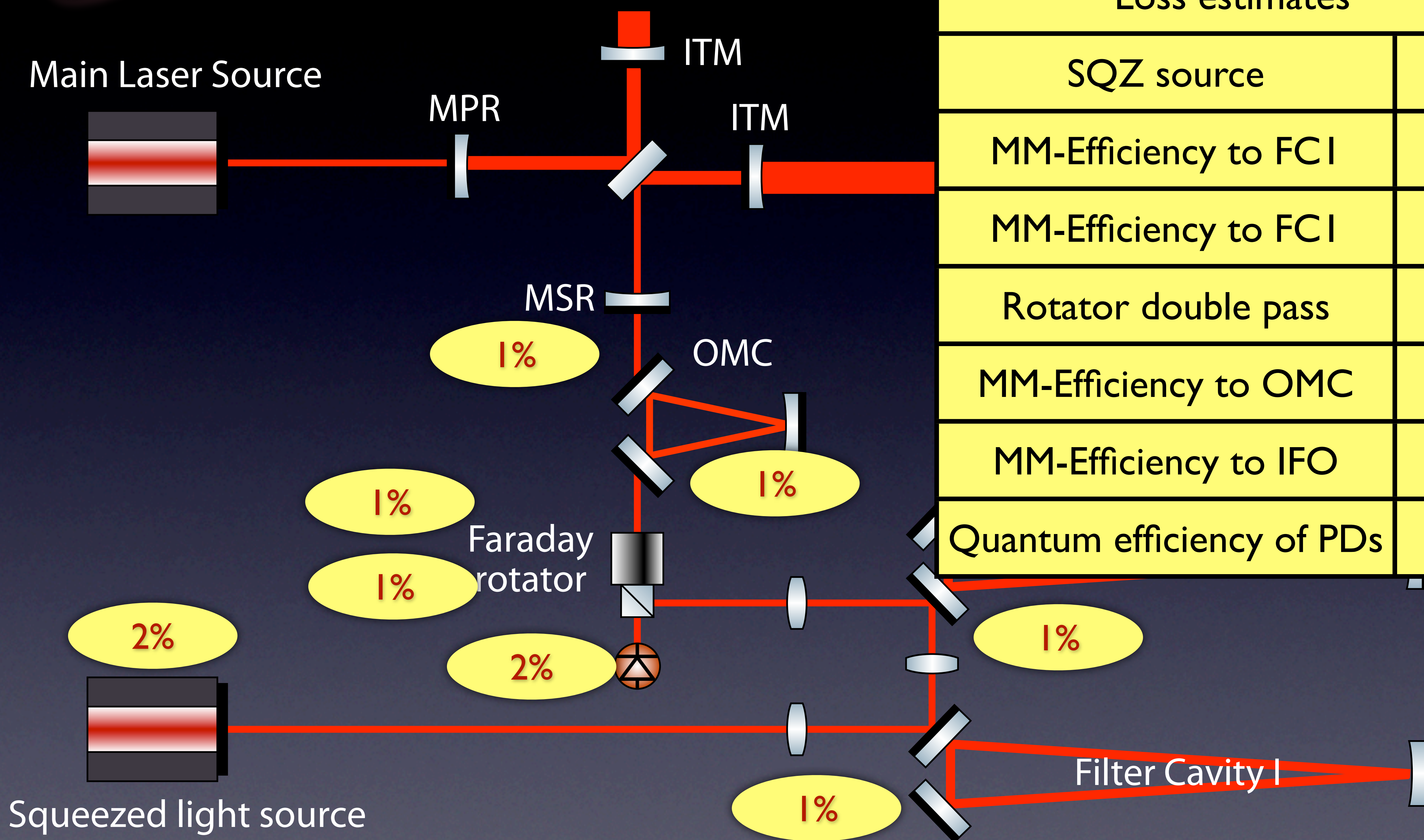


Standard PDH-scheme fails. DC-Lock? Sub-carrier? Double demodulation?

Loss estimate for the squeezing path

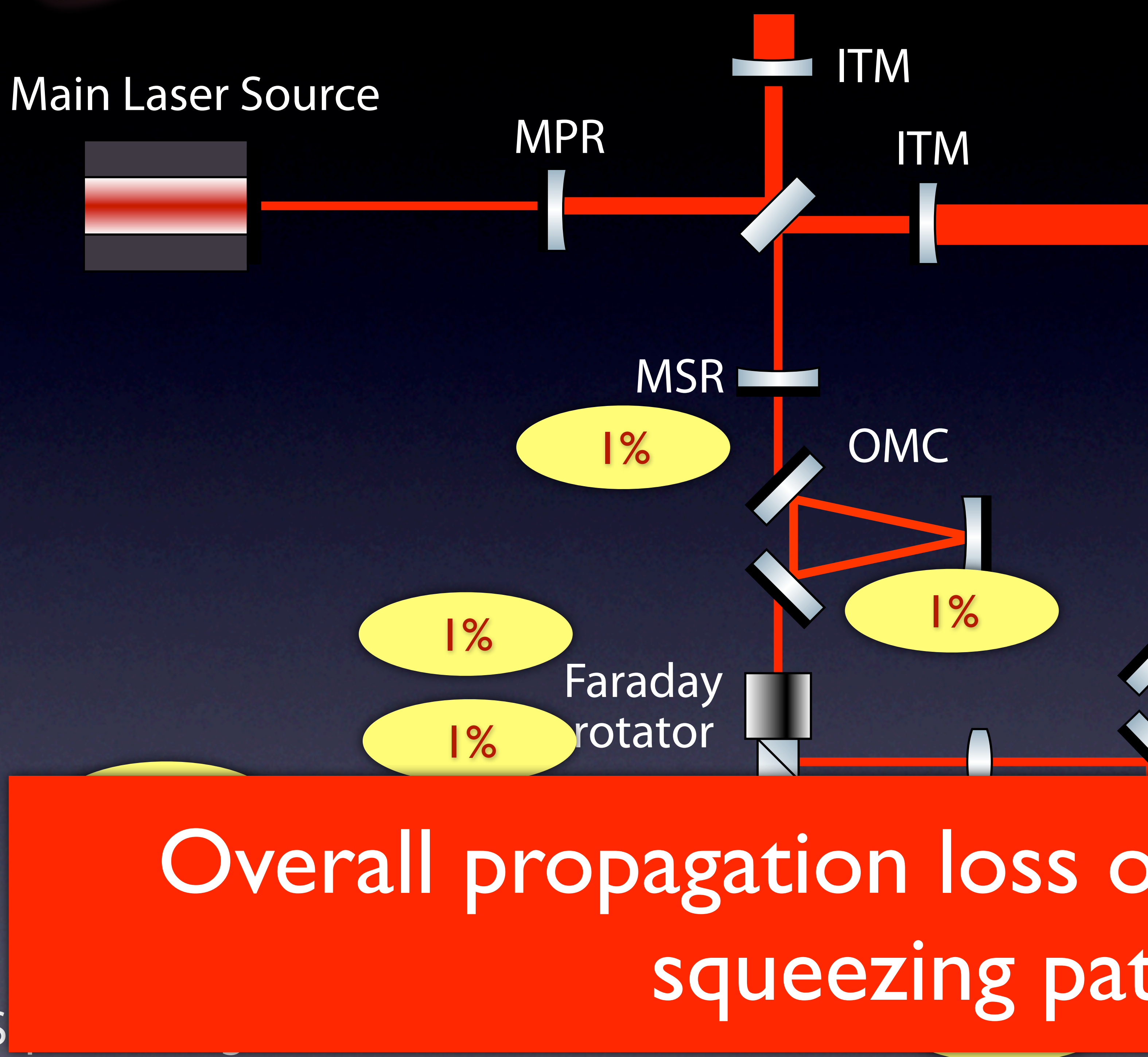


Loss estimate for the squeezing path



Loss estimates	
SQZ source	0.02
MM-Efficiency to FC1	0.01
MM-Efficiency to FC1	0.01
Rotator double pass	0.02
MM-Efficiency to OMC	0.01
MM-Efficiency to IFO	0.01
Quantum efficiency of PDs	0.02

Loss estimate for the squeezing path



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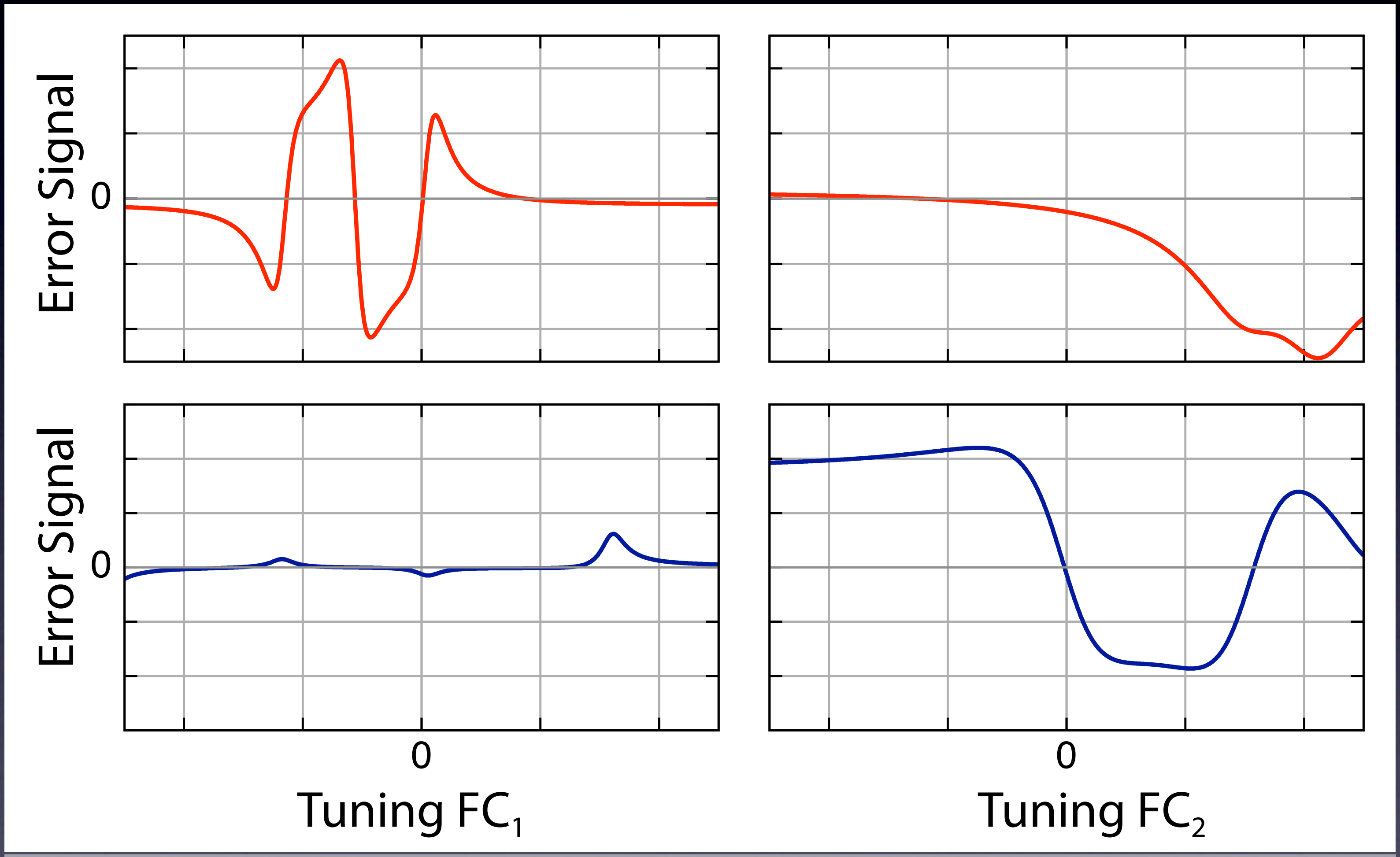
Overall propagation loss of 9.58% in the squeezing path

Error signals for subsequent FCs from one port?

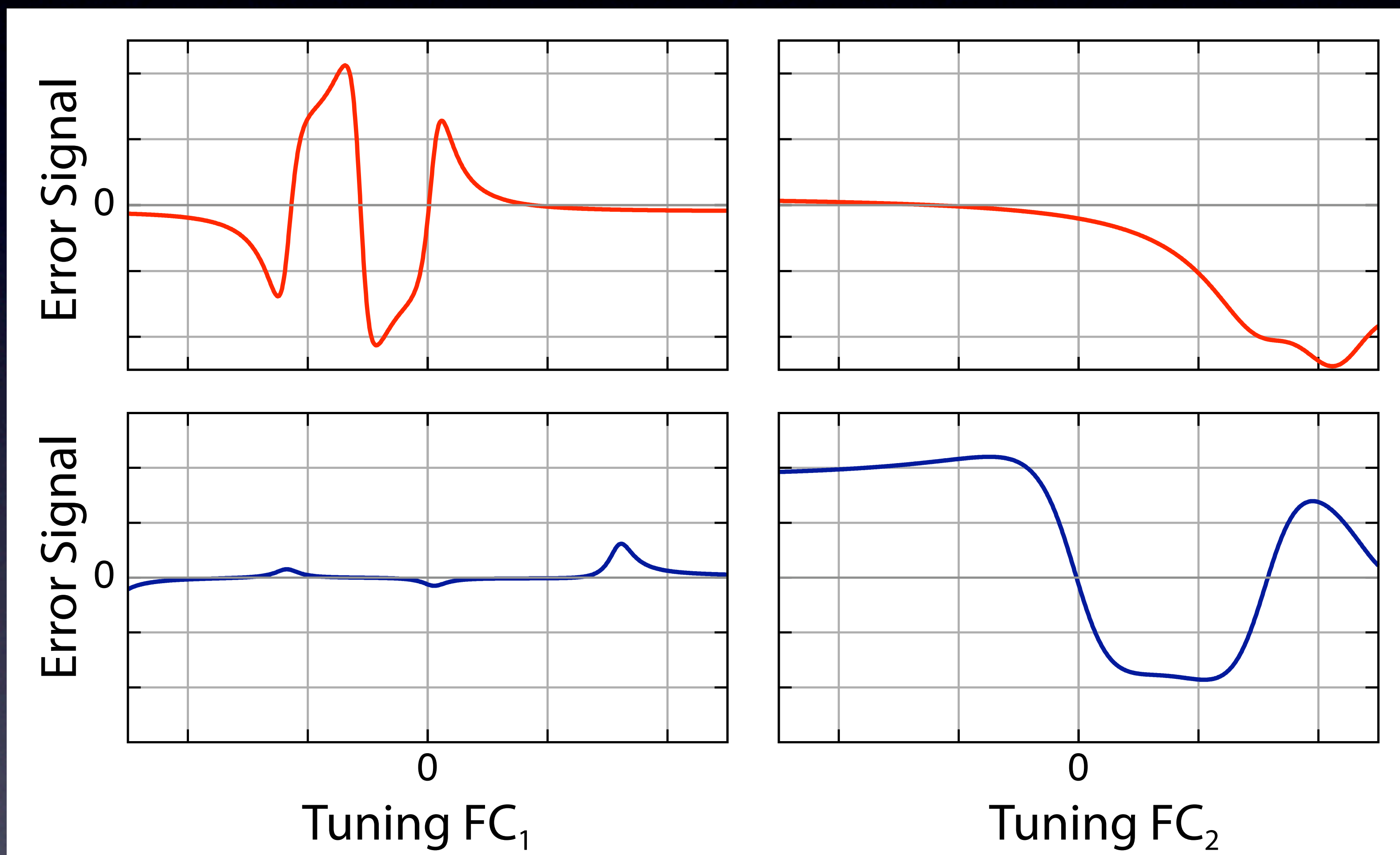
<u>Save the squeezing:</u> Create as less as possible additional detection ports, reduce loss



	FC_1	FC_2
ERR_{FC1}	1	-0.018
ERR_{FC2}	0.110	1

Error signals for subsequent FCs from one port?

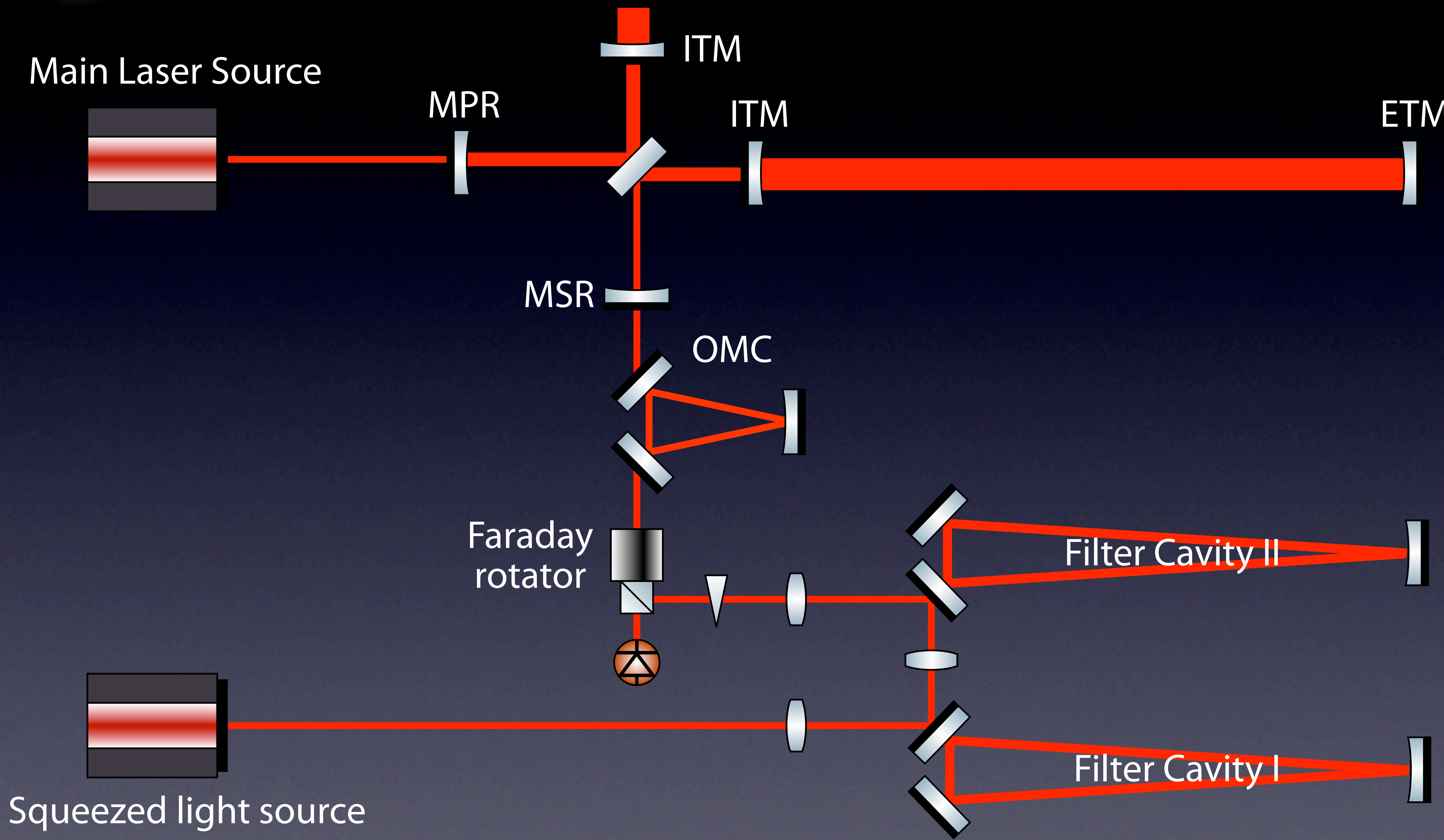
Save the squeezing: Create as less as possible additional detection ports, reduce loss



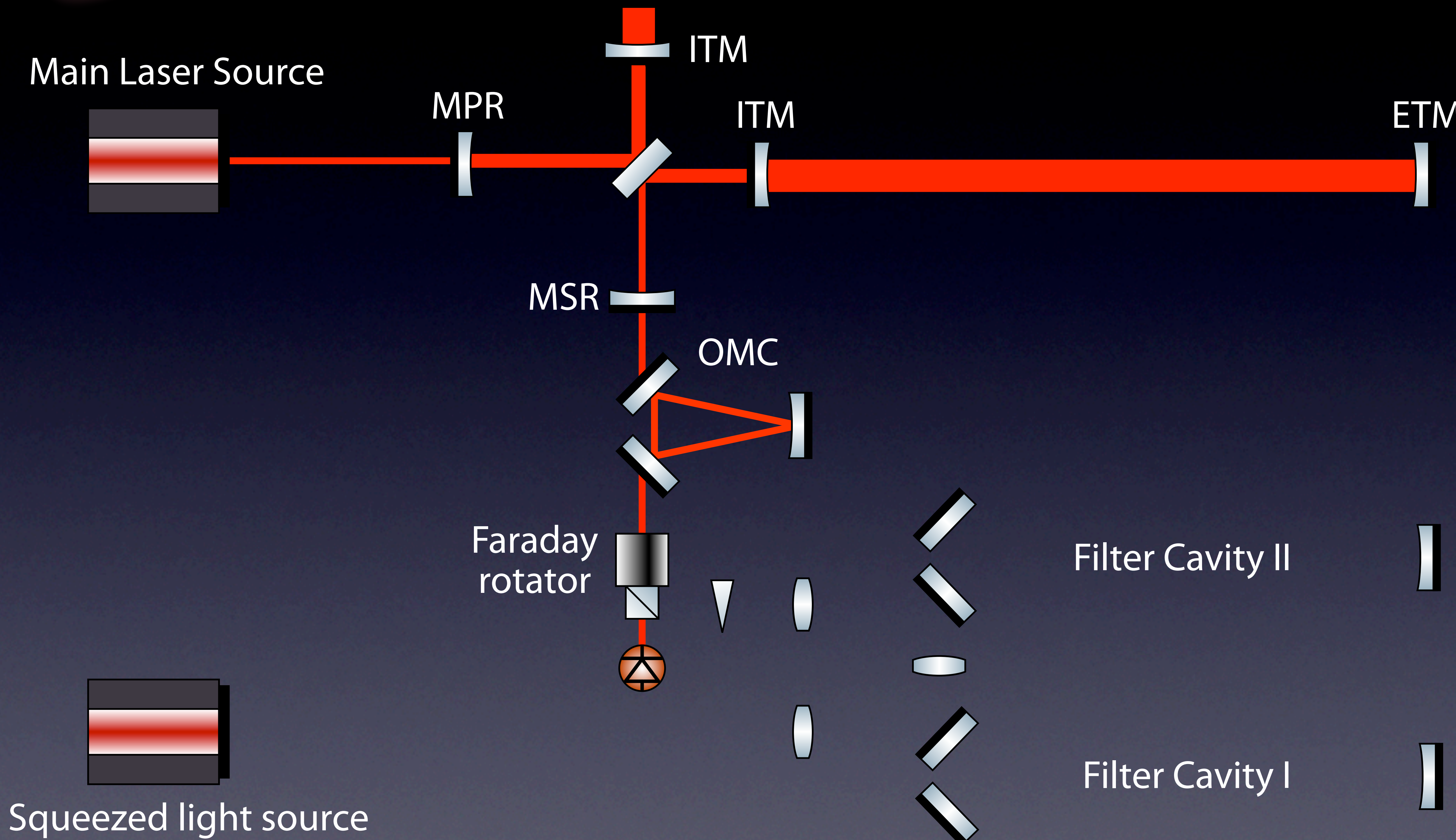
	FC_1	FC_2
ERR_{FC1}	1	-0.018
ERR_{FC2}	0.110	1

First snapshot investigation: At least error signals for the longitudinal DOFs of the **two subsequents FCs** for ET LF can be obtained from **one detection port**

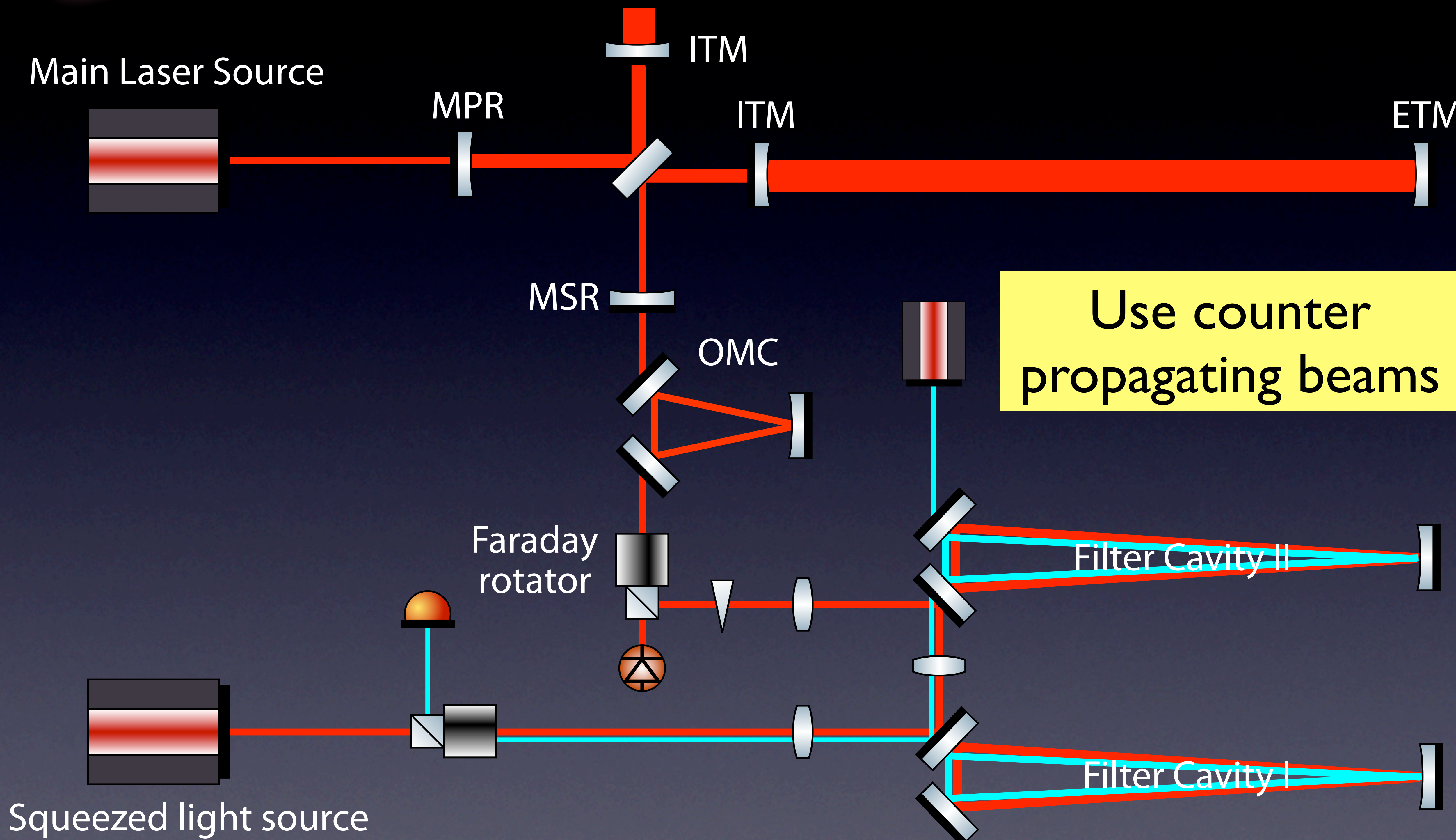
Transfer the „classical“ scheme to squeezed light



Squeezed vacuum means there is no carrier

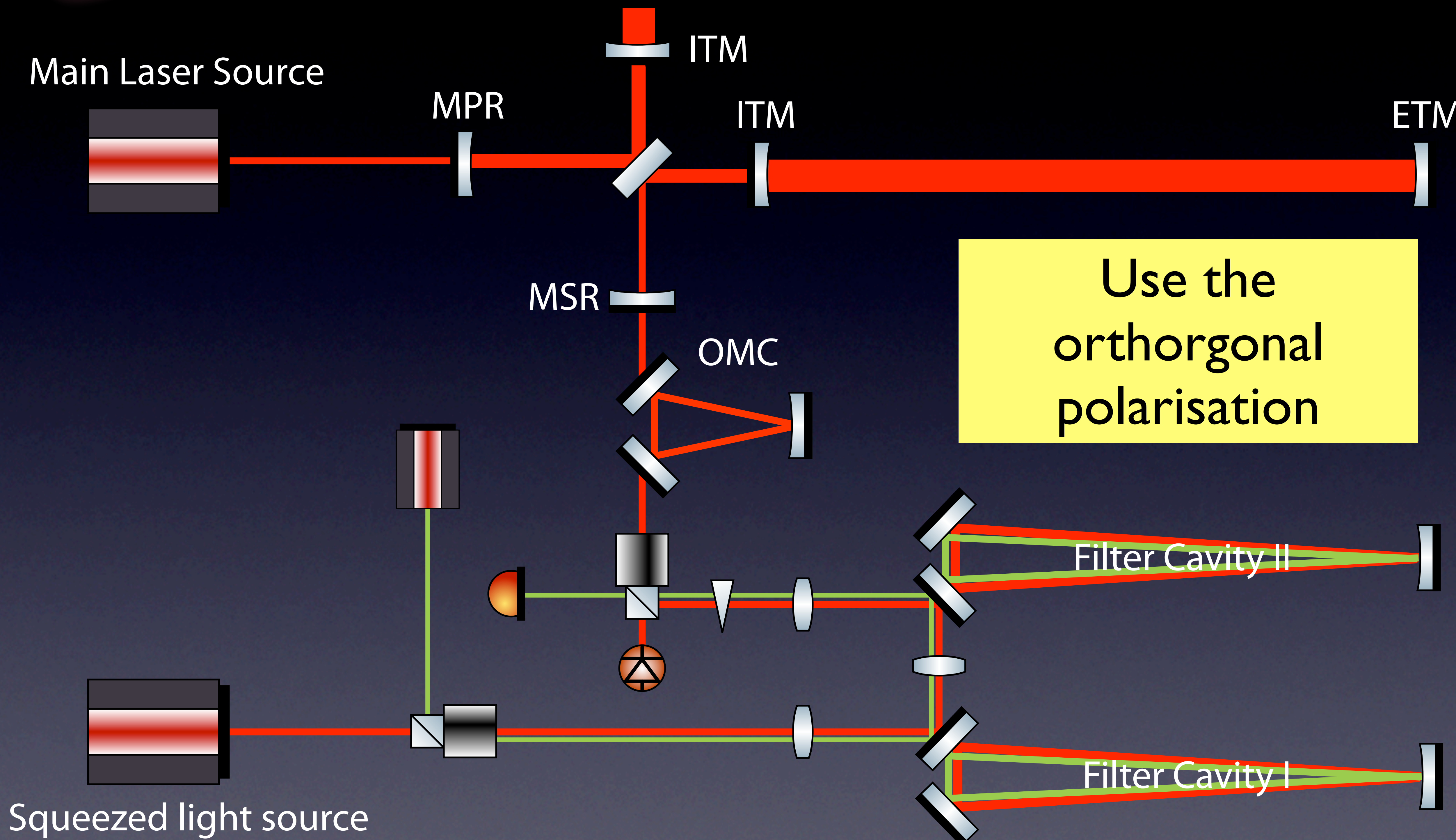


Ideas for creating an auxiliary carrier



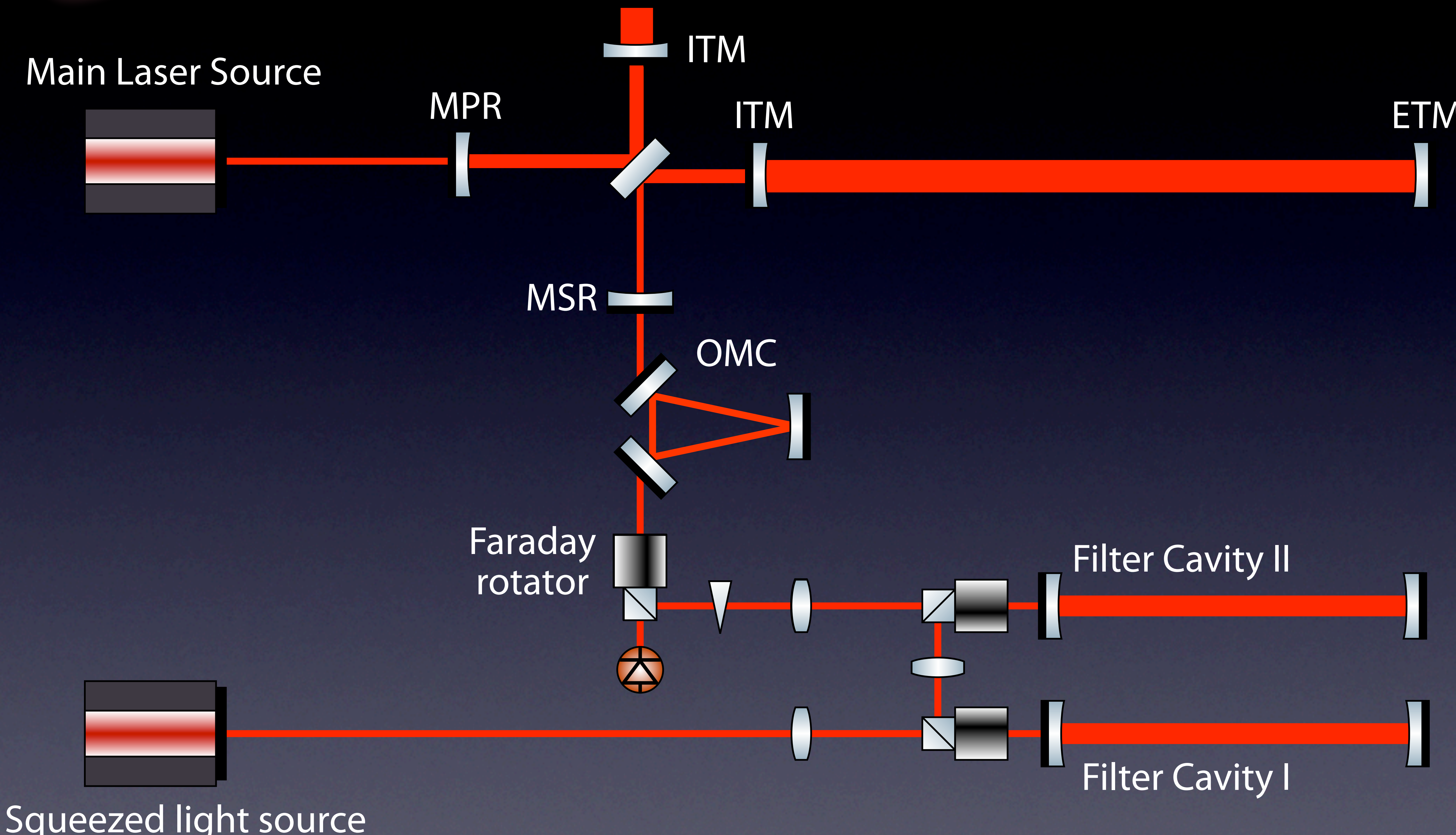
Use counter propagating beams

Ideas for creating an auxiliary carrier



Use the orthorgonal polarisation

The FCs will be linear Fabry-Perot-Cavities



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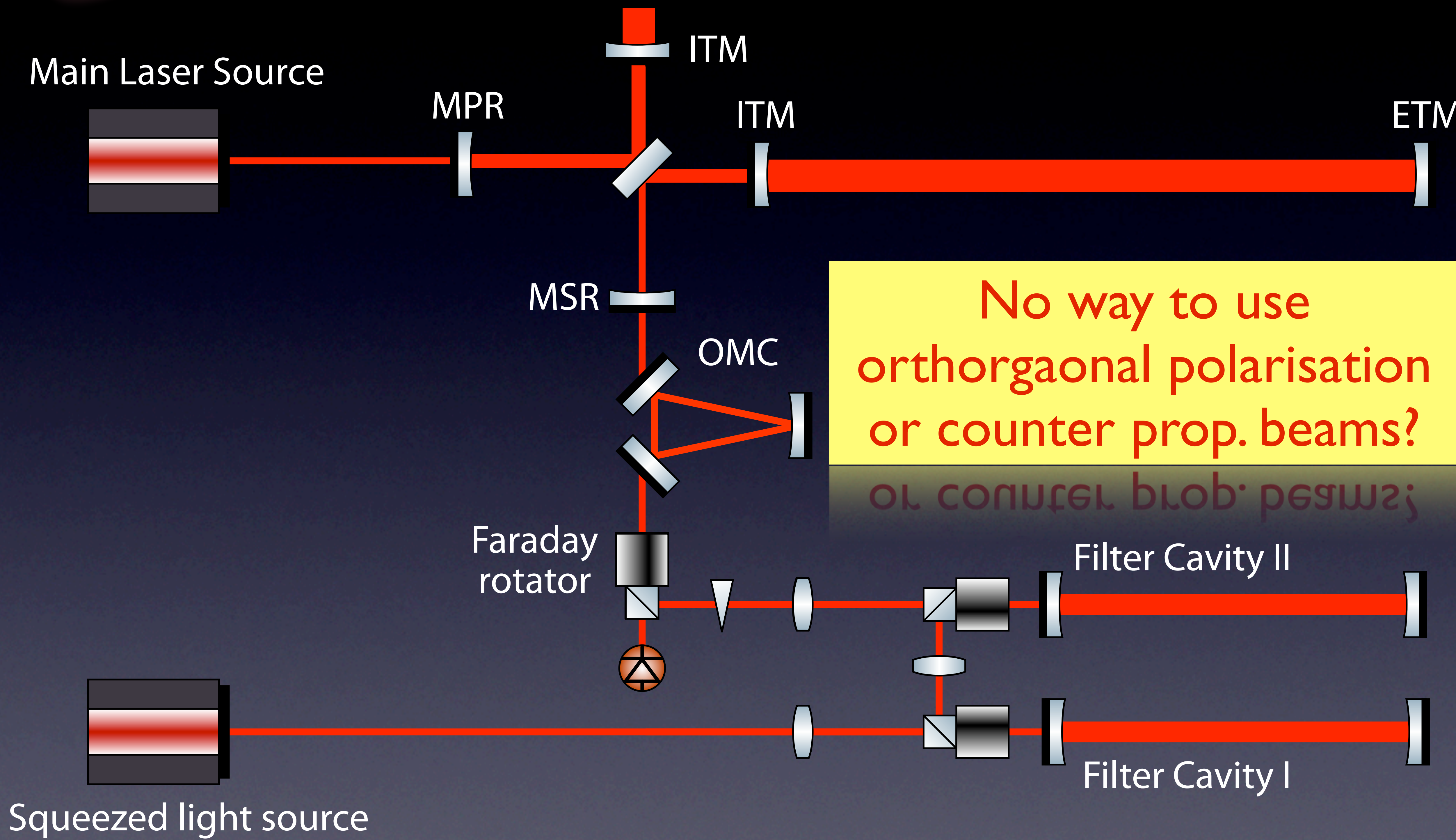
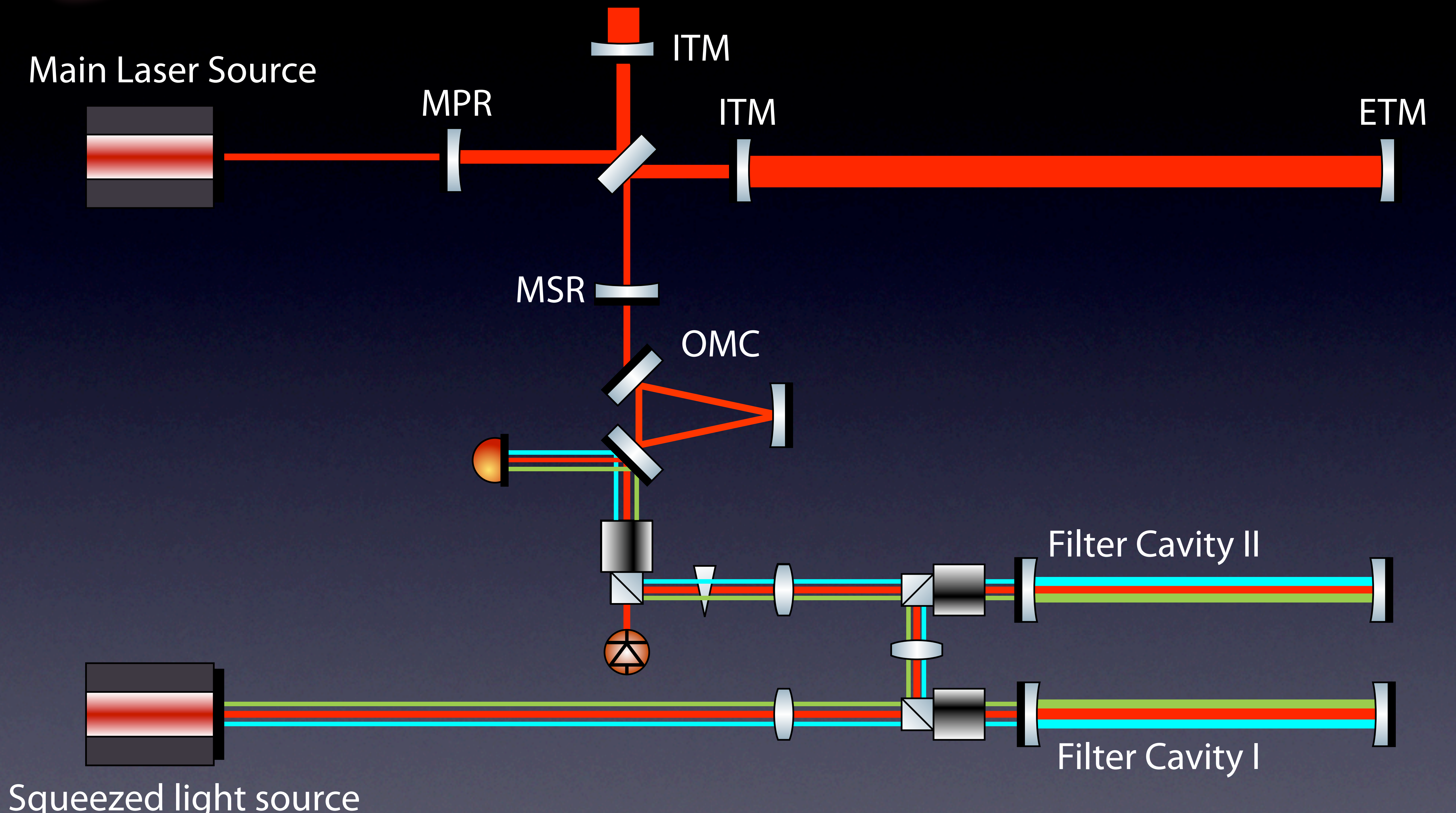


No way to use orthorgaonal polarisation or counter prop. beams?

Auxiliary fields from the squeezed light source



Future Work

Evaluate the displacement noise requirements for the FCs

Investigate the locking scheme in more detail

Especially for the angular degrees of freedom

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Evaluate the displacement noise requirements for the FCs

Investigate the locking scheme in more detail

Especially for the angular degrees of freedom

Think of a Filter Cavity with adjustable bandwidth, e.g. a Three-Mirror-Cavity:
That will relax the requirements for the coatings
Yields more flexibility
Means even more complex locking scheme