Potential quantum noise reduction schemes for KAGRA post-O5

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Michael Page, Zonghong Zhu

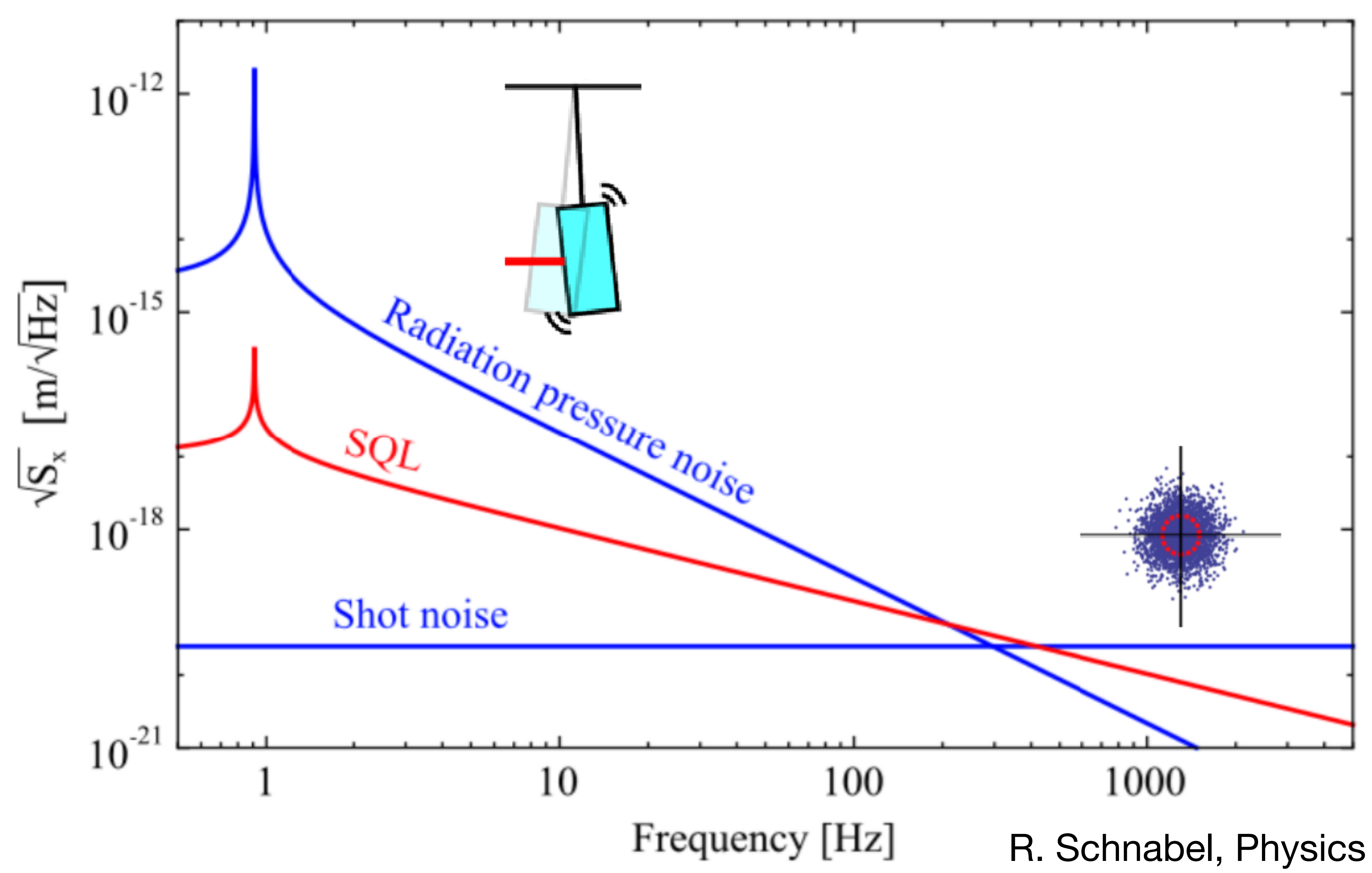
The 14th KAGRA international workshop, Perugia, 15th-16th May 2026

Content

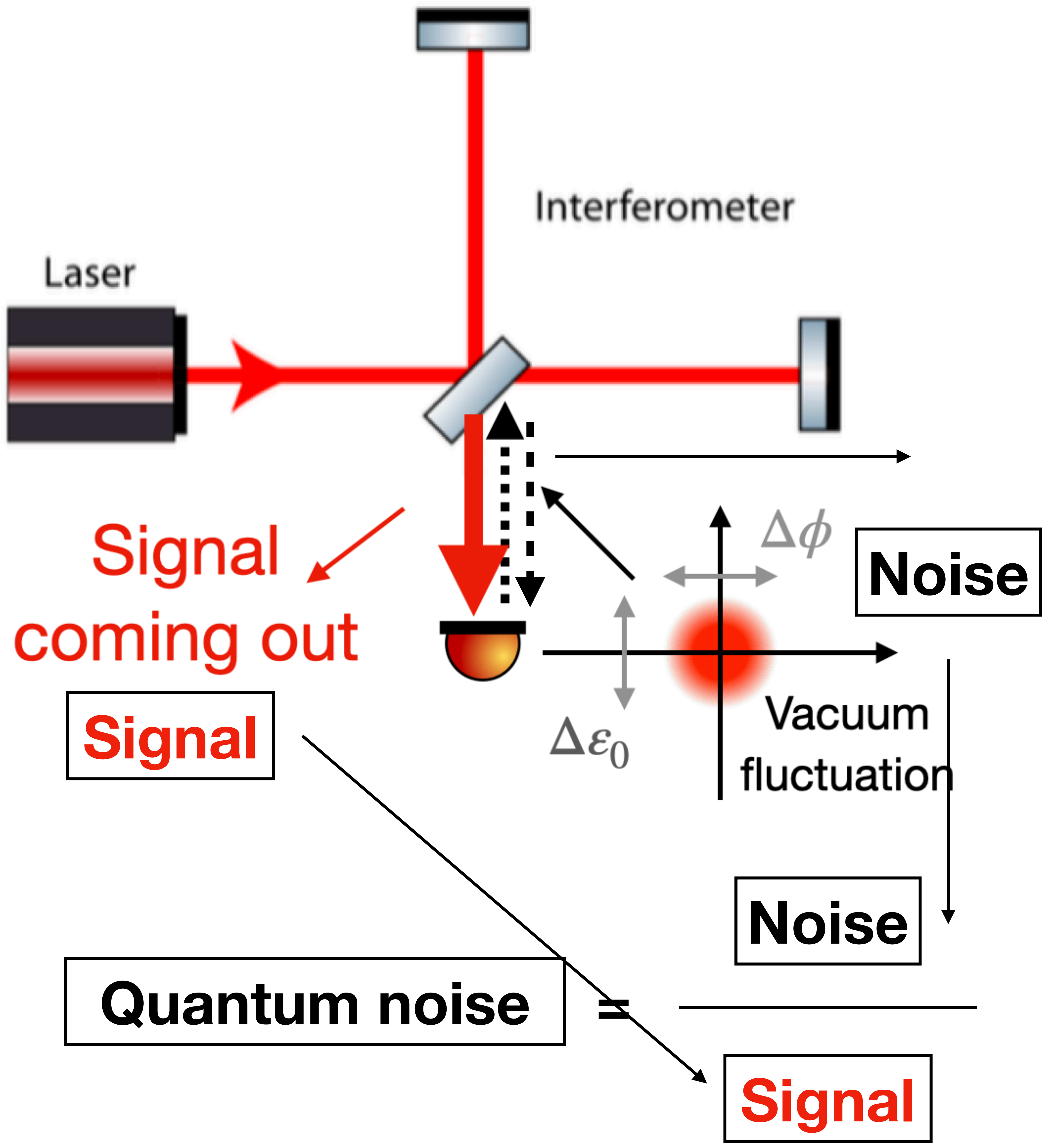
- Background of quantum noise reduction
- Various quantum noise reduction schemes
- Previous work and particular situation in KAGRA
- Comparison of different schemes
- Conclusion and next step

Quantum noise

- Quantum noise can be understood to be originated from the fluctuation of photon number
- Mathematically, quantum noise is due to the amplitude and phase operators don't commute and result in a minimum uncertainty



R. Schnabel, Physics Reports, 684(2017)

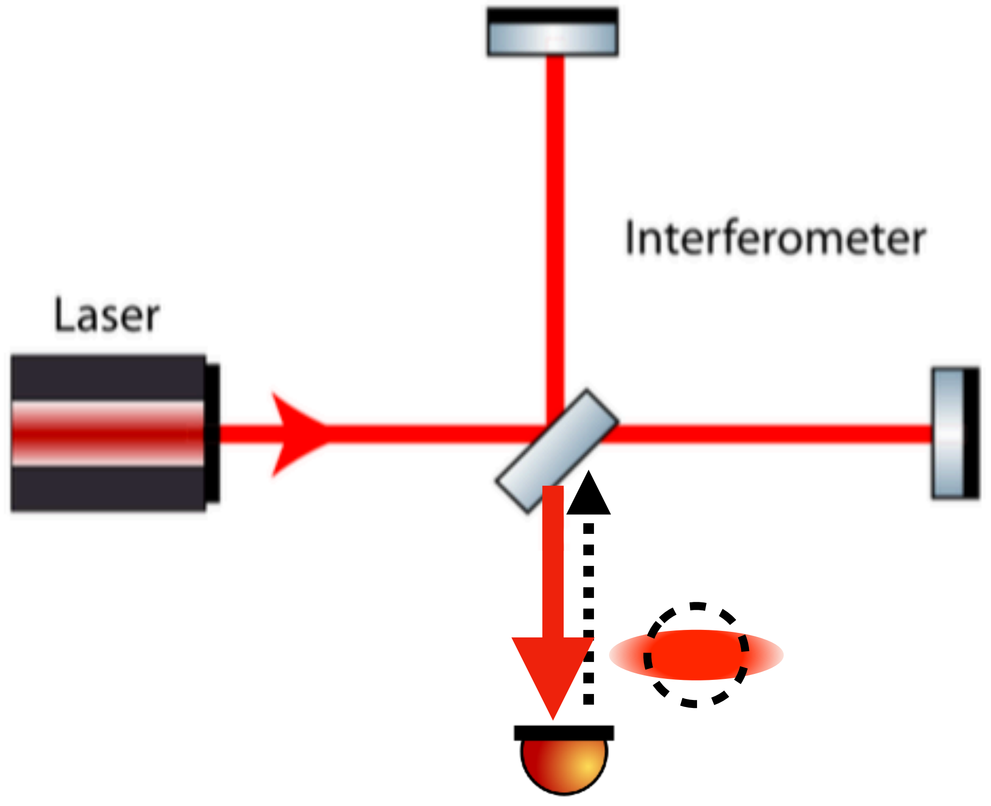


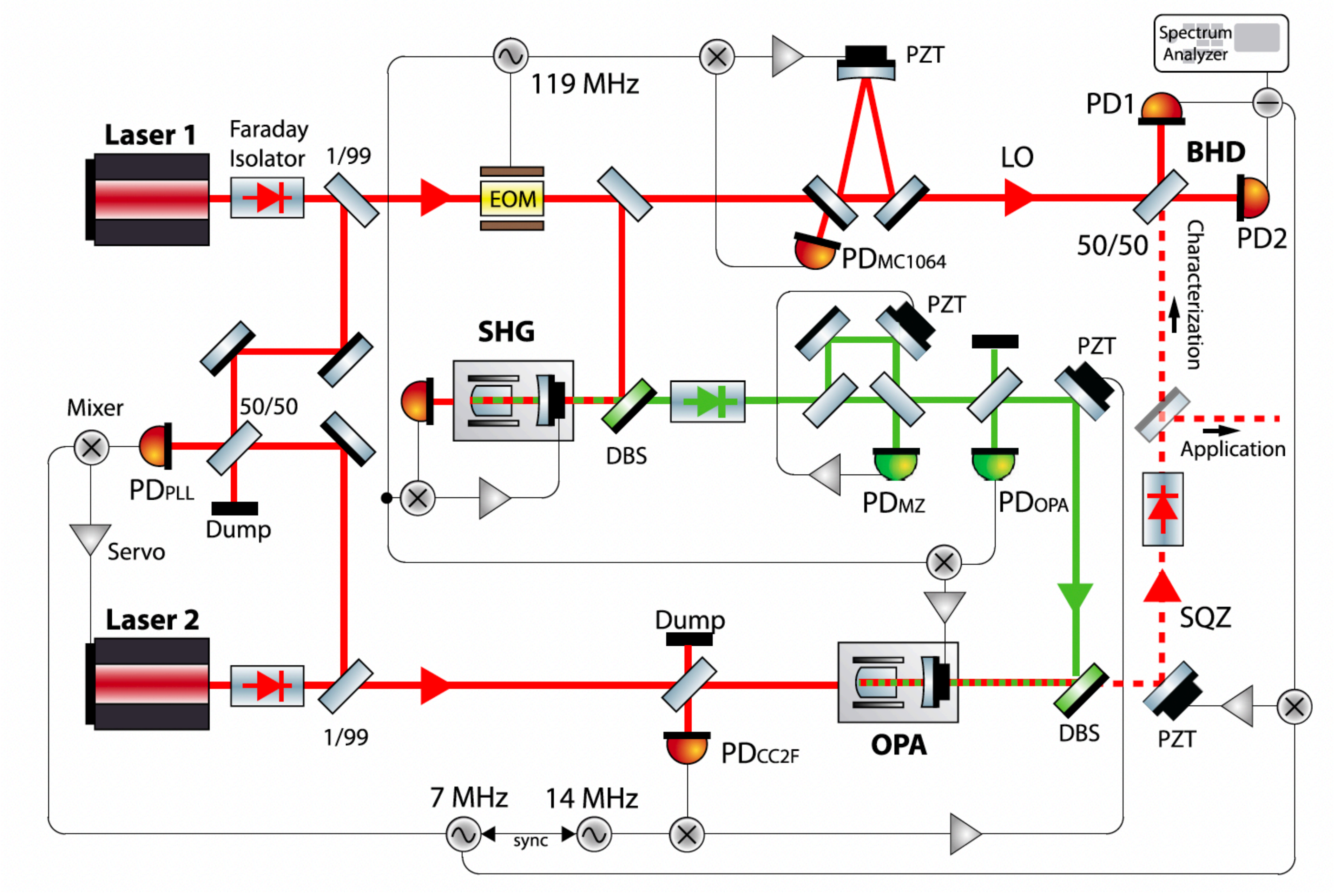
Signal coming out

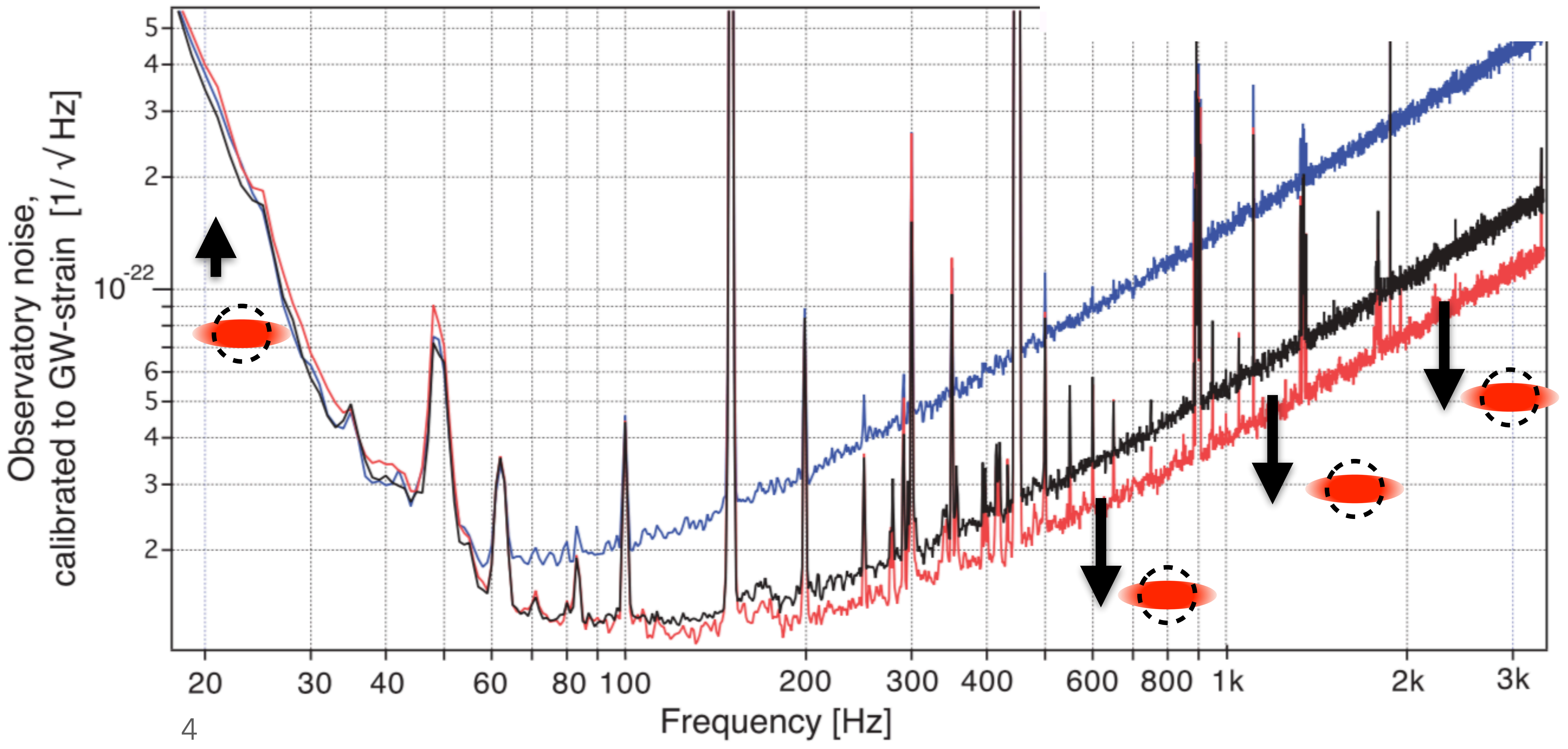
$$\boxed{\text{Quantum noise}} = \frac{\boxed{\text{Noise}}}{\boxed{\text{Signal}}}$$

Quantum noise reduction (FIS)

- The vacuum state could be manipulated to have either amplitude or phase quadratures fluctuation smaller or larger, called squeezed vacuum
- The generation of squeezed vacuum is typically **frequency-independent squeezing** (FIS)



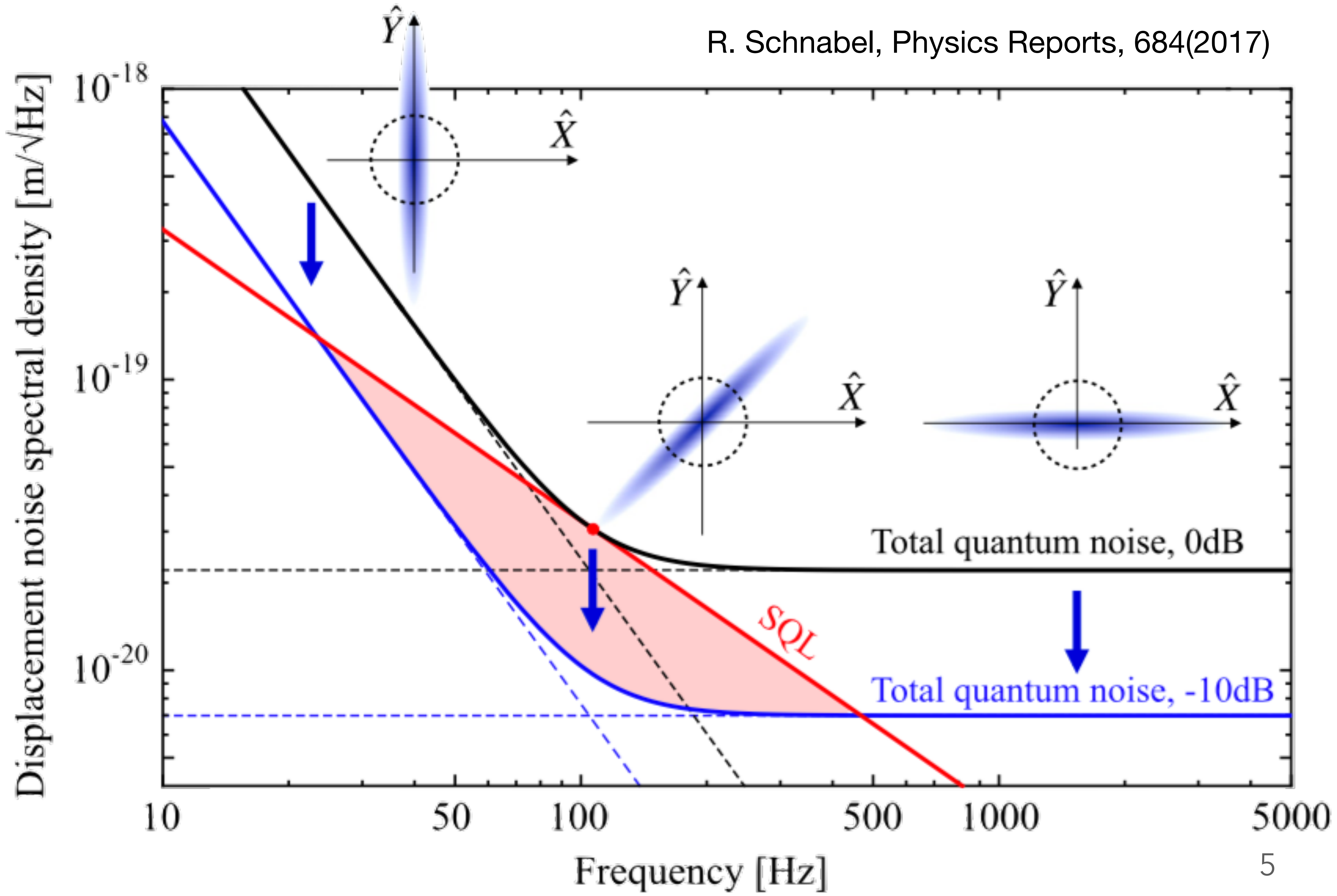




PRL 123,231108 (2019)

Quantum noise reduction (FDS)

- Since the dominating component of quantum noise is frequency dependent, a **frequency dependent squeezing** (FDS) could reduce quantum noise at all frequencies

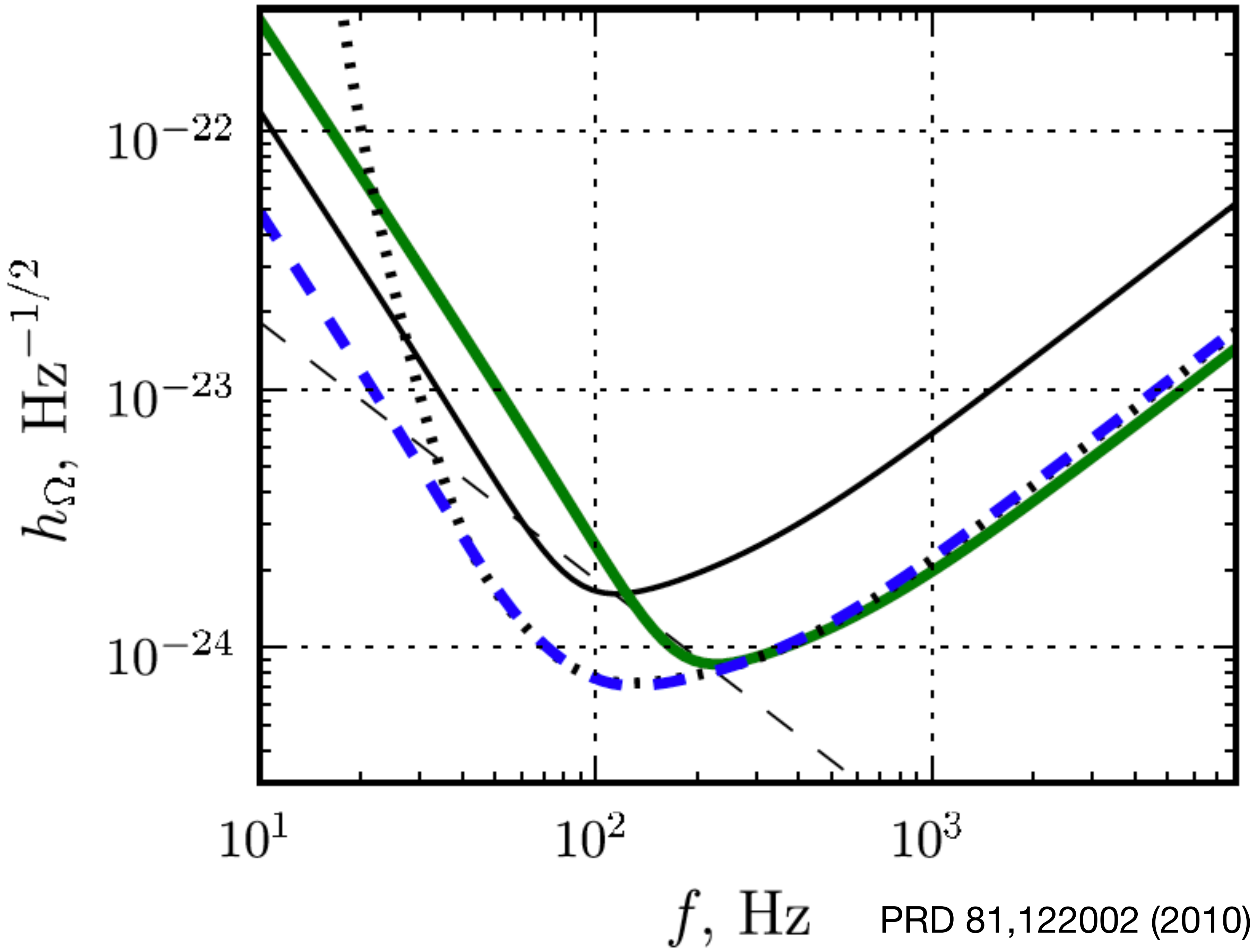


Several ways to achieve FDS

- Filter cavity
- Amplitude filter cavity
- Frequency dependent beam splitter
- EPR entanglement
- Quantum teleportation
- …

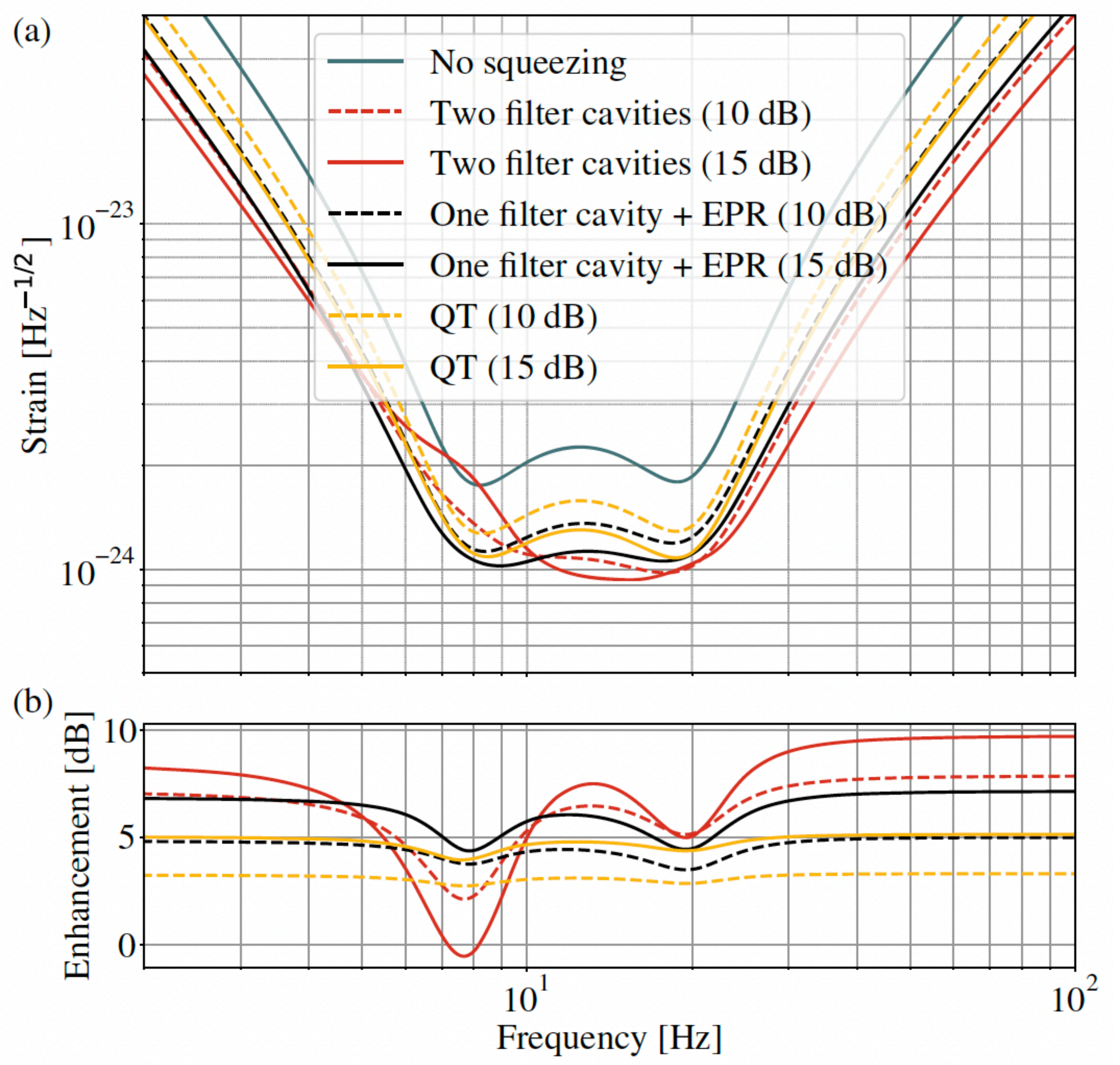
Previous work

- Different frequency dependent squeezing schemes have been compared in the past



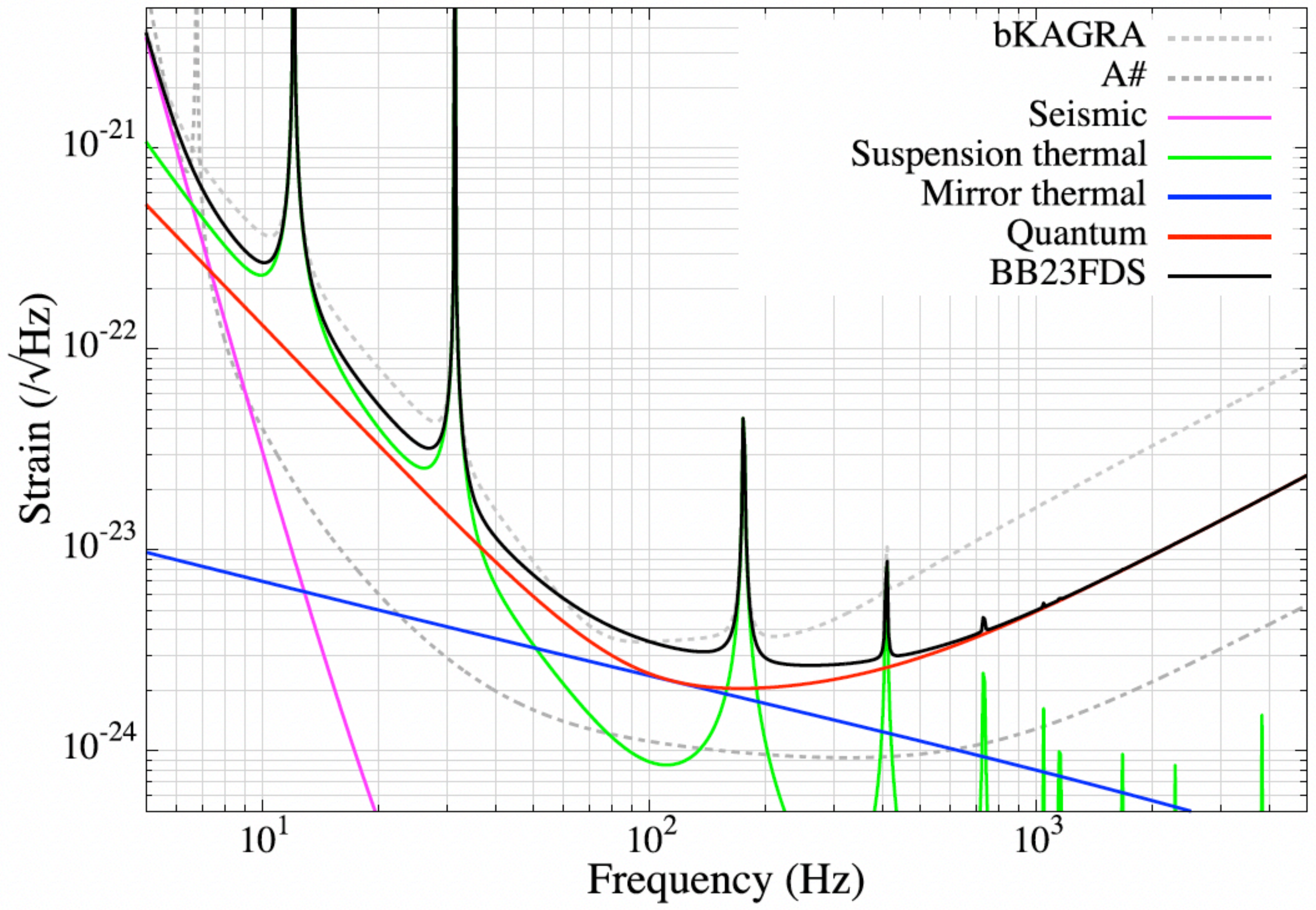
PRD 81,122002 (2010)

Thin dashed lines: SQL; thin solid lines: ordinary interferometer, vacuum input; thick solid lines: ordinary interferometer, frequency-independent squeezing; thick dashed lines: phase prefiltering; dotted line: phase post-filtering.



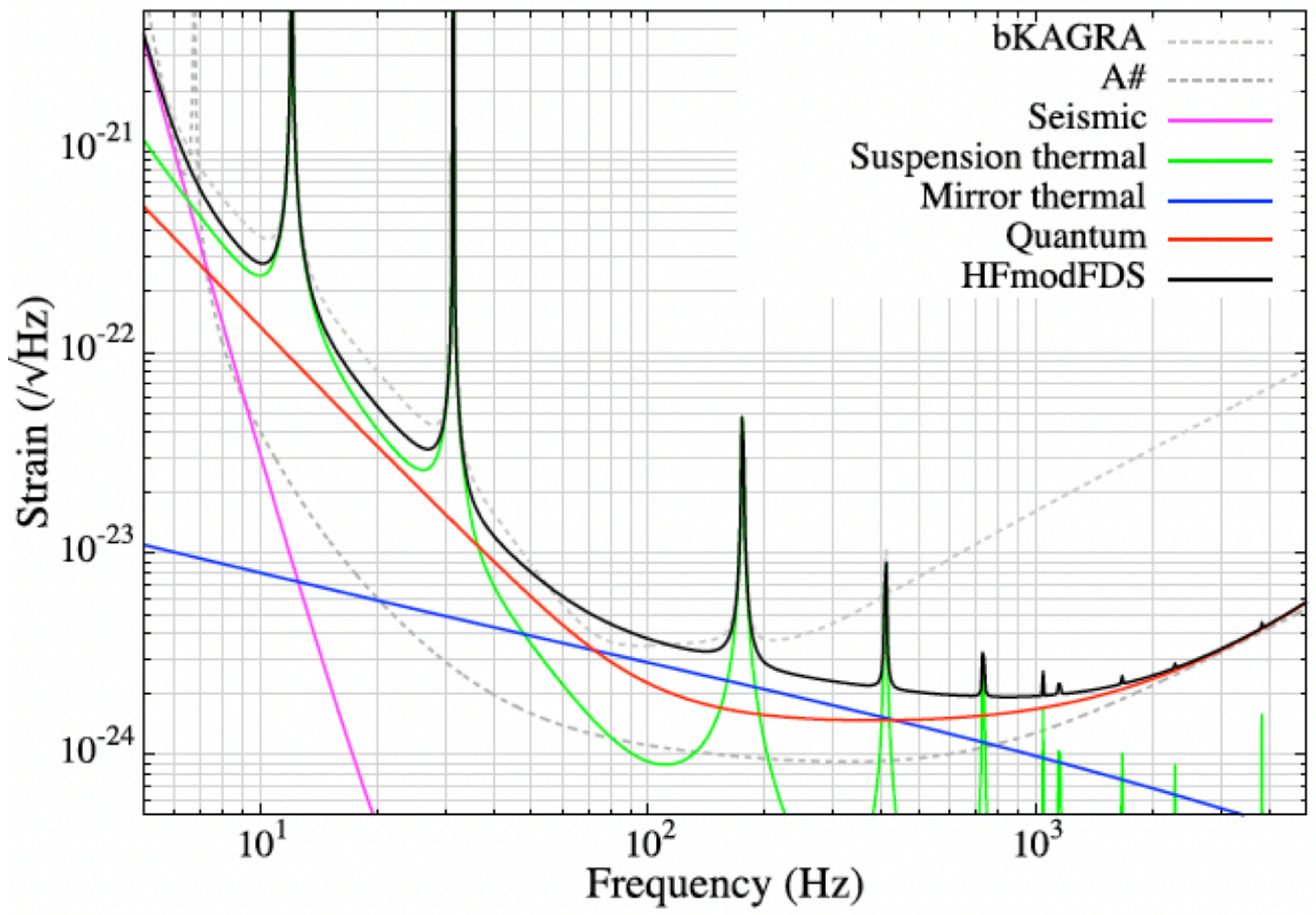
PRD 110,082006 (2024)

KAGRA post-O5



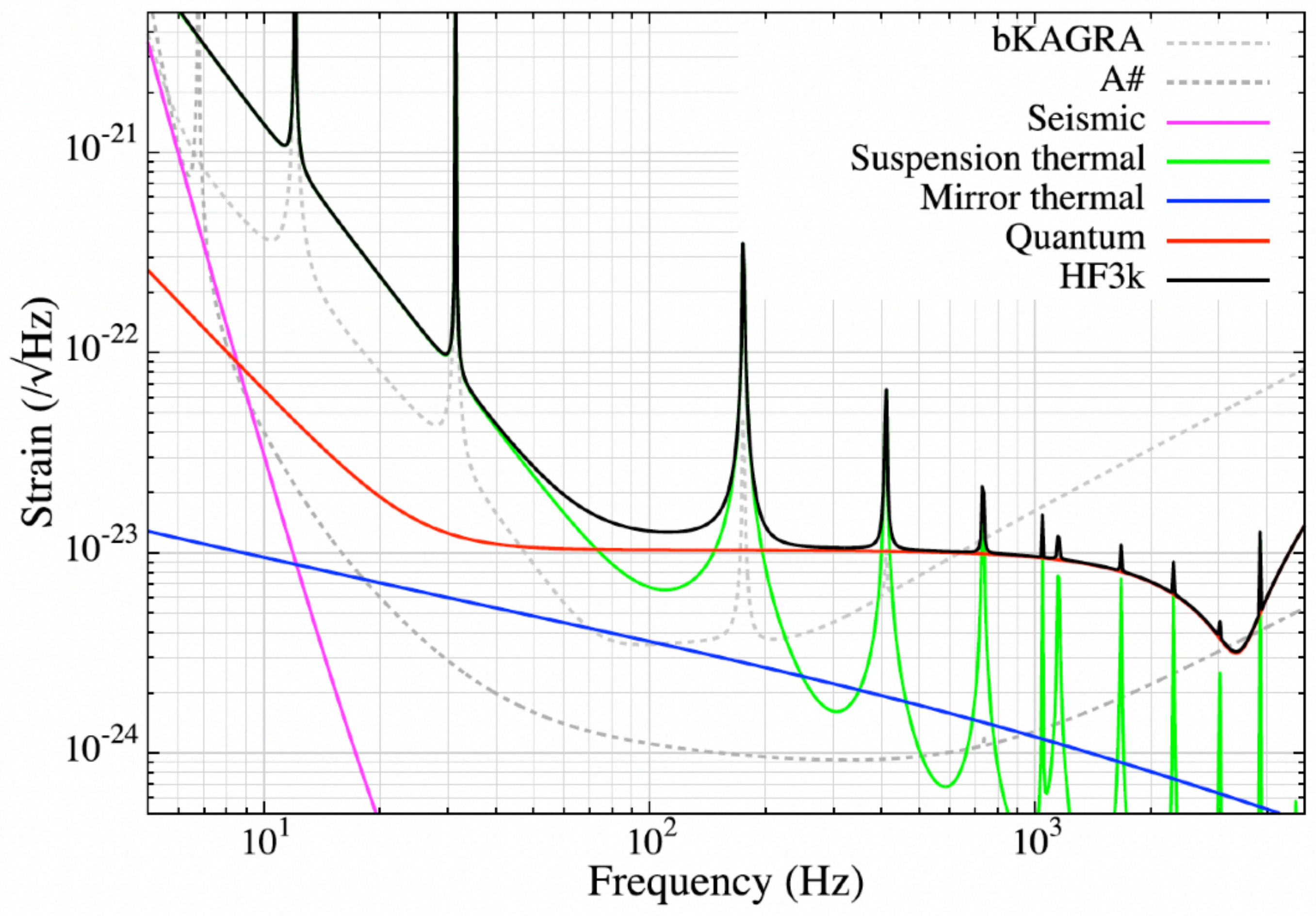
(a) BB23FDS-HQS

Quantum noise limits all frequencies



(b) HFmodFDS-HQS

Quantum noise limits low and high frequencies, thermal noise limits middle frequencies



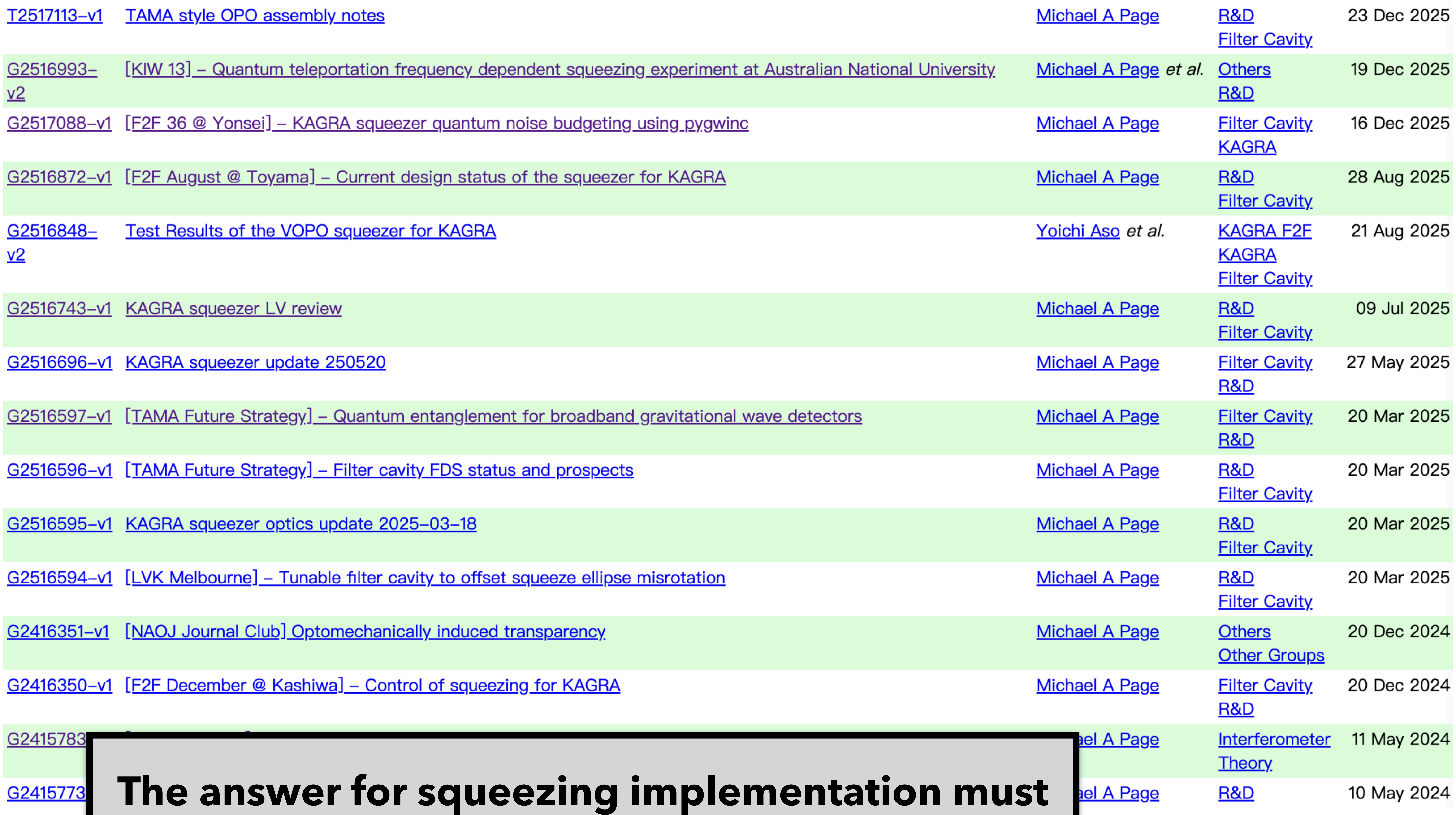
(a) HF3k

Quantum noise limits middle and high frequencies, thermal noise limits low frequencies

Therefore, it’s crucial to investigate the frequency dependent behaviours of squeezing scheme

Previous work within KAGRA

- M. Page has investigated many possibilities for squeezing implementation in KAGRA

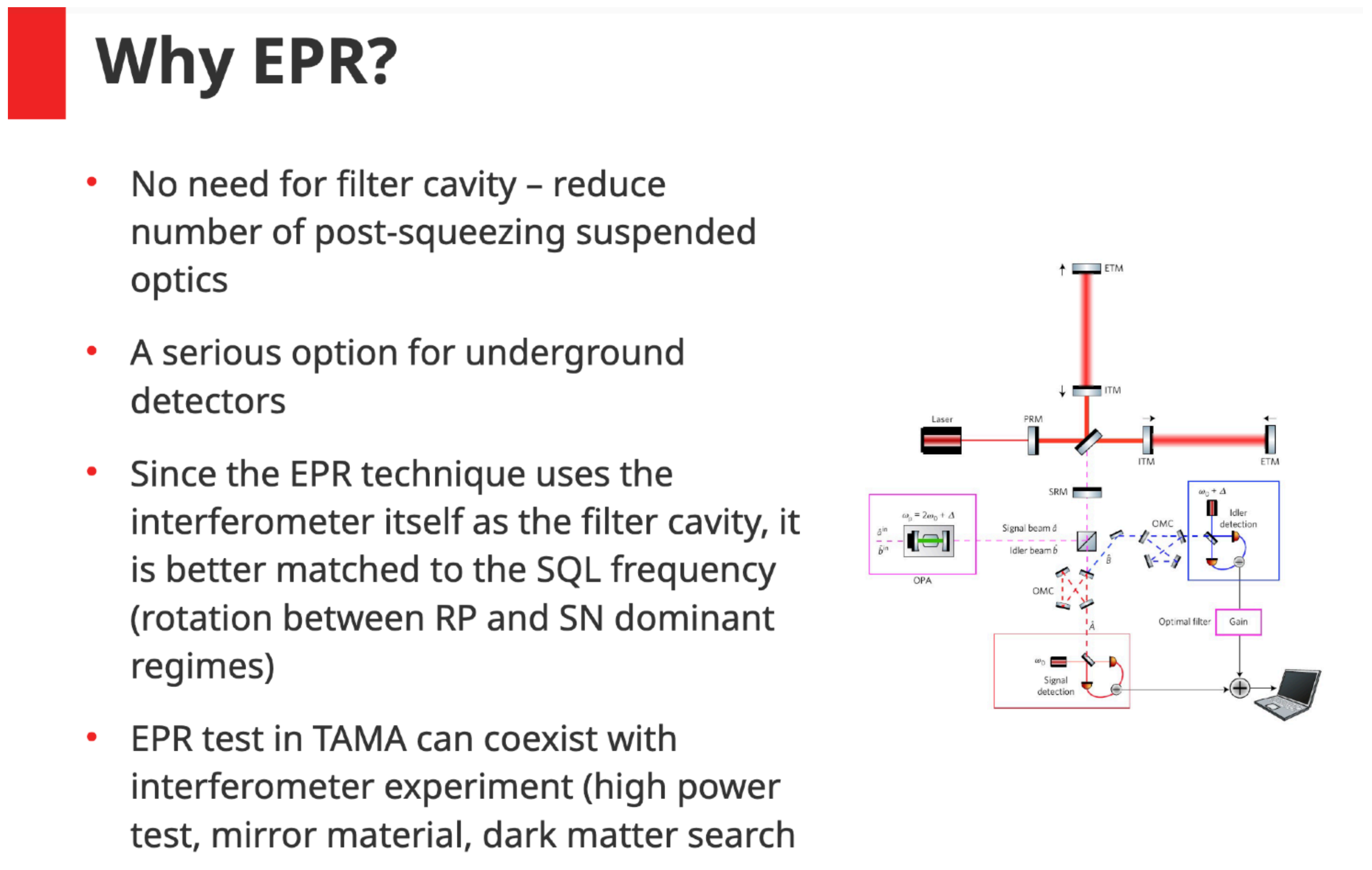


T2517113–v1	TAMA style OPO assembly notes	Michael A Page	R&D Filter Cavity	23 Dec 2025
G2516993–v2	[KIW 13] – Quantum teleportation frequency dependent squeezing experiment at Australian National University	Michael A Page *et al.*	Others R&D	19 Dec 2025
G2517088–v1	[F2F 36 @ Yonsei] – KAGRA squeezer quantum noise budgeting using pygwinc	Michael A Page	Filter Cavity KAGRA	16 Dec 2025
G2516872–v1	[F2F August @ Toyama] – Current design status of the squeezer for KAGRA	Michael A Page	R&D Filter Cavity	28 Aug 2025
G2516848–v2	Test Results of the VOPO squeezer for KAGRA	Yoichi Aso *et al.*	KAGRA F2F KAGRA Filter Cavity	21 Aug 2025
G2516743–v1	KAGRA squeezer LV review	Michael A Page	R&D Filter Cavity	09 Jul 2025
G2516696–v1	KAGRA squeezer update 250520	Michael A Page	Filter Cavity R&D	27 May 2025
G2516597–v1	[TAMA Future Strategy] – Quantum entanglement for broadband gravitational wave detectors	Michael A Page	Filter Cavity R&D	20 Mar 2025
G2516596–v1	[TAMA Future Strategy] – Filter cavity FDS status and prospects	Michael A Page	R&D Filter Cavity	20 Mar 2025
G2516595–v1	KAGRA squeezer optics update 2025–03–18	Michael A Page	R&D Filter Cavity	20 Mar 2025
G2516594–v1	[LVK Melbourne] – Tunable filter cavity to offset squeeze ellipse misrotation	Michael A Page	R&D Filter Cavity	20 Mar 2025
G2416351–v1	[NAOJ Journal Club] Optomechanically induced transparency	Michael A Page	Others Other Groups	20 Dec 2024
G2416350–v1	[F2F December @ Kashiwa] – Control of squeezing for KAGRA	Michael A Page	Filter Cavity R&D	20 Dec 2024
G2415783		el A Page	Interferometer Theory	11 May 2024
G2415773		el A Page	R&D	10 May 2024

The answer for squeezing implementation must be within the comparison of different squeezing schemes

Filter cavity

- 85 m allowed by space in Kamioka mine



Why EPR?

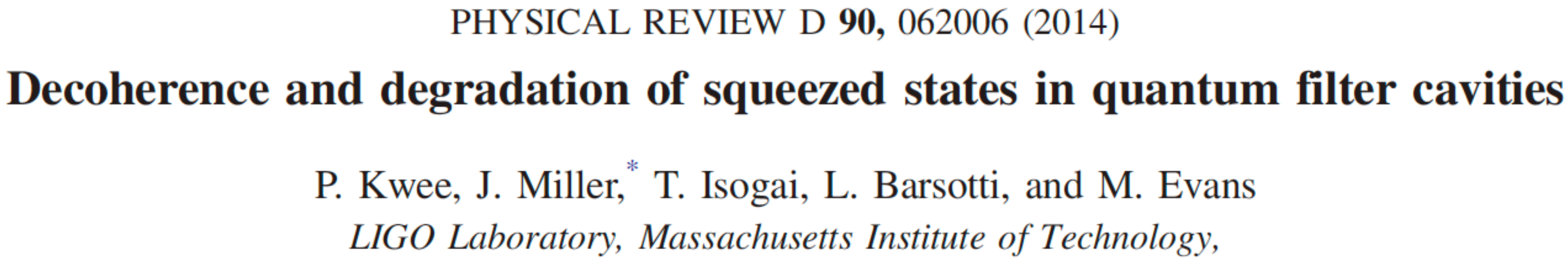
- No need for filter cavity – reduce number of post-squeezing suspended optics
- A serious option for underground detectors
- Since the EPR technique uses the interferometer itself as the filter cavity, it is better matched to the SQL frequency (rotation between RP and SN dominant regimes)
- EPR test in TAMA can coexist with interferometer experiment (high power test, mirror material, dark matter search

Theoretical framework

- The two-photon formalism is used throughout this work, from following papers:

Mathematical framework for simulation of quantum fields in complex interferometers using the two-photon formalism

Thomas Corbitt[1], Yanbei Chen[2,3], and Nergis Mavalvala[1]   Phys. Rev. A **72**, 013818 – **Published 22 July, 2005**

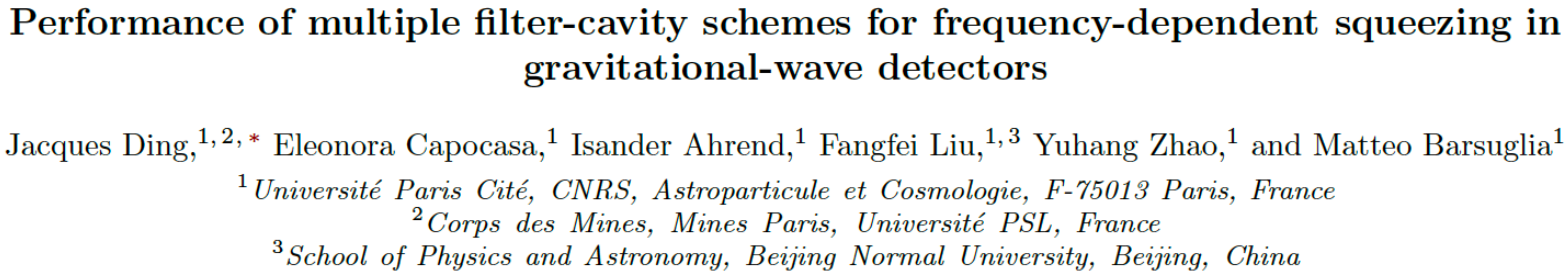


PHYSICAL REVIEW D **90,** 062006 (2014)

Decoherence and degradation of squeezed states in quantum filter cavities

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

LIGO Laboratory, Massachusetts Institute of Technology,



Performance of multiple filter-cavity schemes for frequency-dependent squeezing in gravitational-wave detectors

Jacques Ding,[1,2,*] Eleonora Capocasa,[1] Isander Ahrend,[1] Fangfei Liu,[1,3] Yuhang Zhao,[1] and Matteo Barsuglia[1]

[1] *Université Paris Cité, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France*

[2] *Corps des Mines, Mines Paris, Université PSL, France*

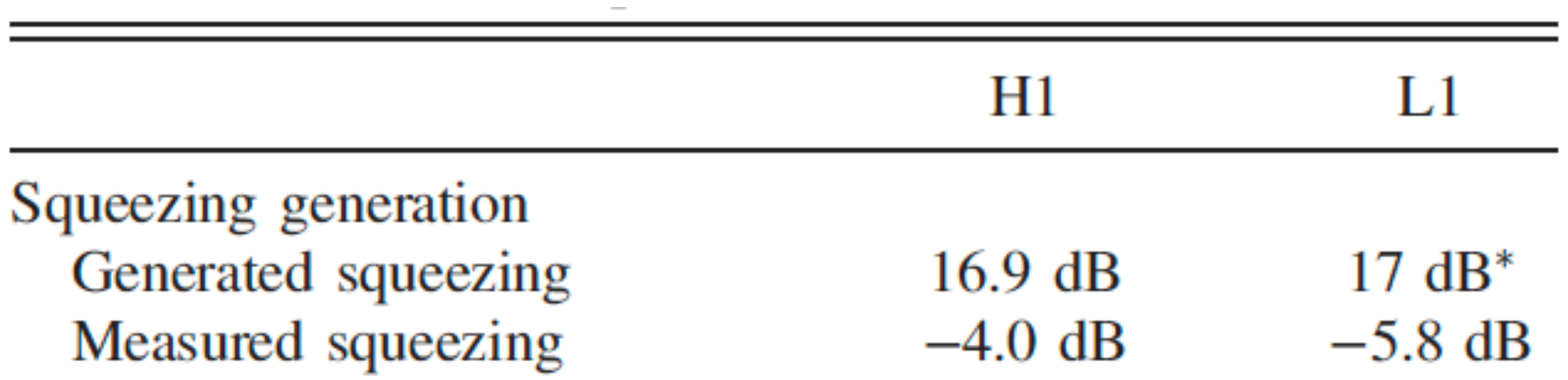
[3] *School of Physics and Astronomy, Beijing Normal University, Beijing, China*

We need quantitative comparisons for deciding which scheme to use for KAGRA

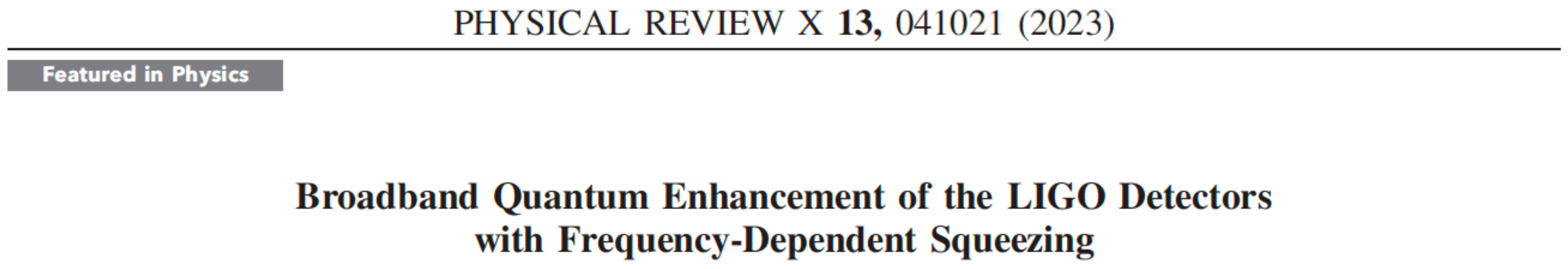
One-mode squeezing source

- This work assumed **15dB** squeezing is injected to the interferometer

Squeezing injection in LIGO O4



	H1	L1
Squeezing generation		
Generated squeezing	16.9 dB	17 dB*
Measured squeezing	−4.0 dB	−5.8 dB

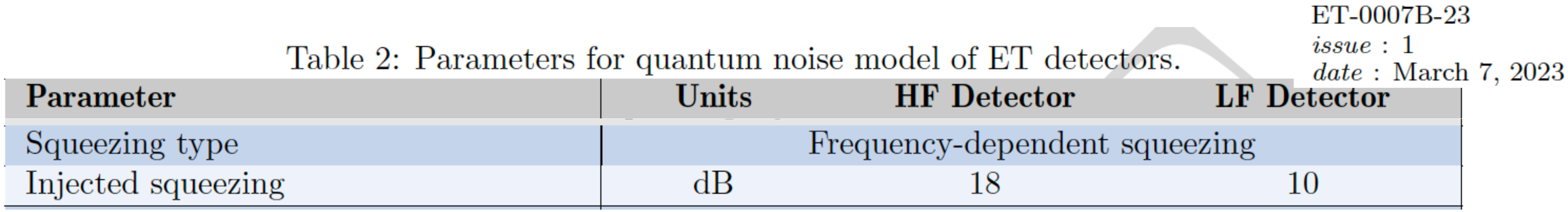


PHYSICAL REVIEW X **13,** 041021 (2023)

Featured in Physics

Broadband Quantum Enhancement of the LIGO Detectors with Frequency-Dependent Squeezing

Squeezing injection plan in ET



ET-0007B-23
issue : 1
date : March 7, 2023

Table 2: Parameters for quantum noise model of ET detectors.

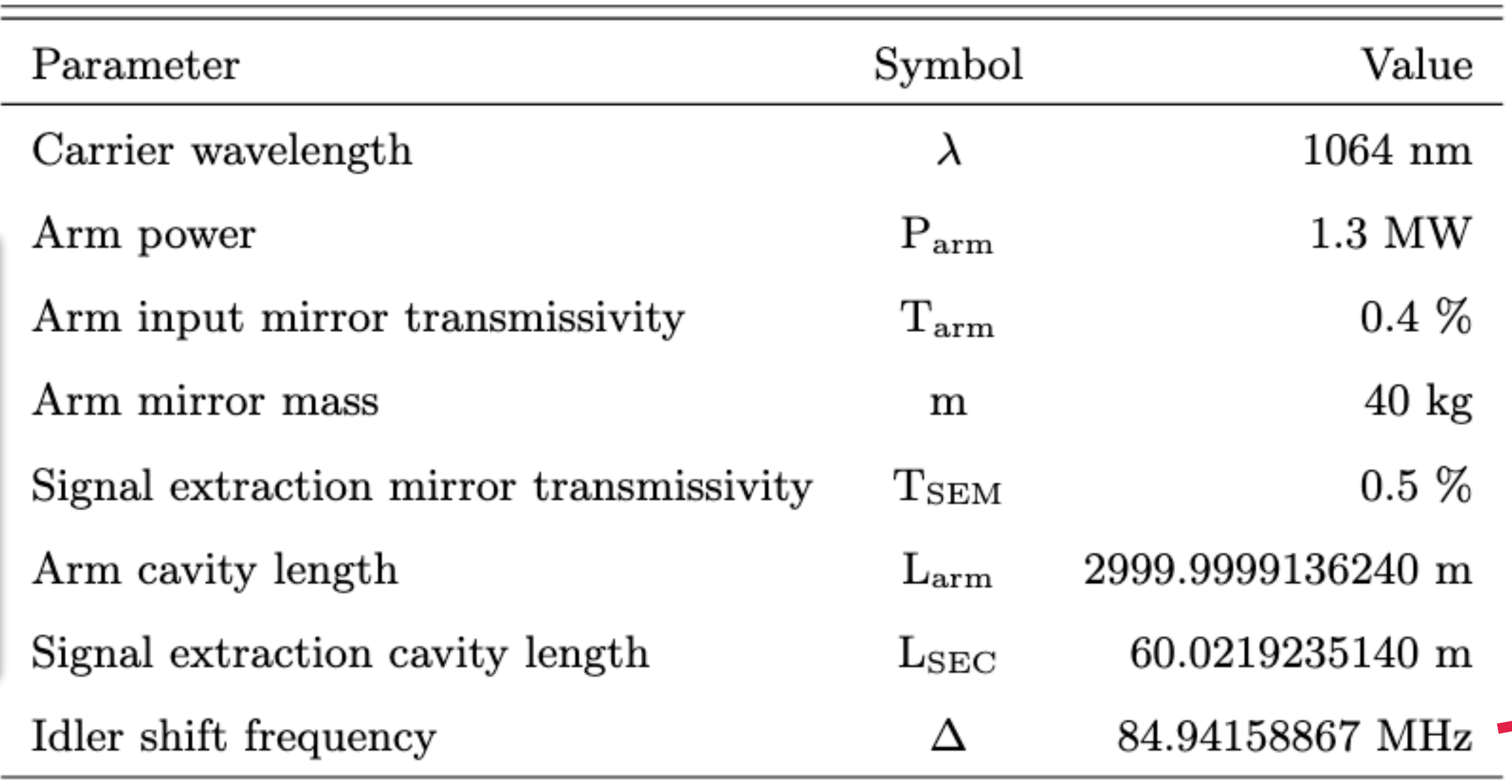
Parameter	**Units**	**HF Detector**	**LF Detector**
Squeezing type	Frequency-dependent squeezing		
Injected squeezing	dB	18	10

Two-mode squeezing source

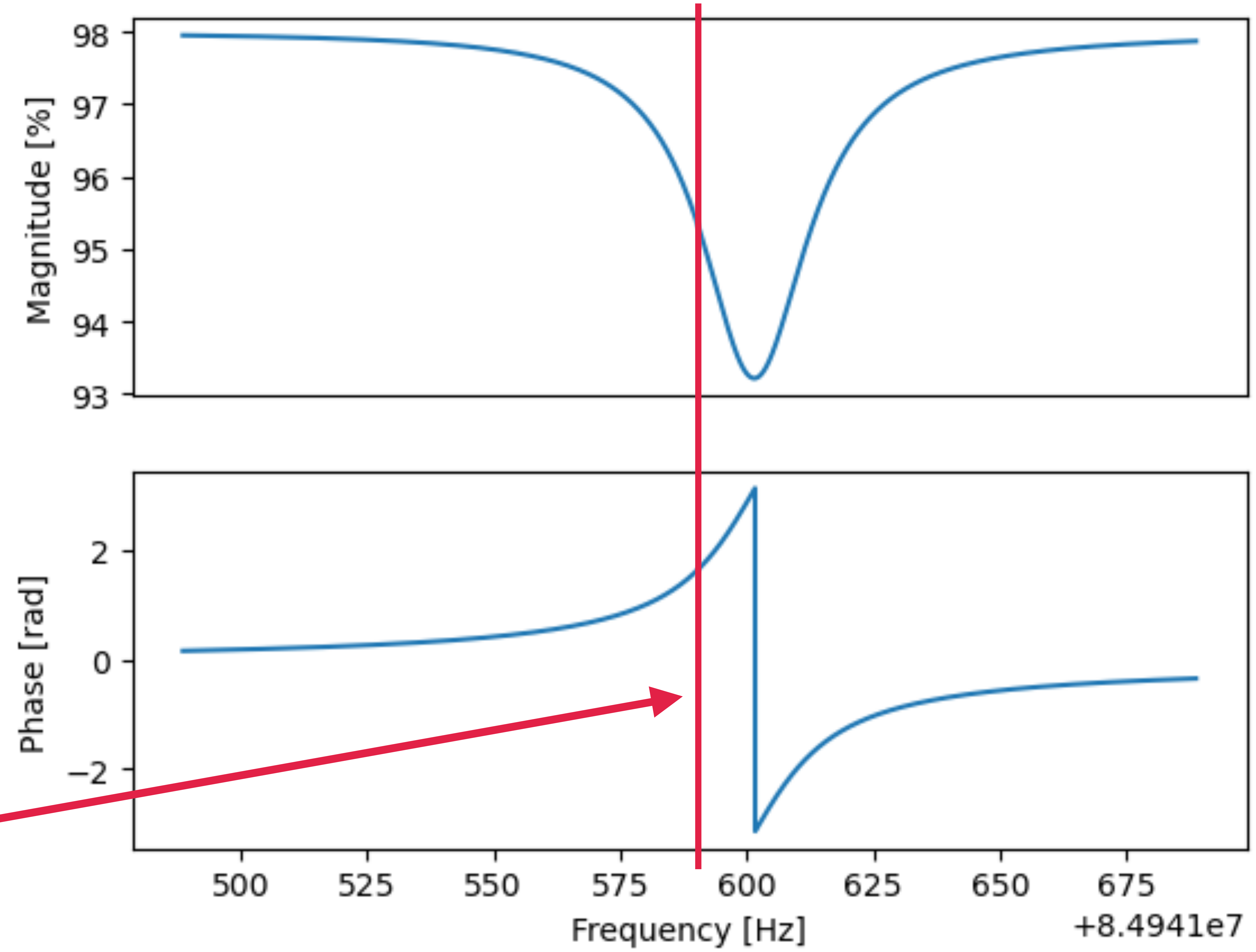
- Compared with one-mode squeezing source, additional hardware:
  - AOM to shift pump frequency
  - Precise control of SRC and arm length
  - An etalon to separate signal and idler
  - An additional homodyne

With parameters in the table, we could realize a coupled-cavity with desirable bandwidth and detuning

These parameters maybe adjusted



Parameter	Symbol	Value
Carrier wavelength	λ	1064 nm
Arm power	P_{arm}	1.3 MW
Arm input mirror transmissivity	T_{arm}	0.4 %
Arm mirror mass	m	40 kg
Signal extraction mirror transmissivity	T_{SEM}	0.5 %
Arm cavity length	L_{arm}	2999.9999136240 m
Signal extraction cavity length	L_{SEC}	60.0219235140 m
Idler shift frequency	Δ	84.94158867 MHz



One-mode squeezing + filter cavity

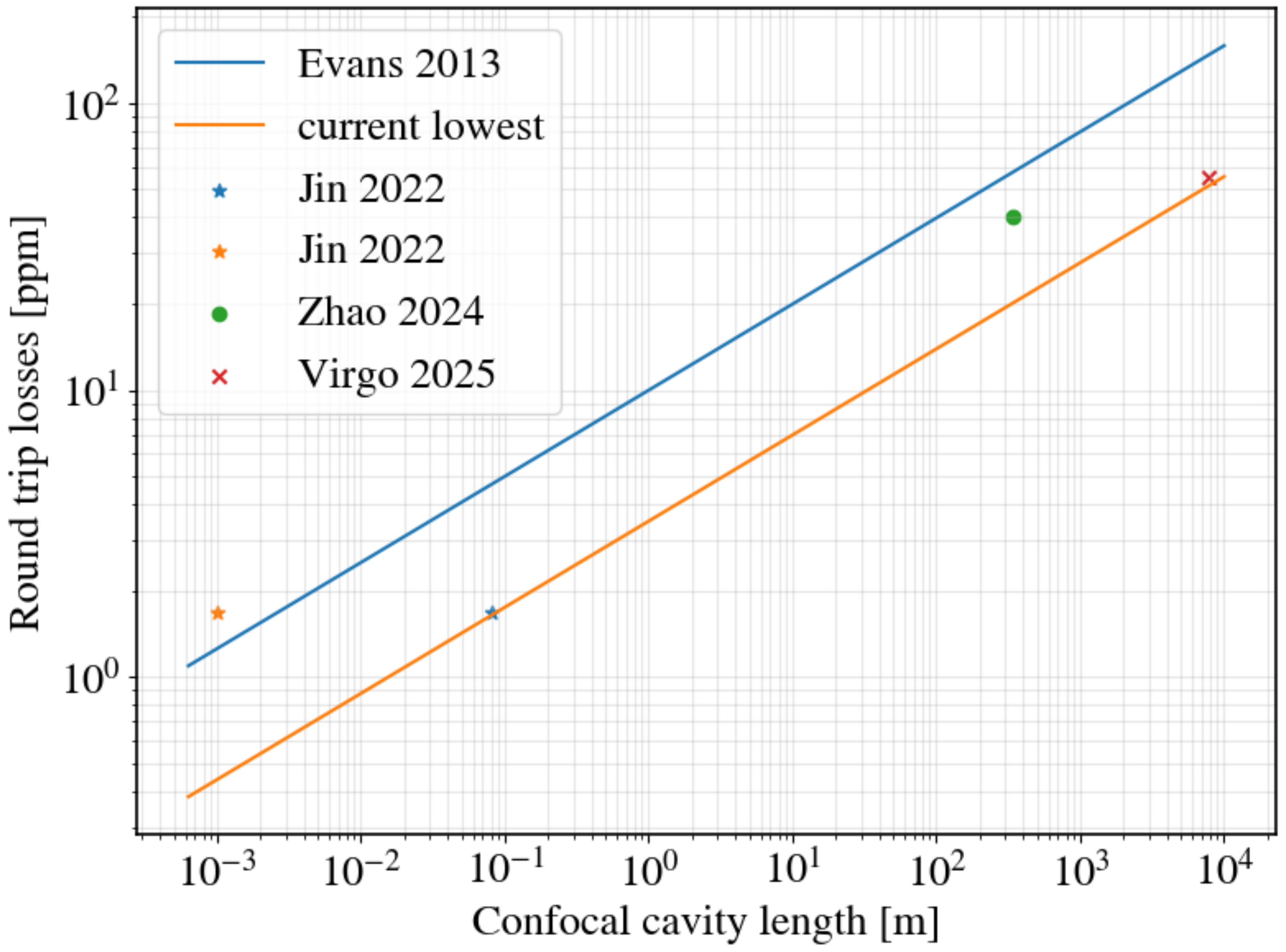
- As mentioned before, there is a potential limitation of filter cavity length of 85 m

Decay rate of cavity caused by optical losses can be expressed as:

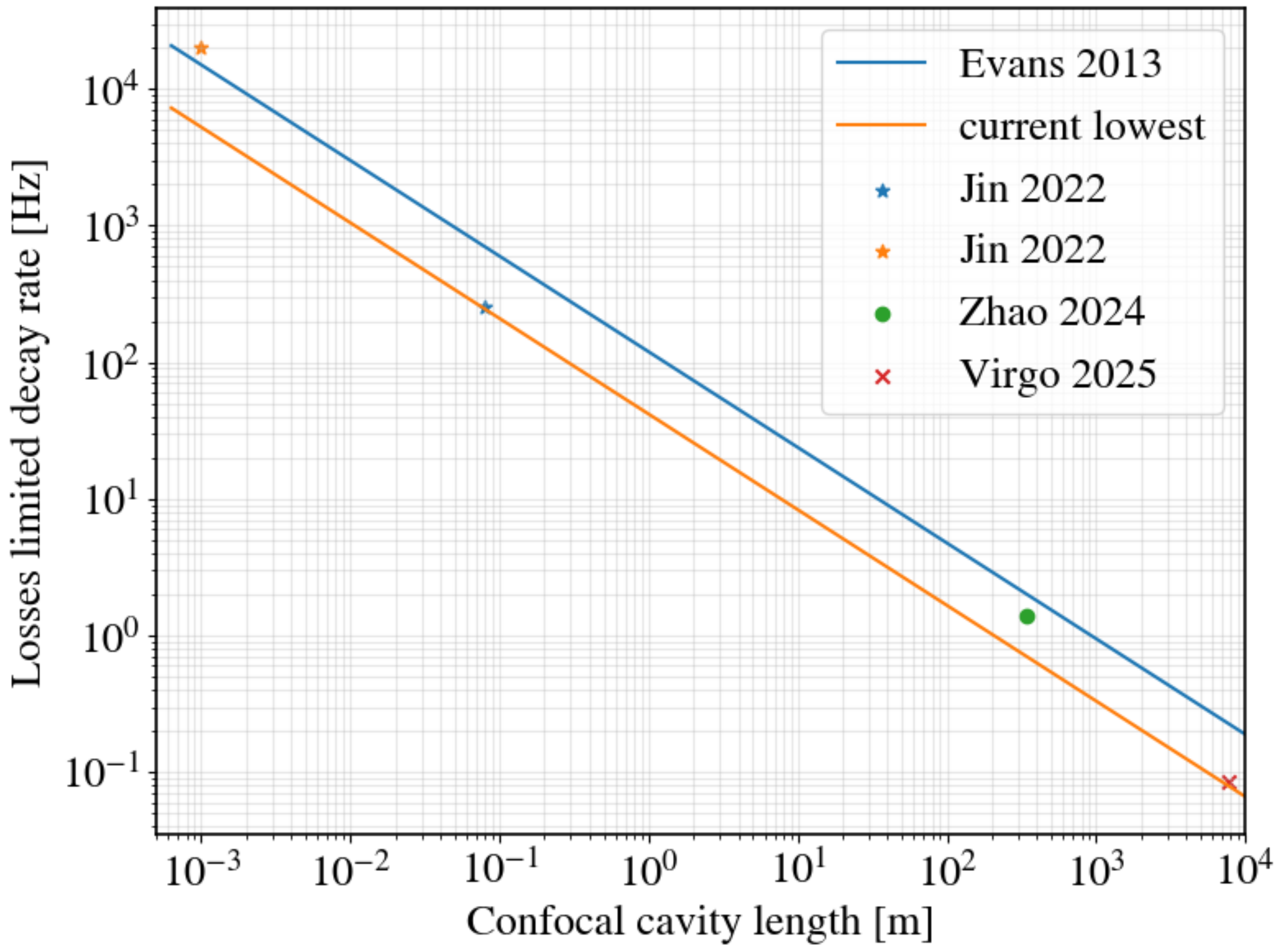
$$\gamma_{loss} = \frac{RTL}{2\tau} = \frac{c \times RTL}{2L}$$

Filter cavity length is important since it determines decay rate

An empirical power law for optical losses



Losses limited decay rate



One-mode squeezing + filter cavity

- What is the optimal filter cavity for KAGRA post-O5?

$$\gamma_{fc} = \sqrt{\frac{2}{(2-\epsilon)\sqrt{1-\epsilon}}}\frac{\Omega_{SQL}}{\sqrt{2}},$$

$$\delta_{fc} = \sqrt{1-\epsilon}\gamma_{fc},$$

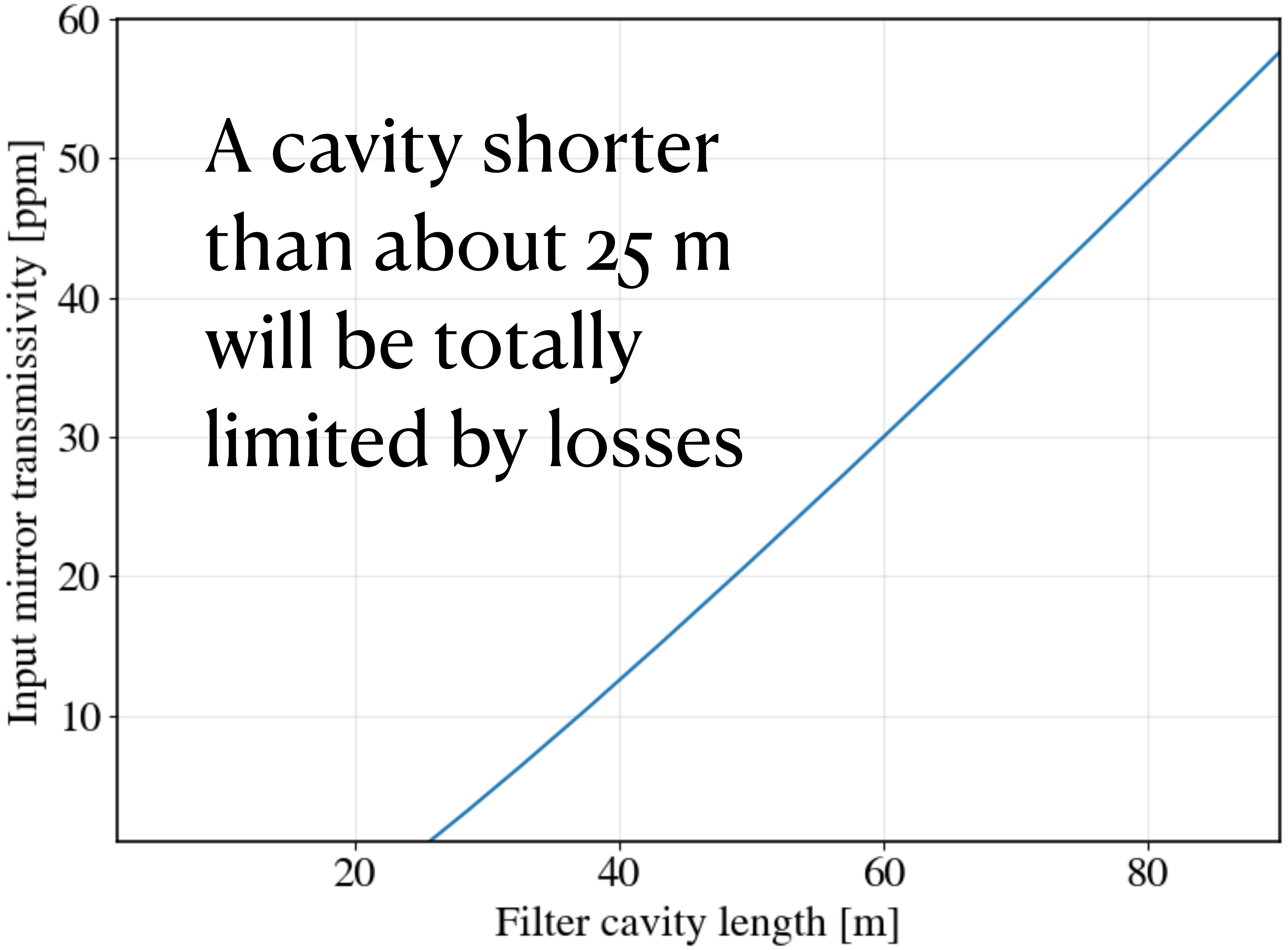
PRD 90,062006 (2014)

Assuming negligible optical losses, the optimal filter cavity bandwidth and detuning are:
12.75 Hz

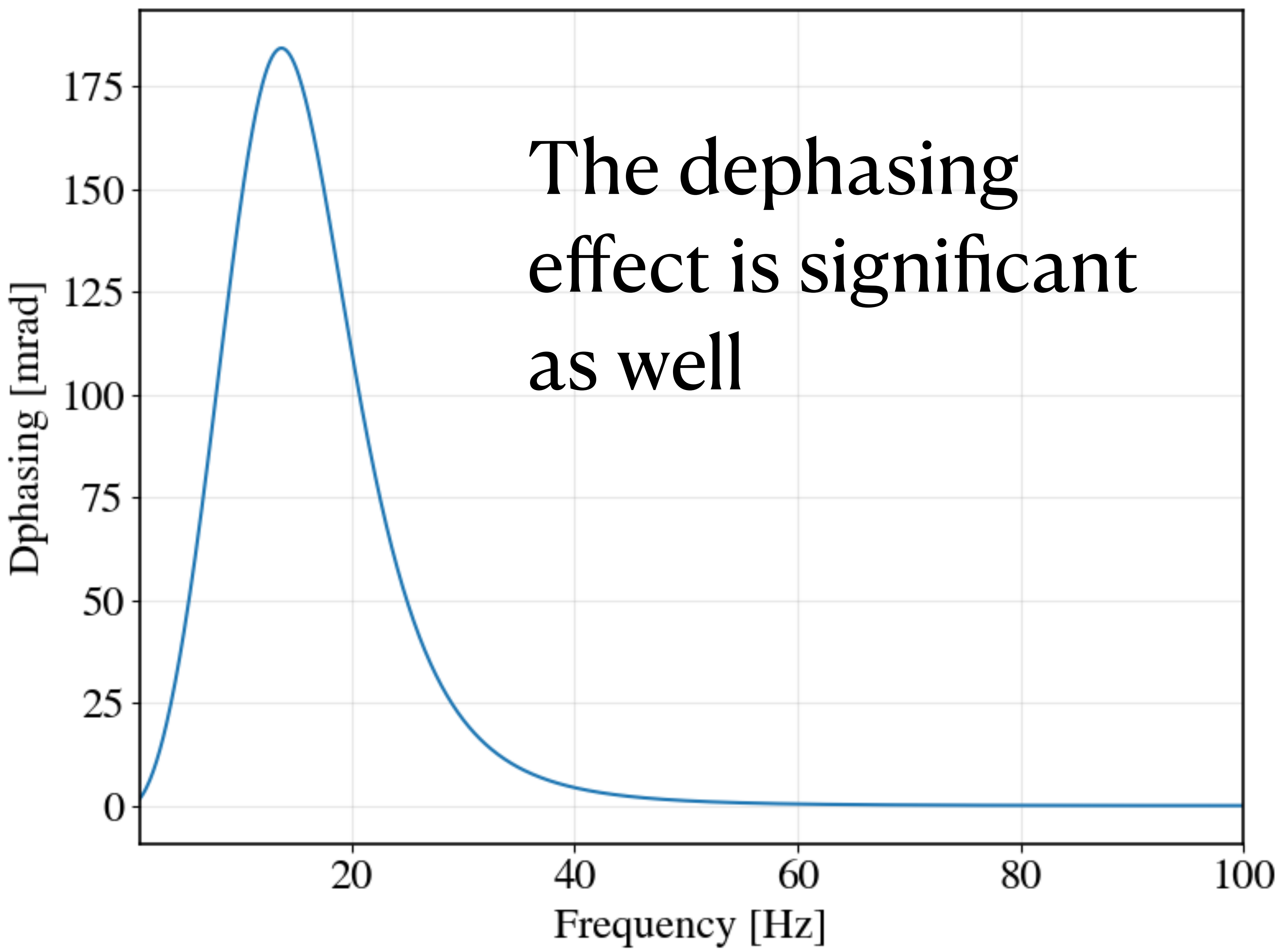
The same filter cavity parameters are also used for EPR coupled cavity as well

One-mode squeezing + filter cavity

- Short filter cavity could introduce problems as following



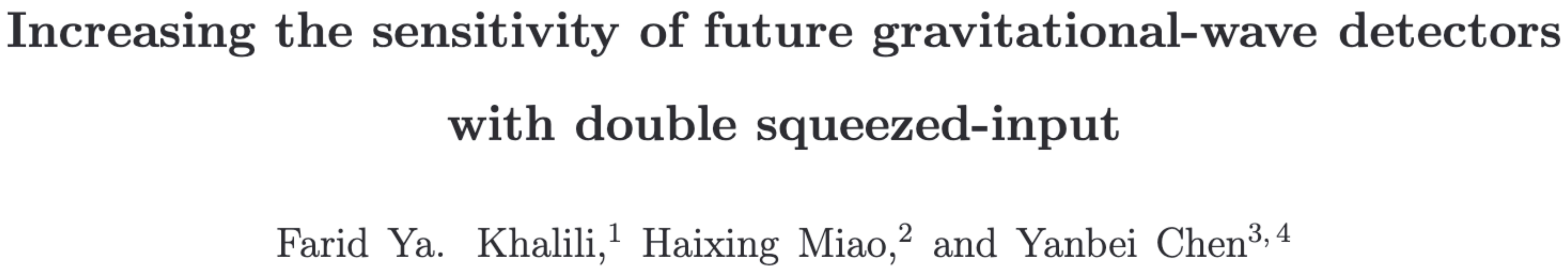
A cavity shorter than about 25 m will be totally limited by losses



The dephasing effect is significant as well

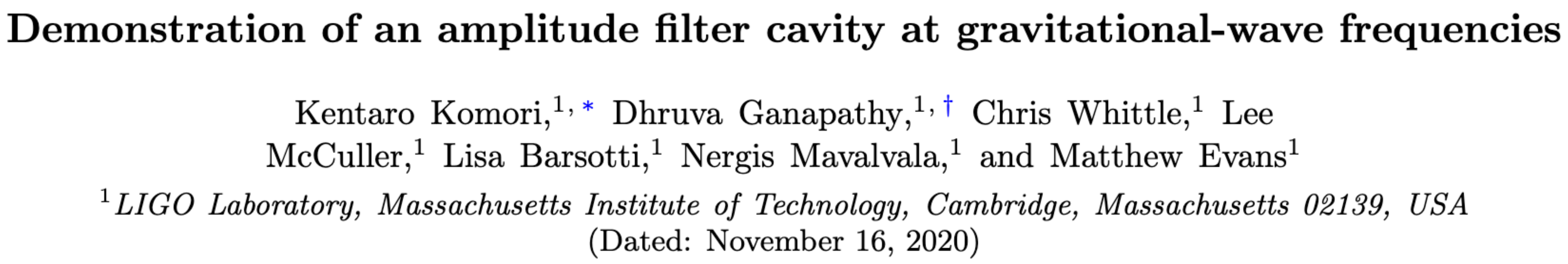
One-mode squeezing + filter cavity

- There are two schemes that detuning can be removed (no dephasing effect)



Increasing the sensitivity of future gravitational-wave detectors with double squeezed-input

Farid Ya. Khalili,[1] Haixing Miao,[2] and Yanbei Chen[3,4]

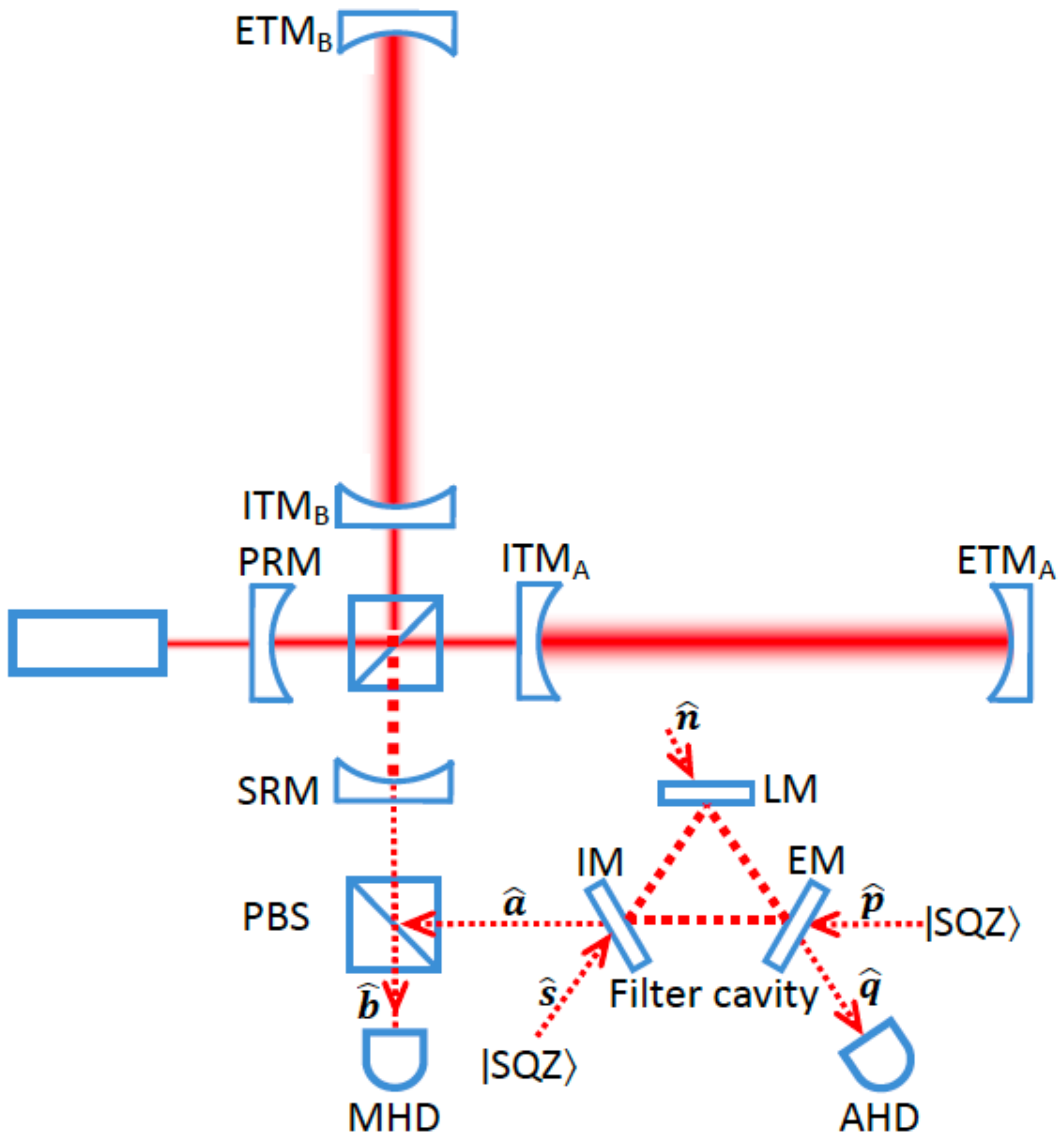


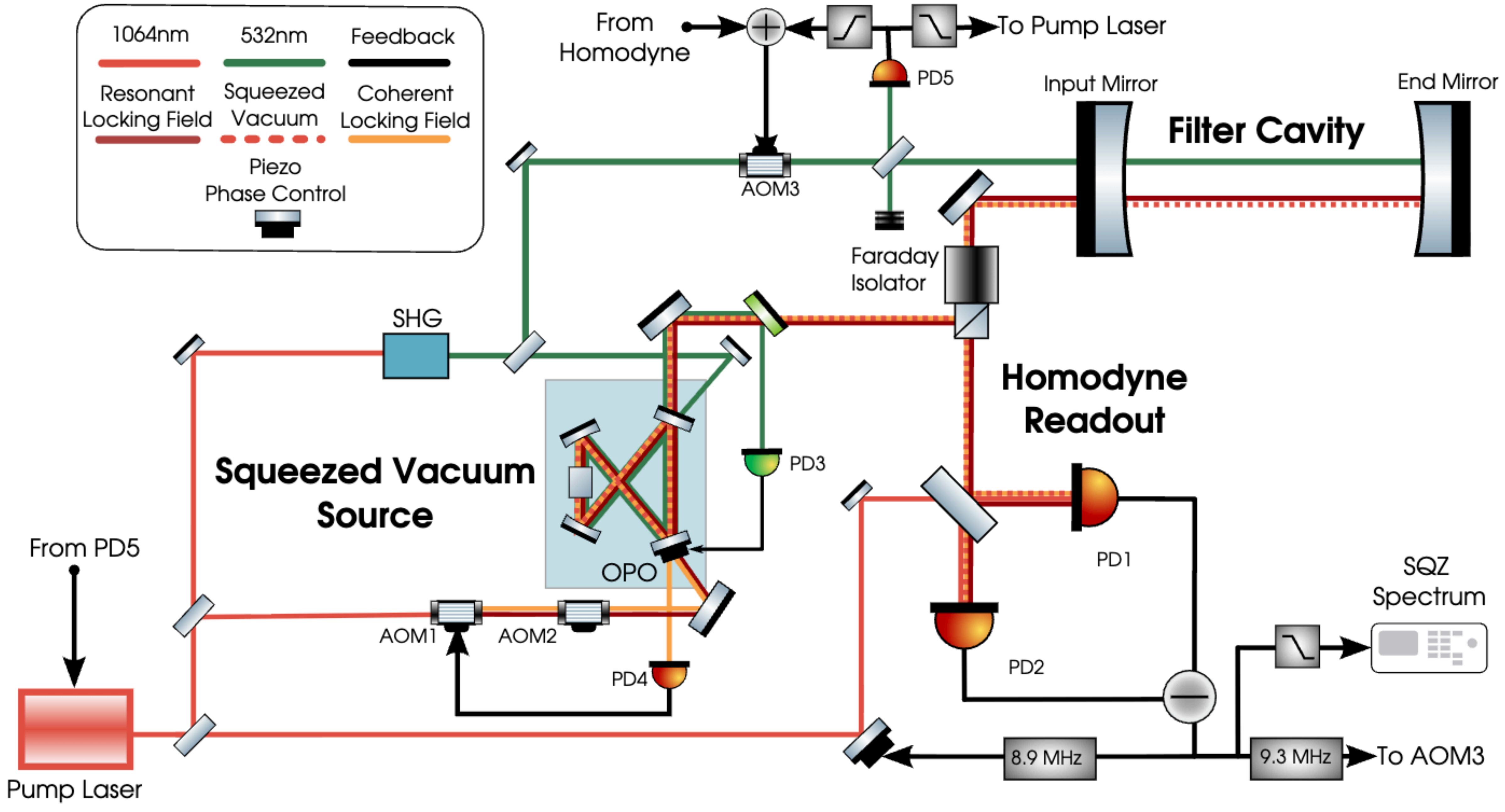
Demonstration of an amplitude filter cavity at gravitational-wave frequencies

Kentaro Komori,[1,*] Dhruva Ganapathy,[1,†] Chris Whittle,[1] Lee McCuller,[1] Lisa Barsotti,[1] Nergis Mavalvala,[1] and Matthew Evans[1]

[1] *LIGO Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

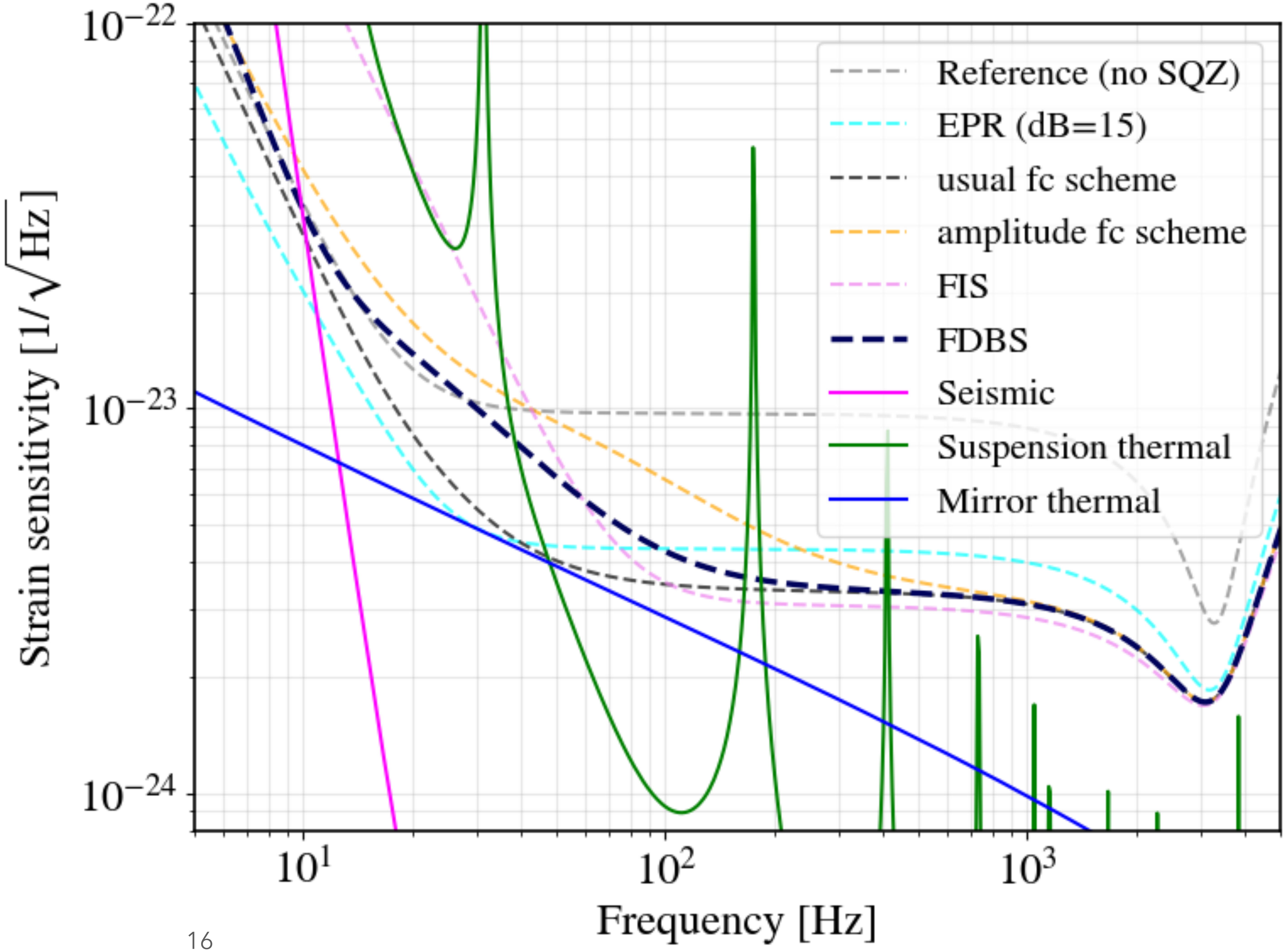
(Dated: November 16, 2020)





Different schemes comparison in the case of KAGRA

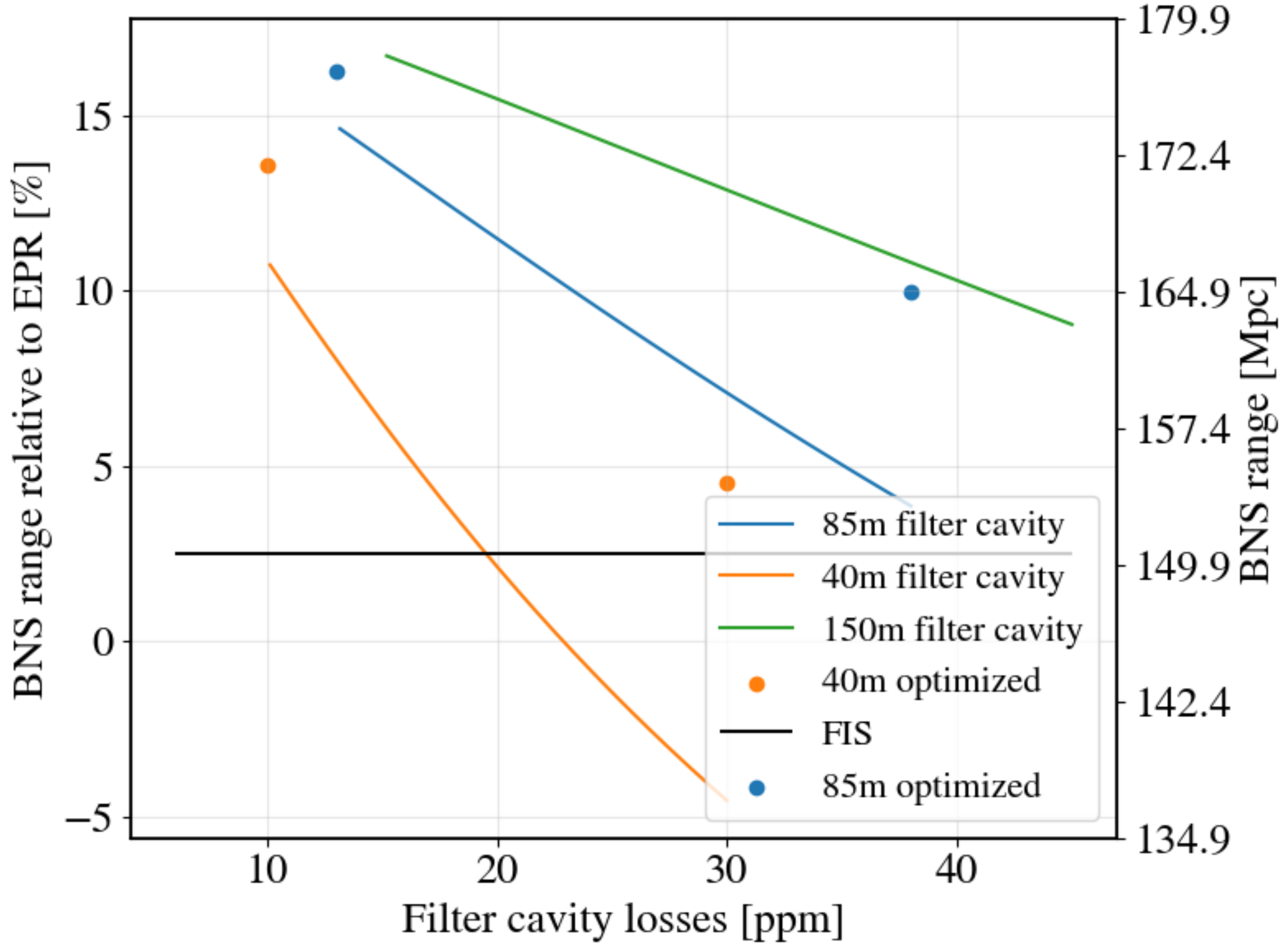
- Considering a 85m filter cavity
- Injection losses: 4%
- Readout losses: 3%
- SEC losses: 500 ppm
- High quality suspension (HQS)



Optimisation of filter cavity (HQS)

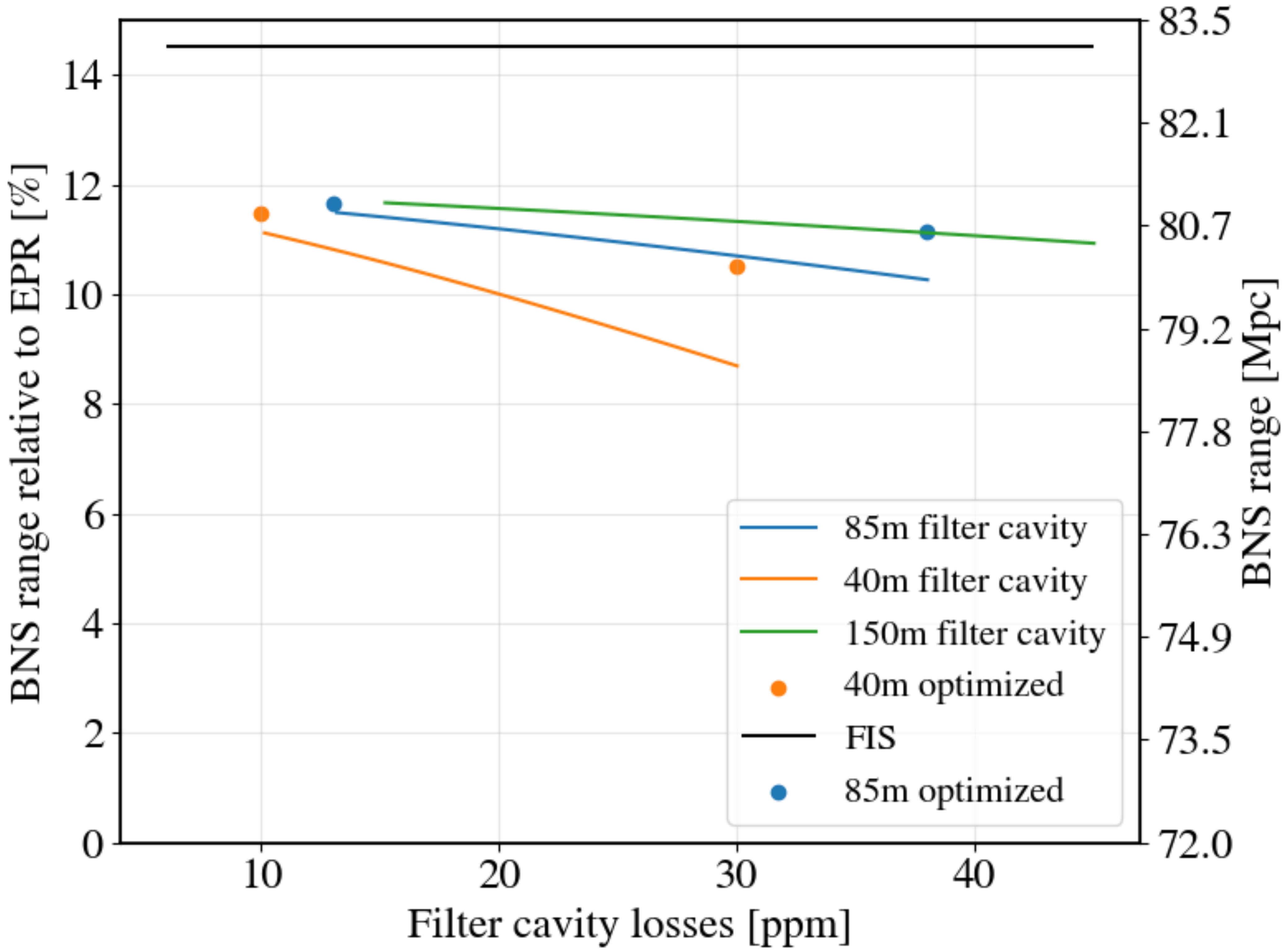
- Filter cavity bandwidth and detuning optimisation cases:
    - Arm power change
    - Filter cavity losses change

- The use of 85m filter cavity can give at least 10% more BNS range, means more than 30% increase of detection rate (compare with EPR)



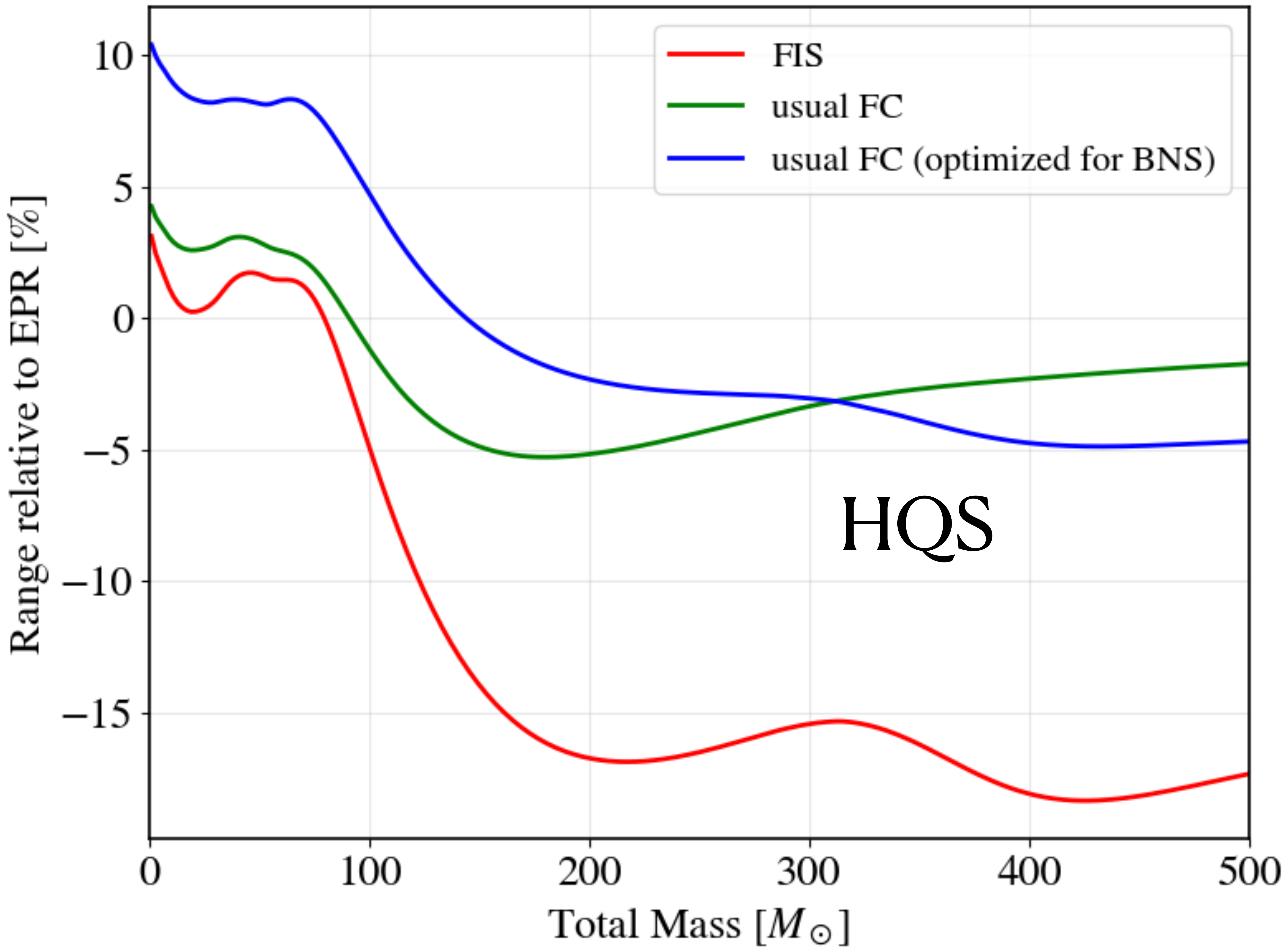
Optimisation of filter cavity (LQS)

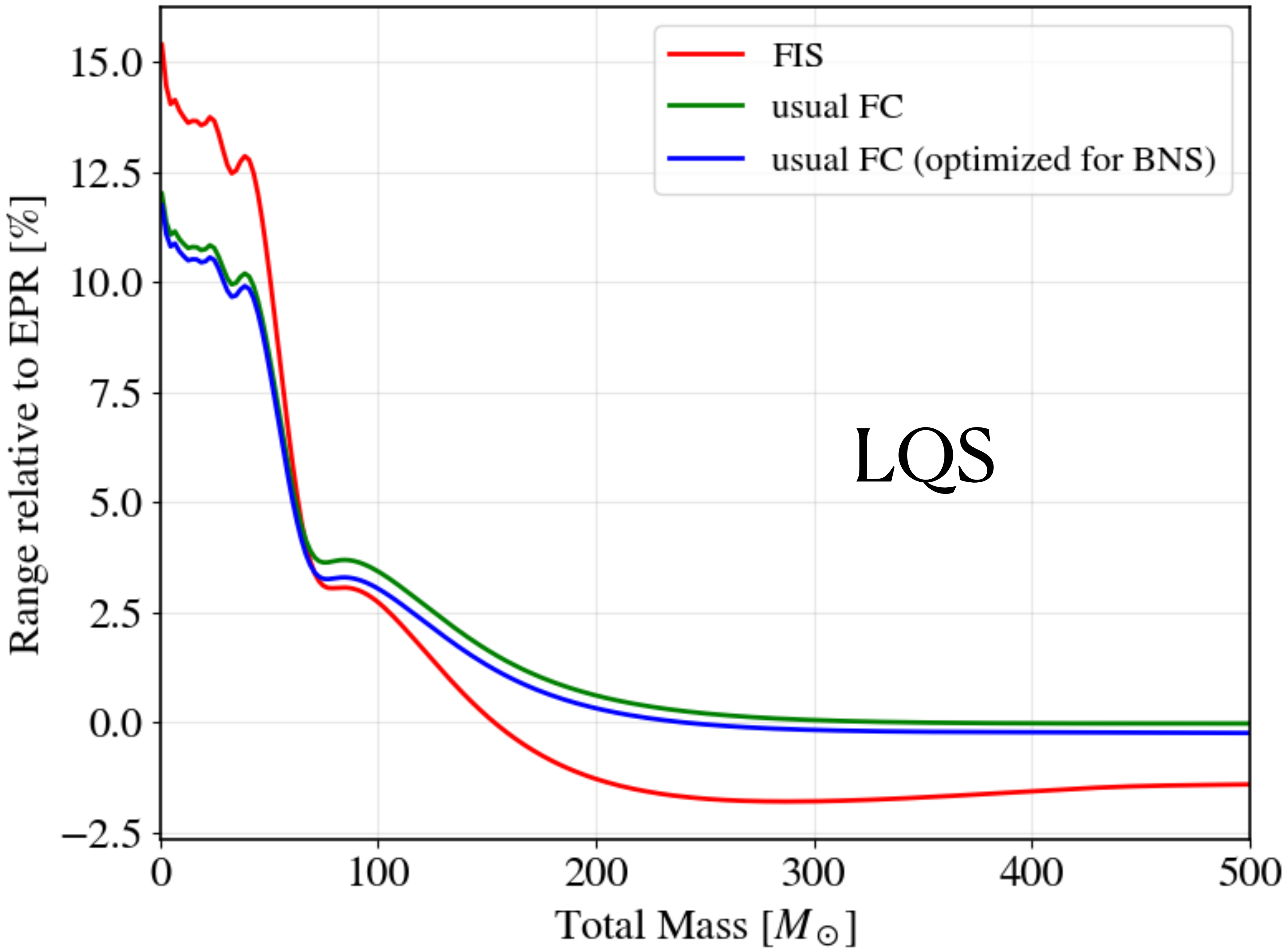
- No matter how filter cavity is optimised, FIS always performs the best when the suspension has a low quality factor



Range for different total mass BBH

- EPR scheme has advantages for high total mass BBH





Conclusion

- Quantum noise reduction is crucial for sensitivity improvement for current and future gravitational wave detectors
- Due to the particular situation in KAGRA, several different quantum noise reduction schemes are considered
- For the case of high quality factor suspension, FIS gives the largest BNS range
- For the case of high quality factor suspension, the usual filter cavity FDS gives the largest BNS range, while the EPR FDS gives the best range for heavy binary systems
- To guarantee the performance of FDS, a tunable filter cavity is preferred

Next steps

- Calculate tunable filter cavity parameters in the case of KAGRA post-O5
  - Such as etalon for cavity input mirror
- Investigate the behaviour of thermal deformation induced mode mismatch influence for KAGRA QNR according to the high power operation plan for post-O5
  - KAGRA is featured to be less sensitive to thermal deformation, but quantitative simulation is crucial

Thank you for your attention!

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• Research Highlight •

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Multiple quantum entanglement empowering quantum technology

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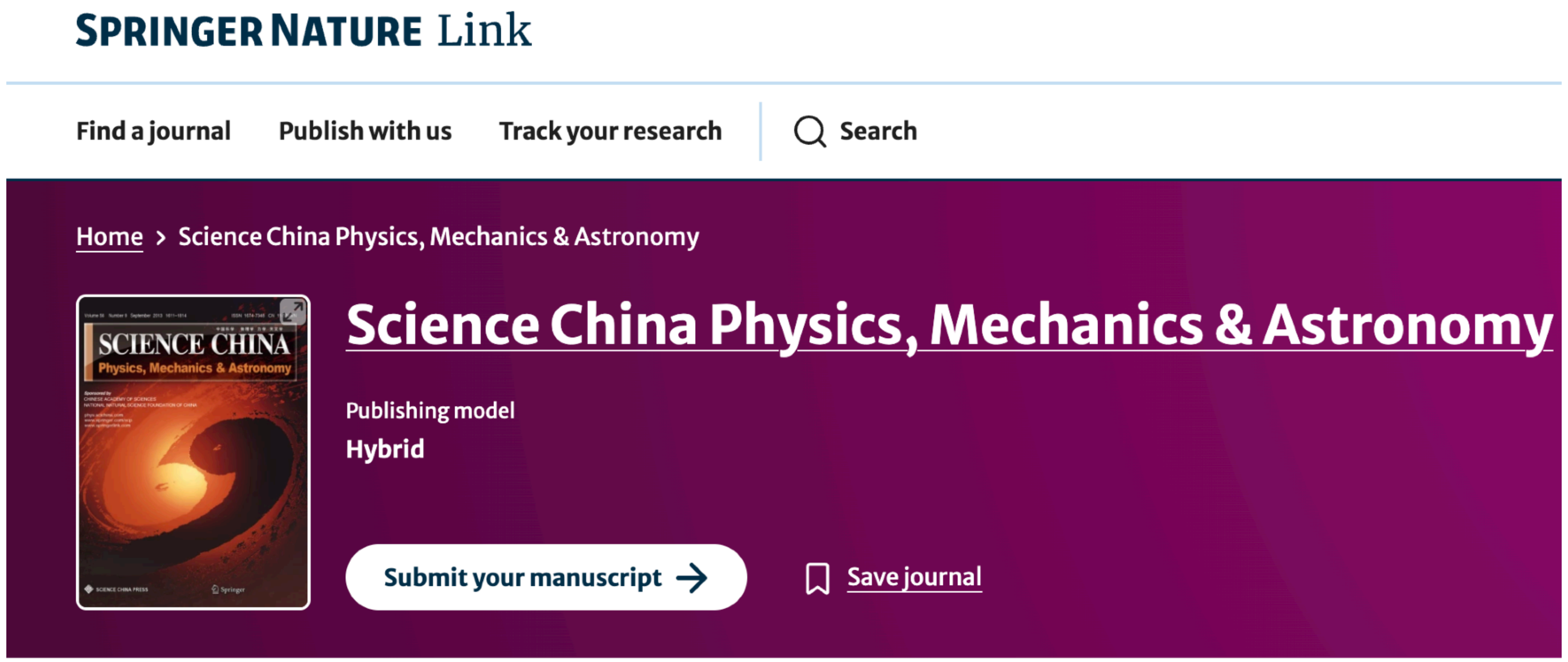
Quantum technology is widely regarded as a central driving force of the next technological revolution, with the potential to fundamentally transform the existing technological landscape. Quantum light sources, as a foundational resource for quantum information processing, play a pivotal role in applications such as quantum metrology and quantum communication. Leveraging the quantum correlations of these light sources enables quantum-enhanced precision measurement schemes leveraging Einstein-Podolsky-Rosen (EPR) entanglement yield comparable quantum enhancement effects [4-6].

In the domain of quantum communication, continuous-variable quantum systems offer distinct advantages such as deterministic entanglement generation and efficient quantum state detection, making them indispensable for quantum information processing [7]. However, constructing large-scale,



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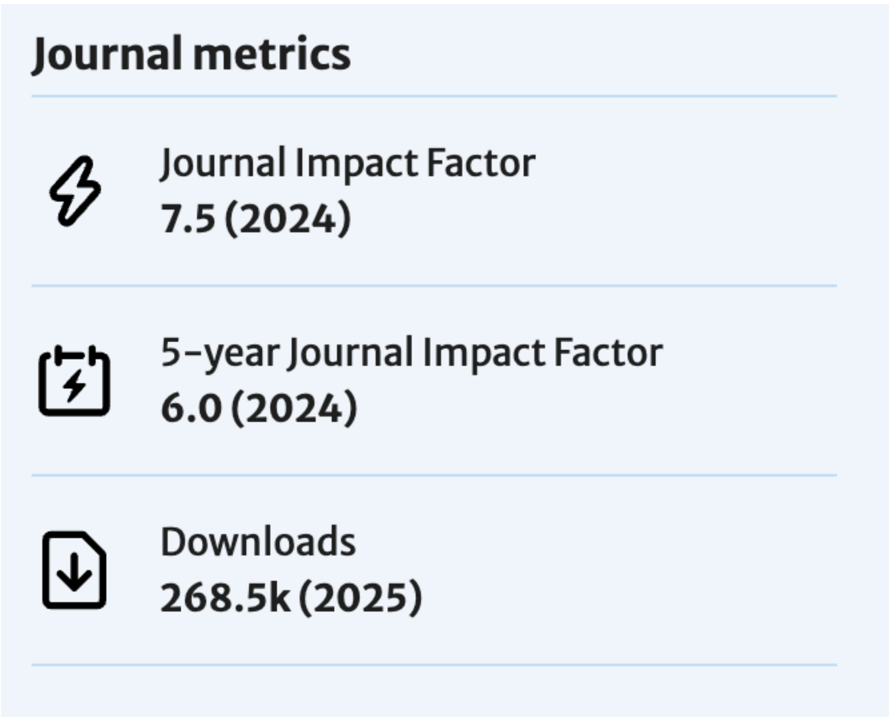

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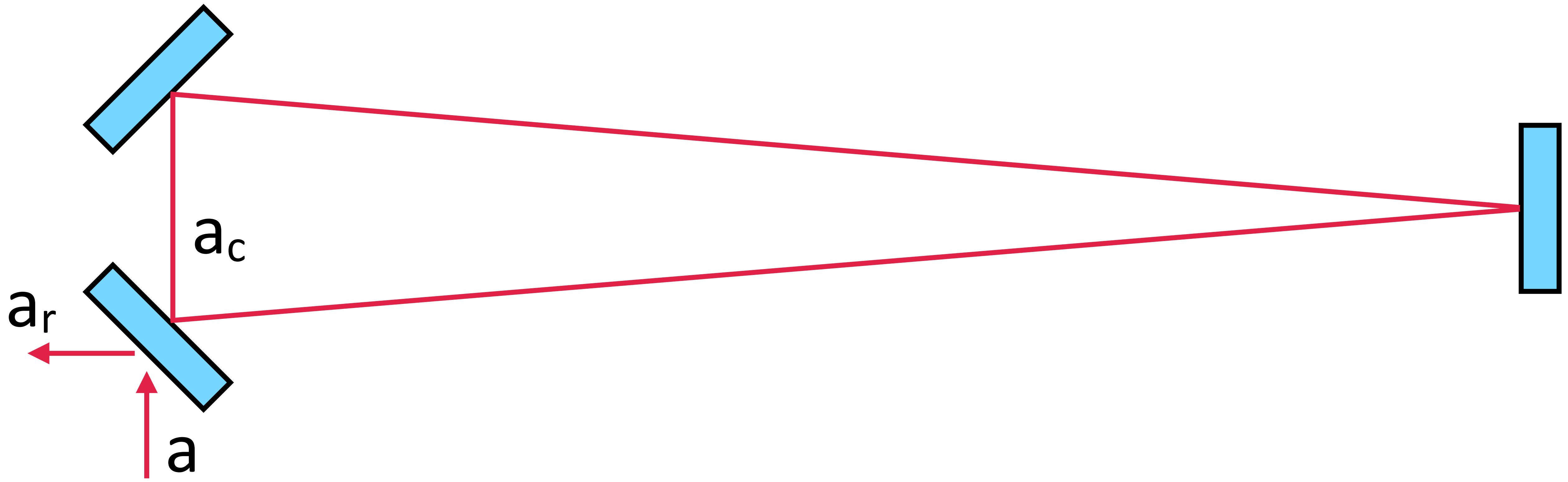
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