CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

EINSTEIN TELESCOPE

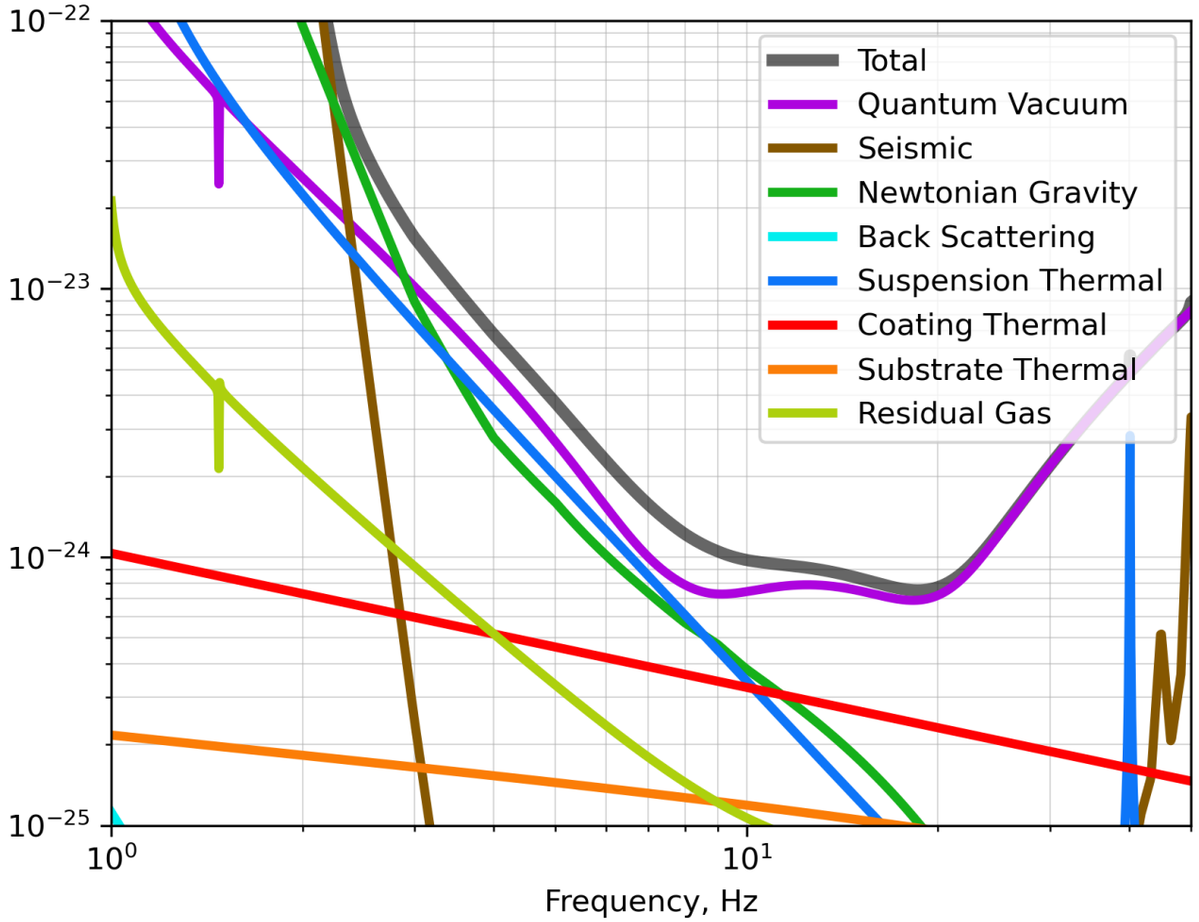
Quantum paths for ET: challenges of quantum noise and alternative detector configurations

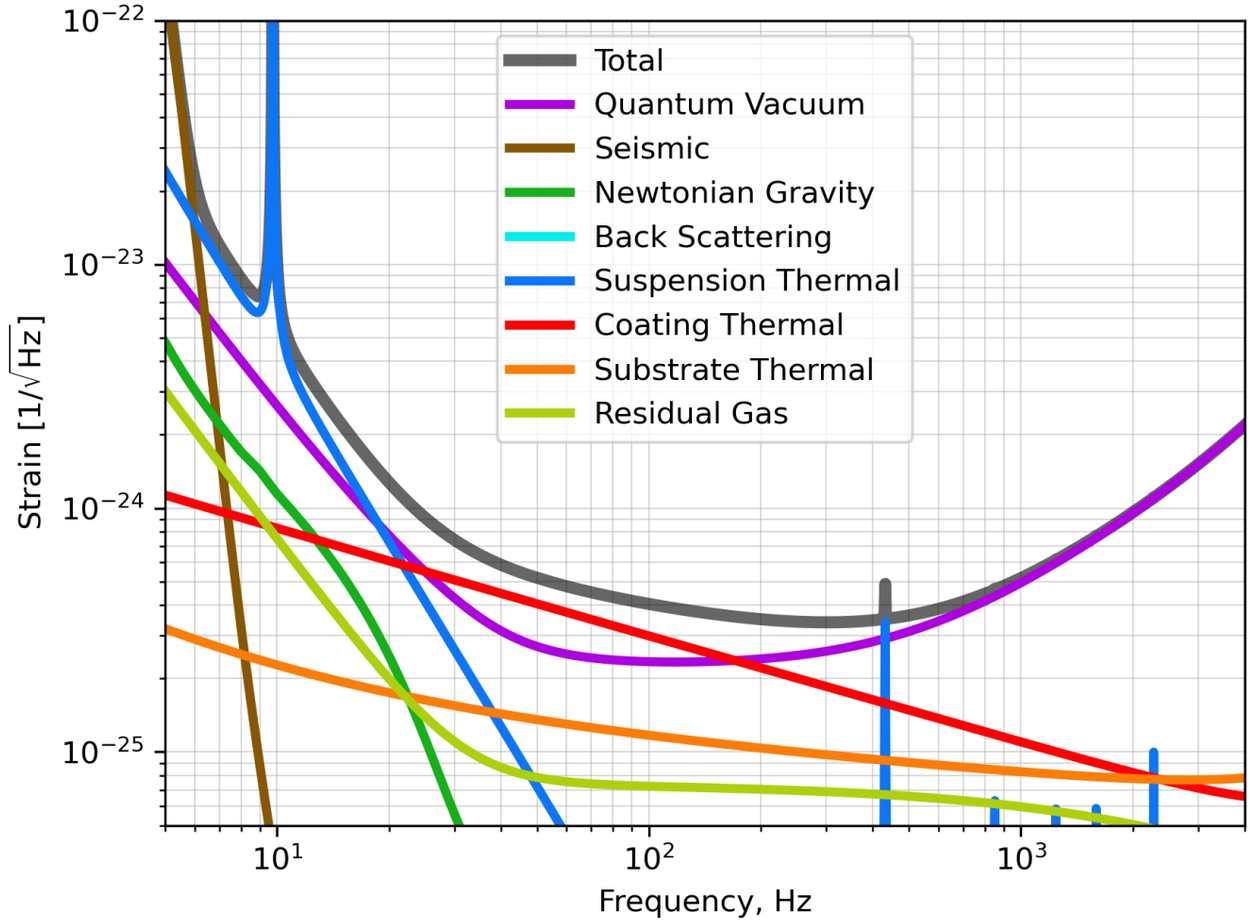
Mikhail Korobko

University of Hamburg

ET Symposium 2025

Quantum noise in ET

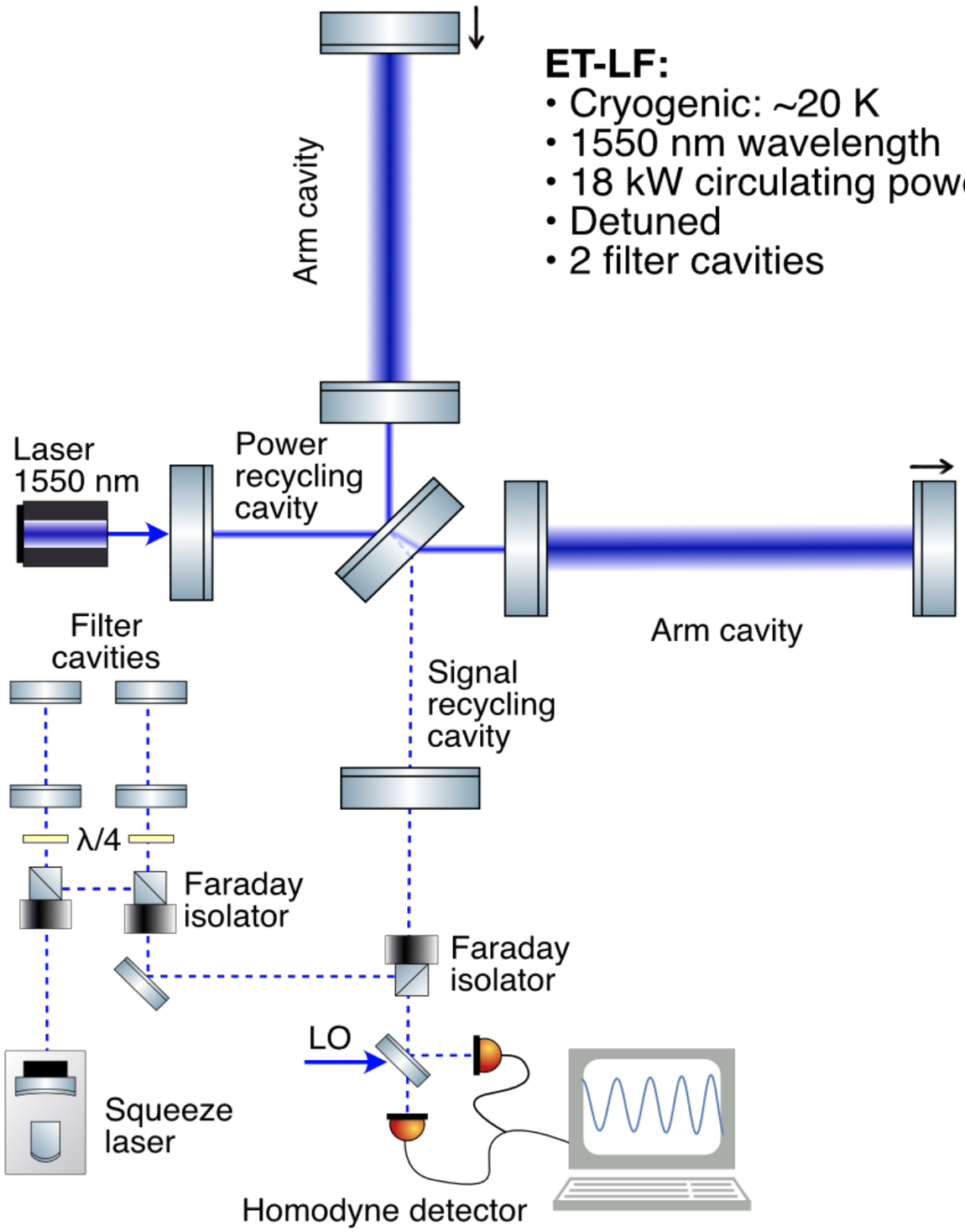




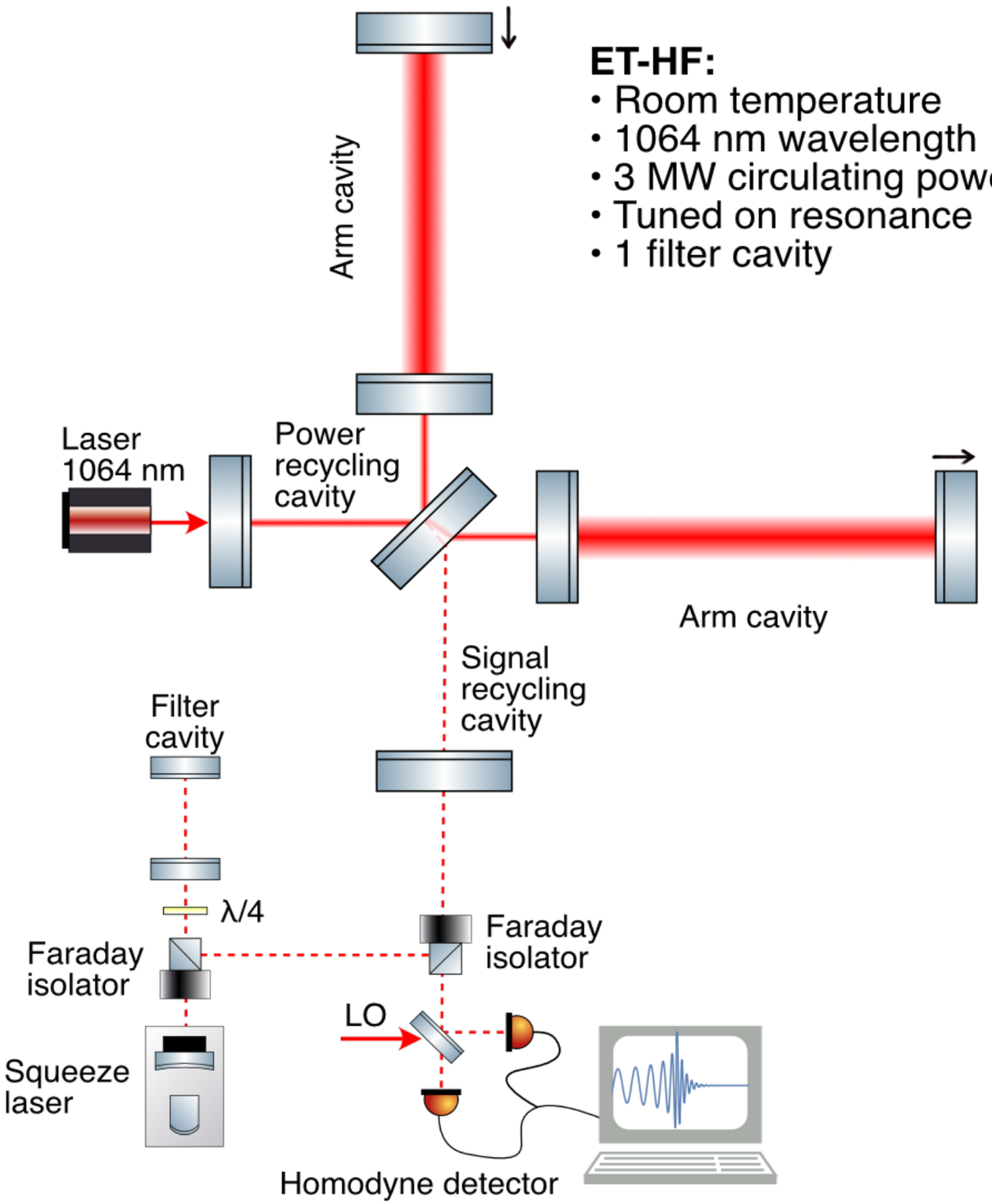
- Quantum noise limits in very broad band + a lot of room for improvement
- Can we actually make quantum noise better: now or later?

Quantum noise in ET

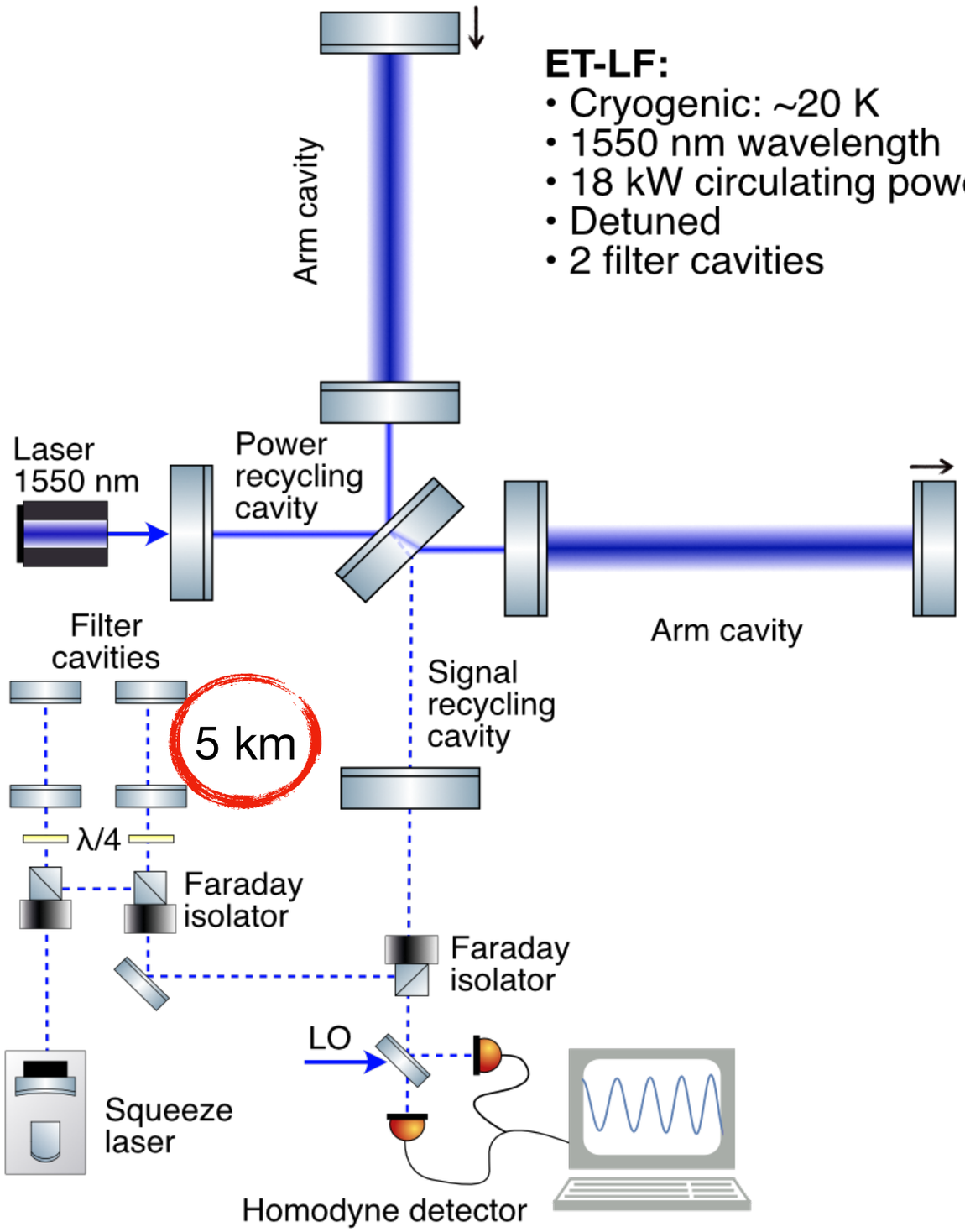
ET-LF:
- Cryogenic: ~20 K
- 1550 nm wavelength
- 18 kW circulating power
- Detuned
- 2 filter cavities

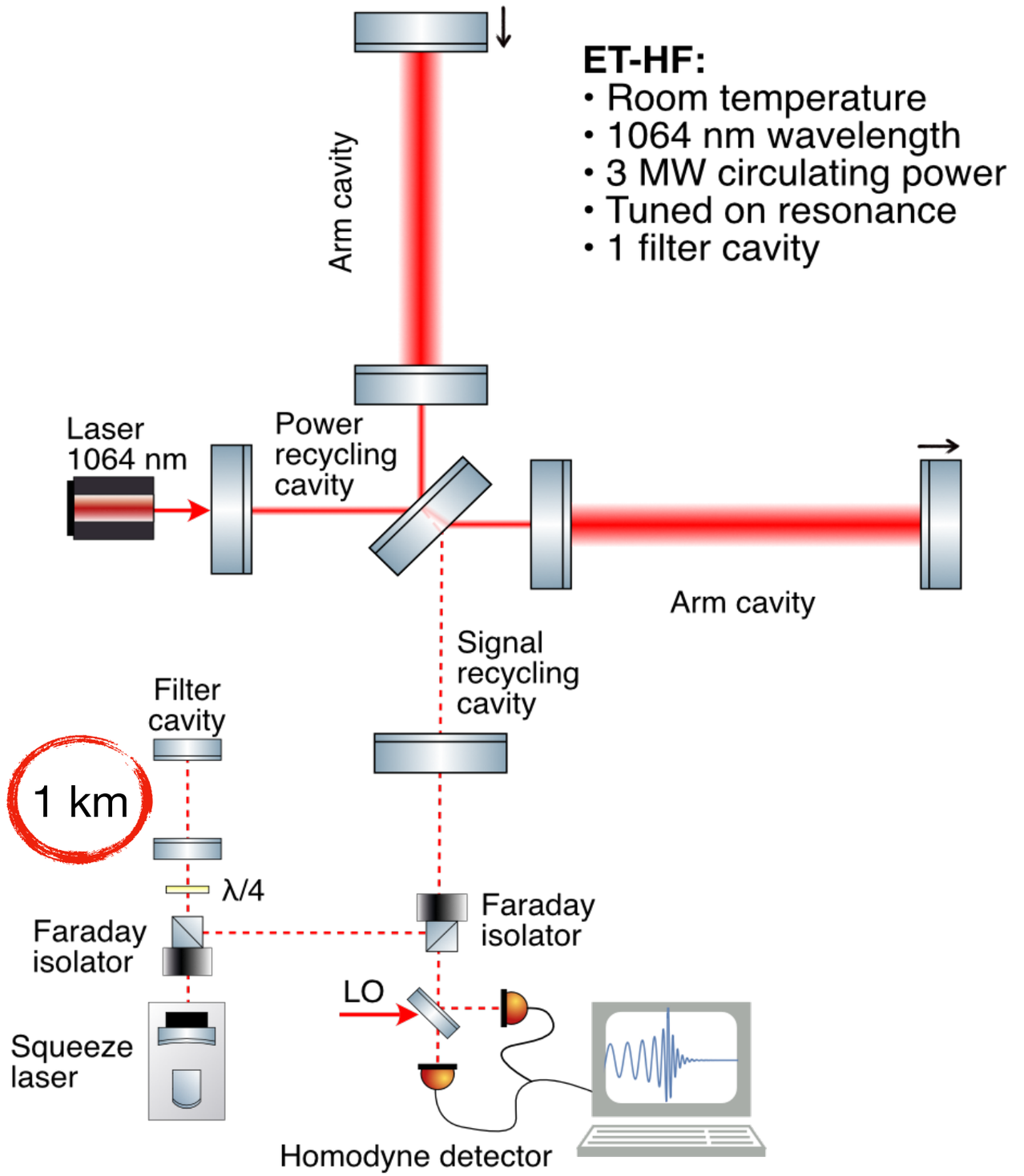


ET-HF:
- Room temperature
- 1064 nm wavelength
- 3 MW circulating power
- Tuned on resonance
- 1 filter cavity

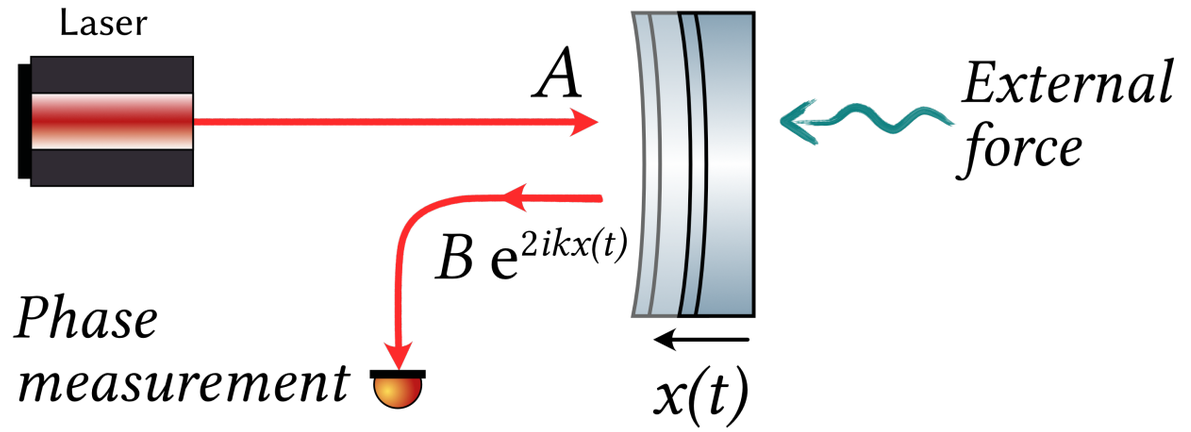


Quantum noise in ET





Brief introduction



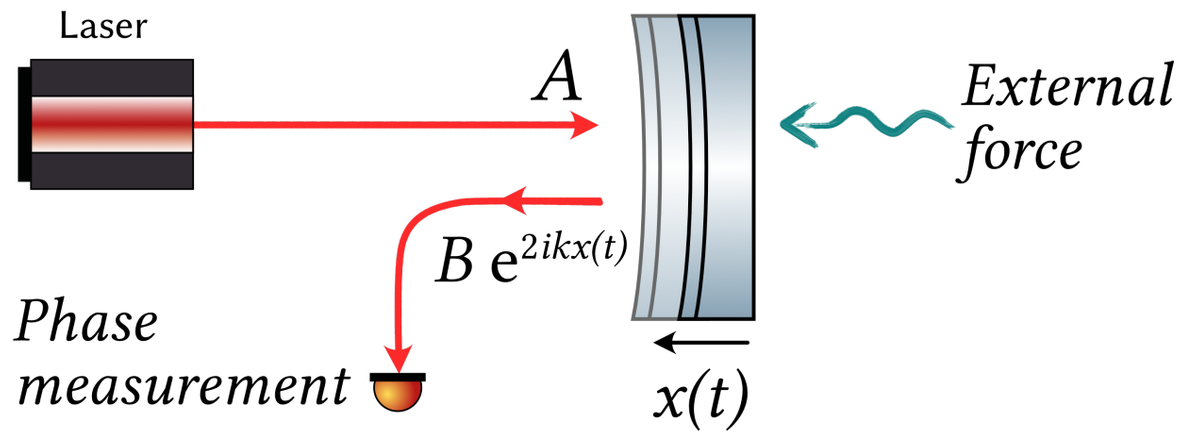
Mirror's position changes due to force

Motion couples to phase

Measure phase of the light

Brief introduction

Amplitude fluctuations:
quantum radiation-pressure noise
(back-action noise)



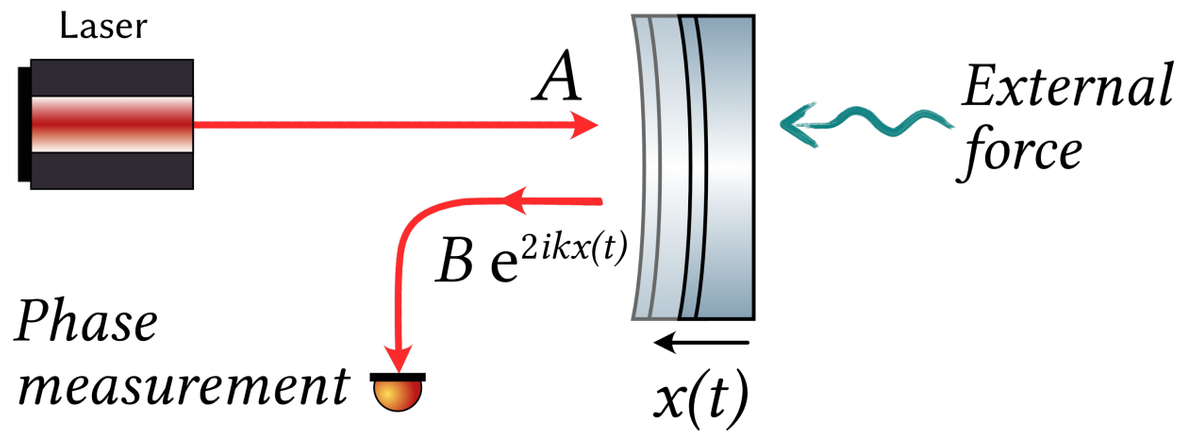
Mirror's position changes due to force

Motion couples to phase

Measure phase of the light

Brief introduction

Amplitude fluctuations:
quantum radiation-pressure noise
(back-action noise)



Mirror's position changes due to force

Light pushes a mirror
force ~ light power

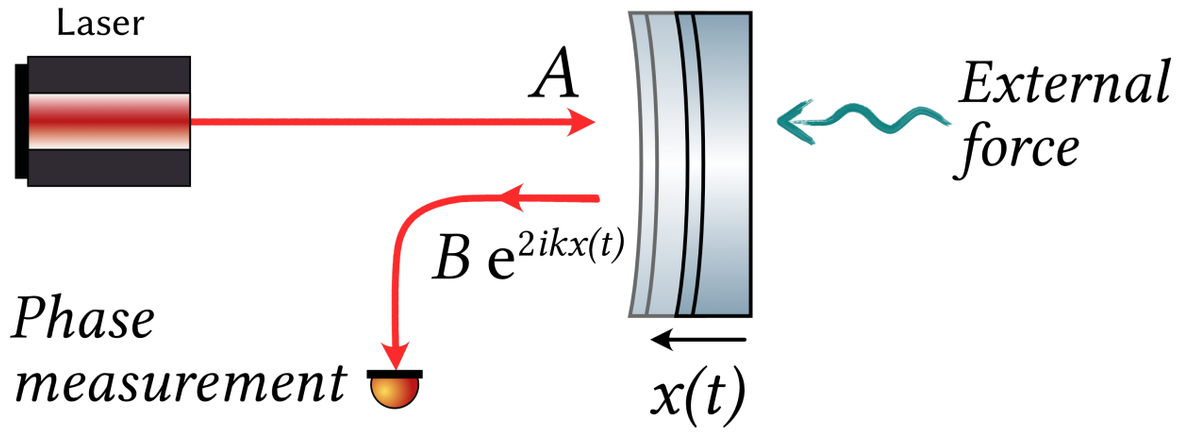
Motion couples to phase

Measure phase of the light

Quantum noise in ET

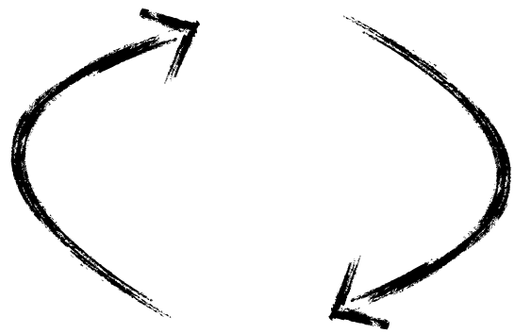
Brief introduction

Amplitude fluctuations:
quantum radiation-pressure noise
(back-action noise)



Mirror's position changes due to force + fluctuates

Light pushes a mirror
force ~ light power

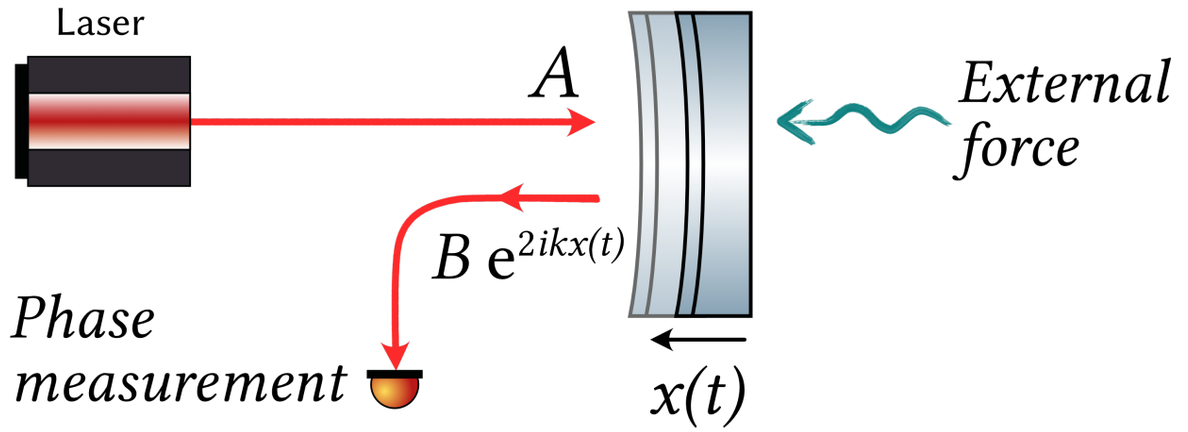


Motion couples to phase

Measure phase of the light

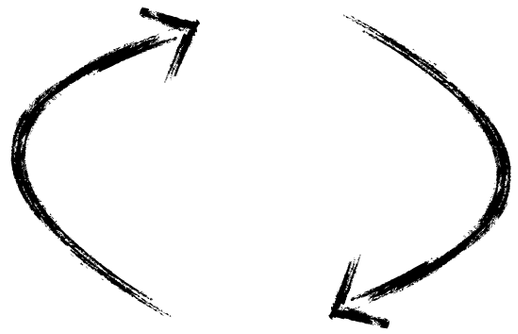
Brief introduction

Amplitude fluctuations:
quantum radiation-pressure noise
(back-action noise)



Mirror's position changes due to force + fluctuates

Light pushes a mirror
force ~ light power

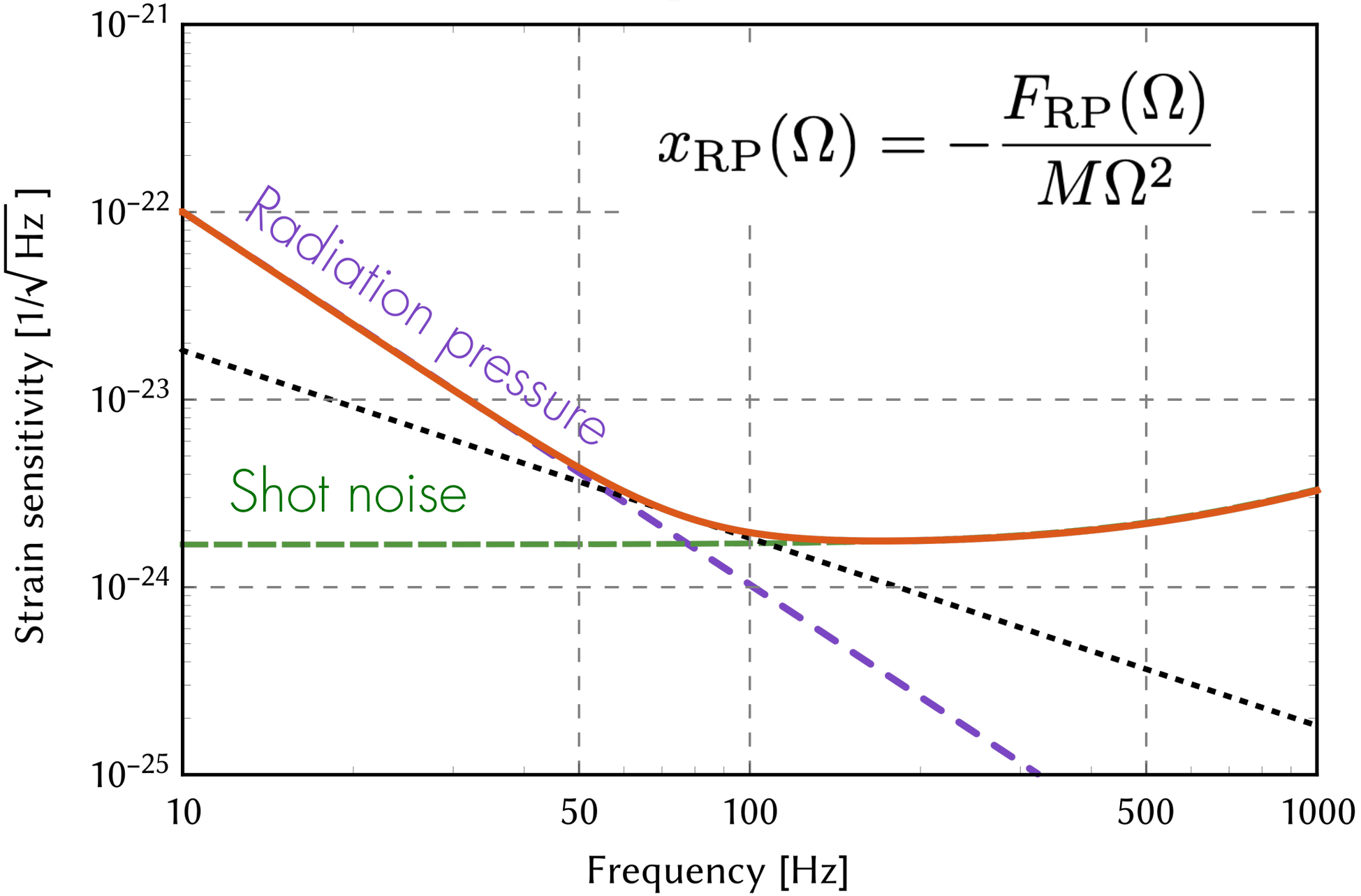


Motion couples to phase

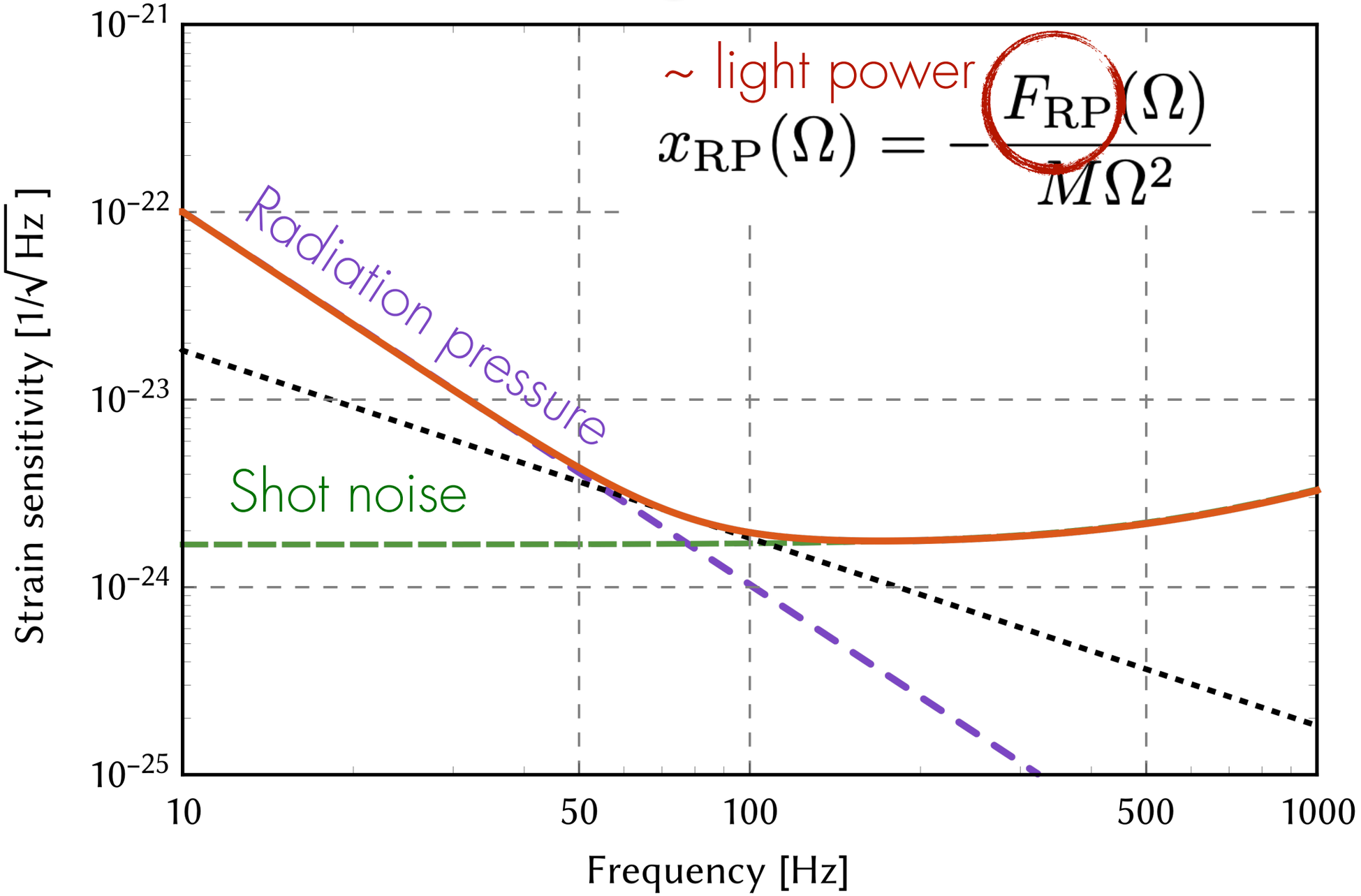
Measure phase of the light

Fluctuations in both amplitude and phase quadrature disturb the measurement

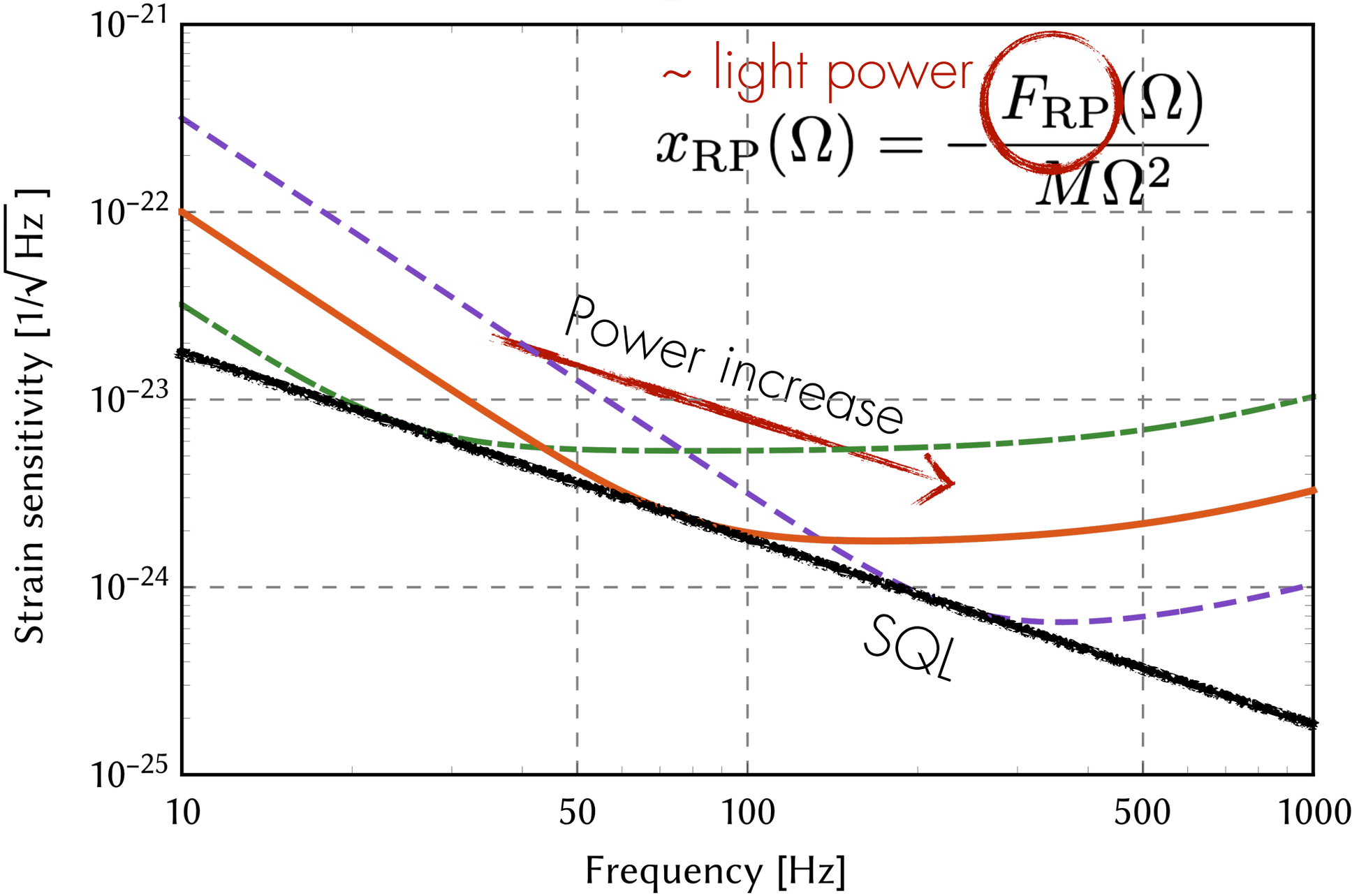
Radiation pressure



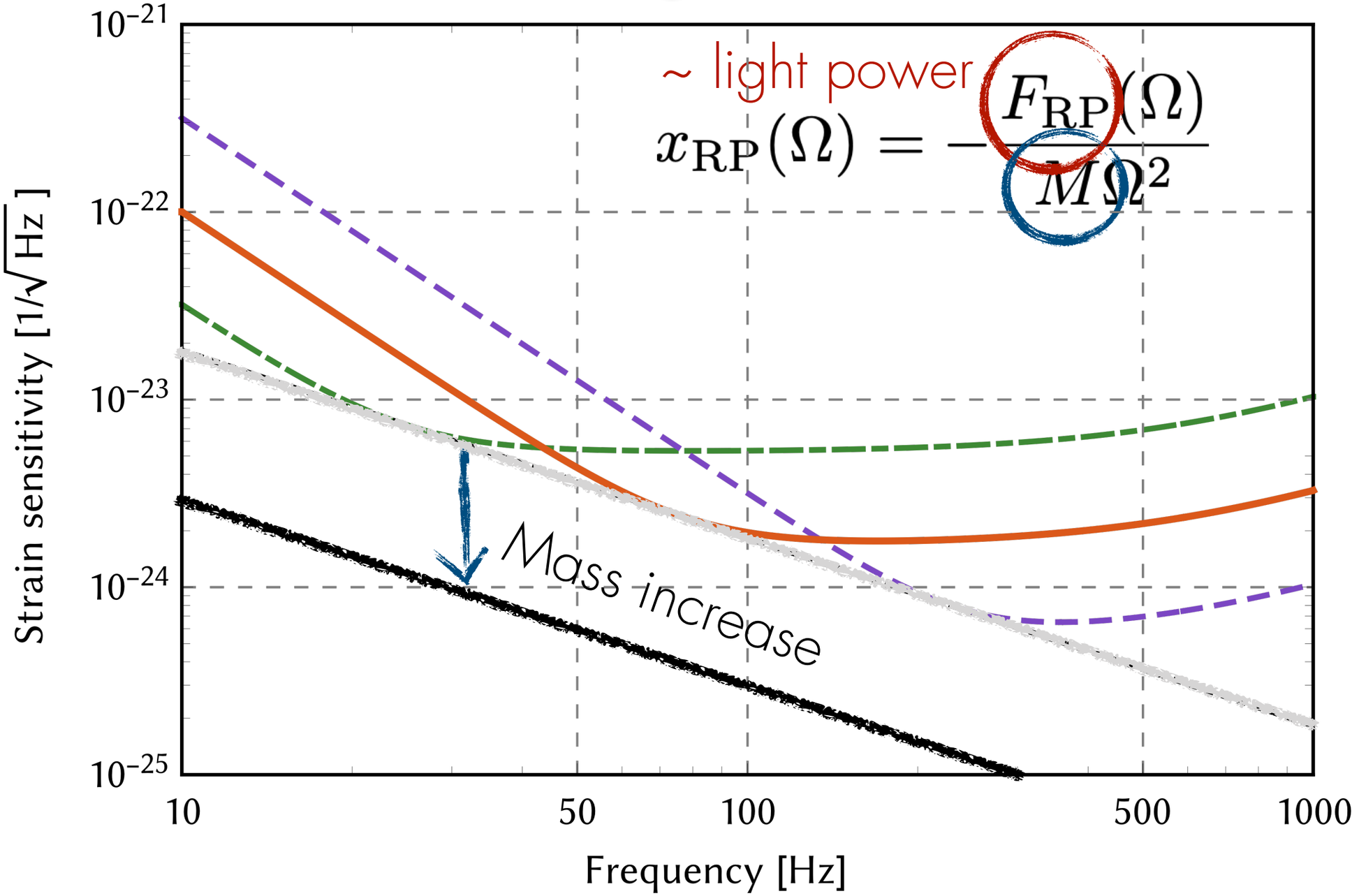
Radiation pressure



Radiation pressure

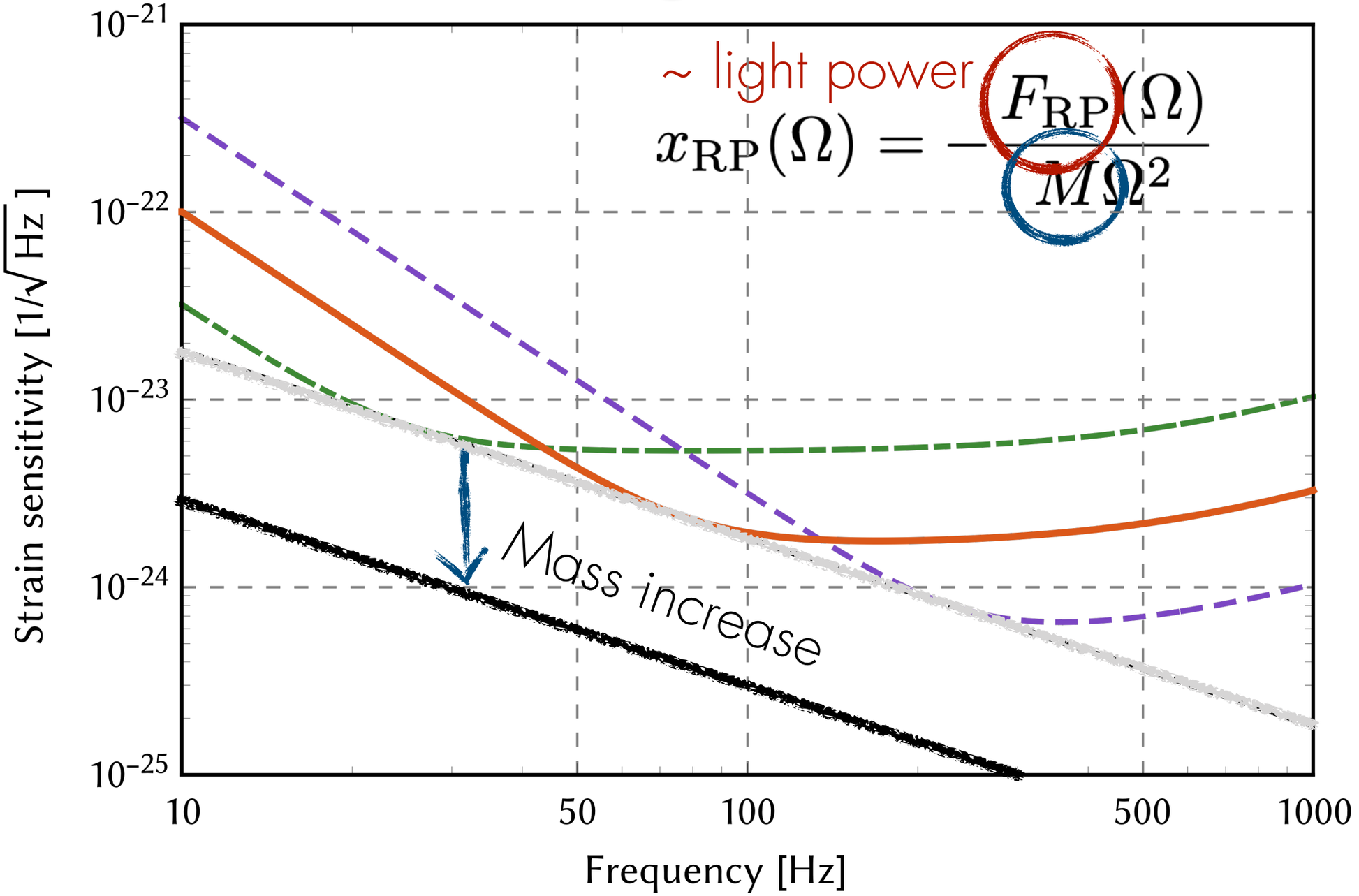


Radiation pressure



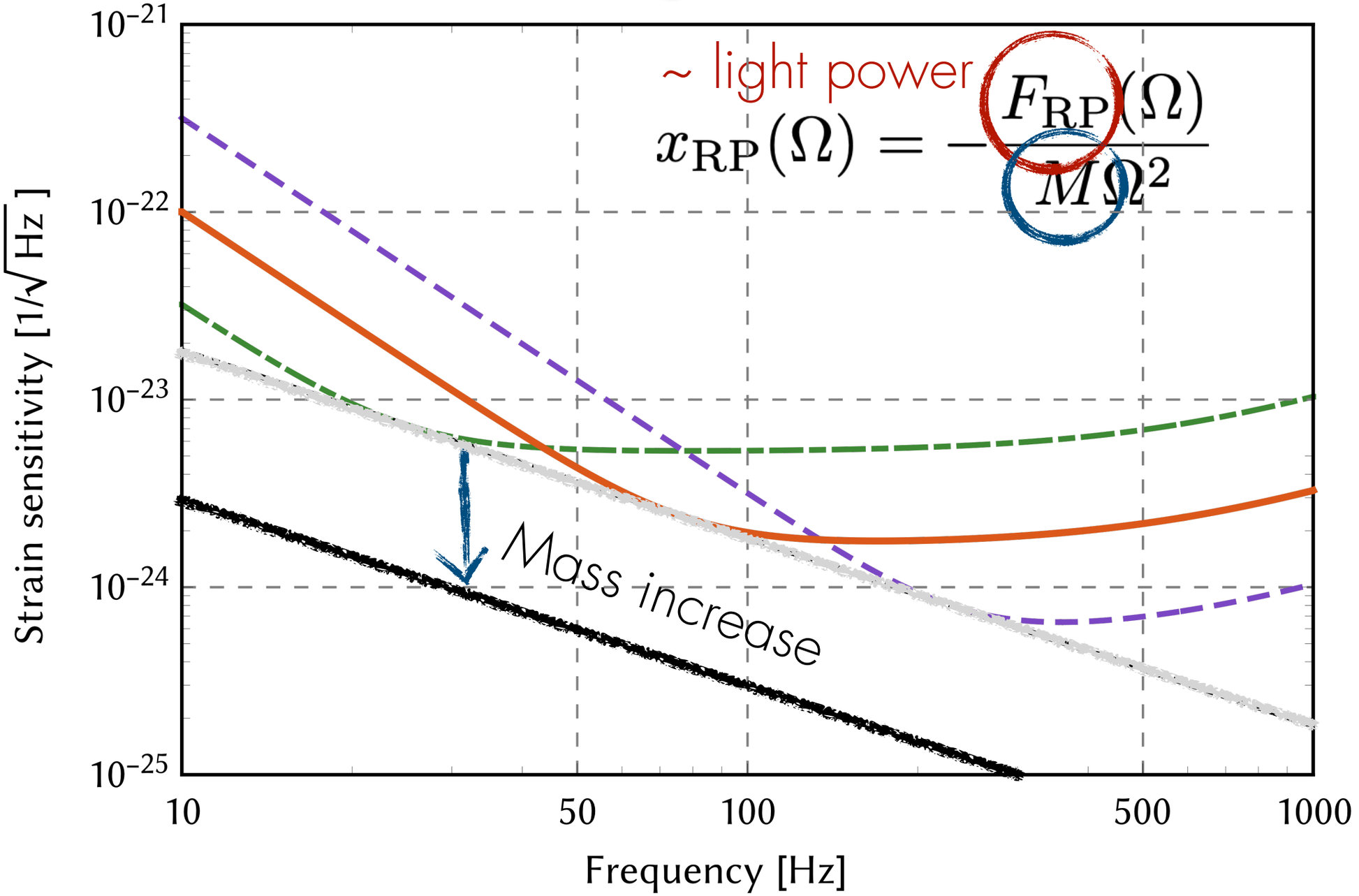
Quantum noise in ET

Radiation pressure



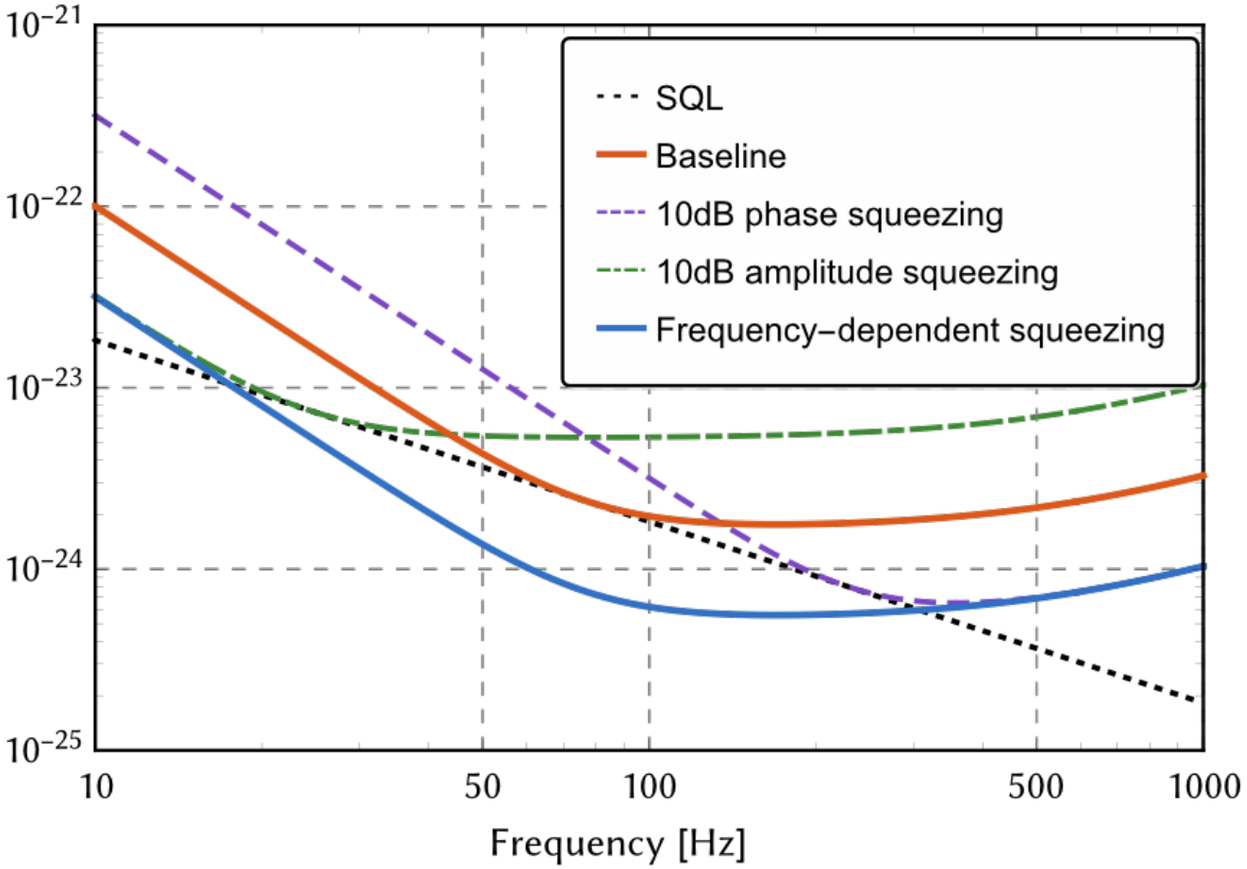
To reduce QRPN classically: increase mass or decrease power

Radiation pressure



To reduce QRPN classically: increase mass or ~~decrease~~ power

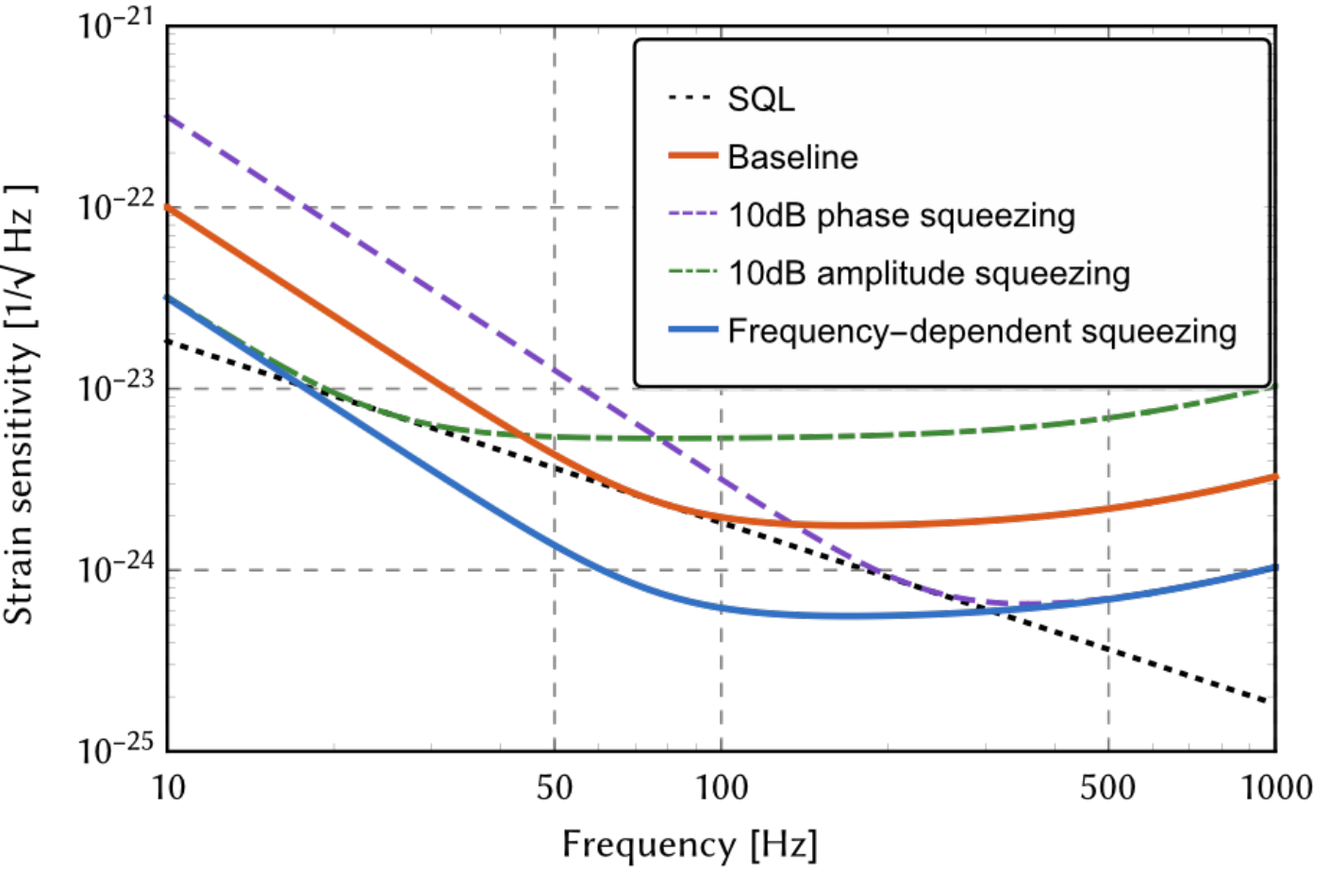
bad: decreases signal

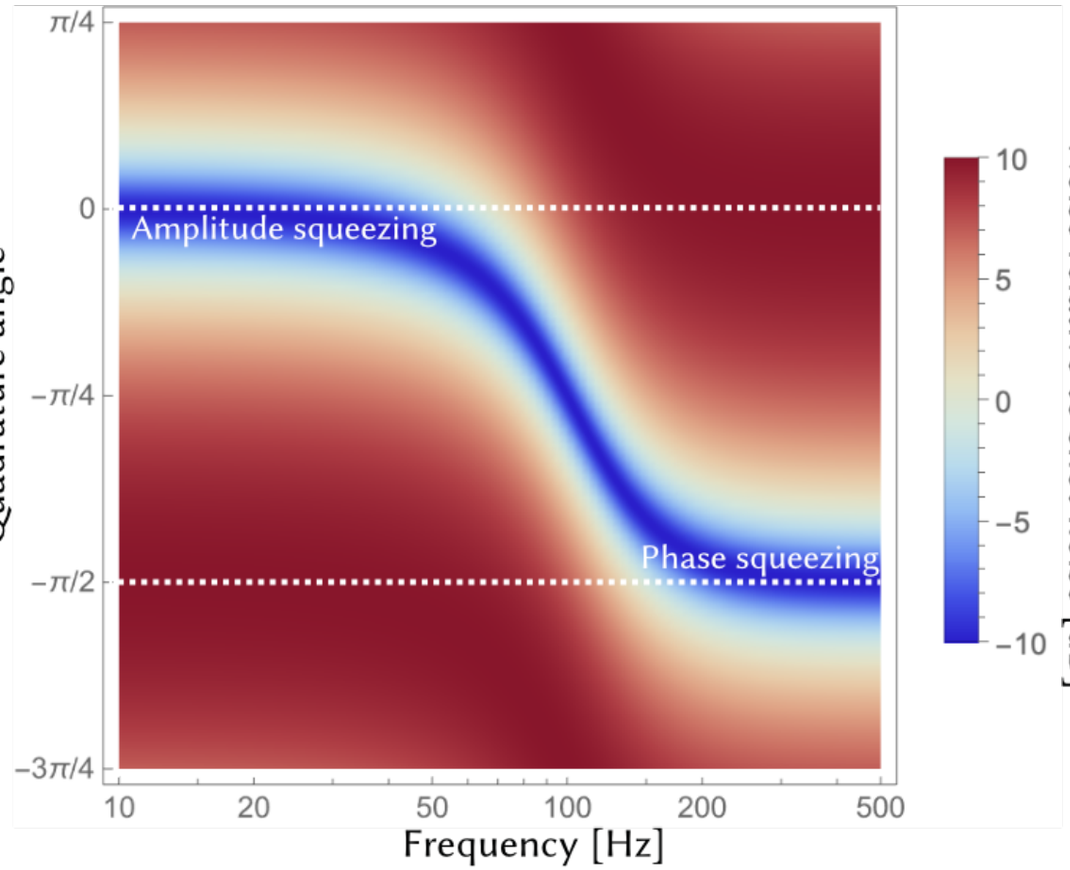


- We need frequency-dependent squeezing to suppress both shot noise and radiation-pressure noise
- For this we create frequency-dependent squeezing by reflecting the light off a single-sided cavity, detuned in a special way

Quantum noise in ET

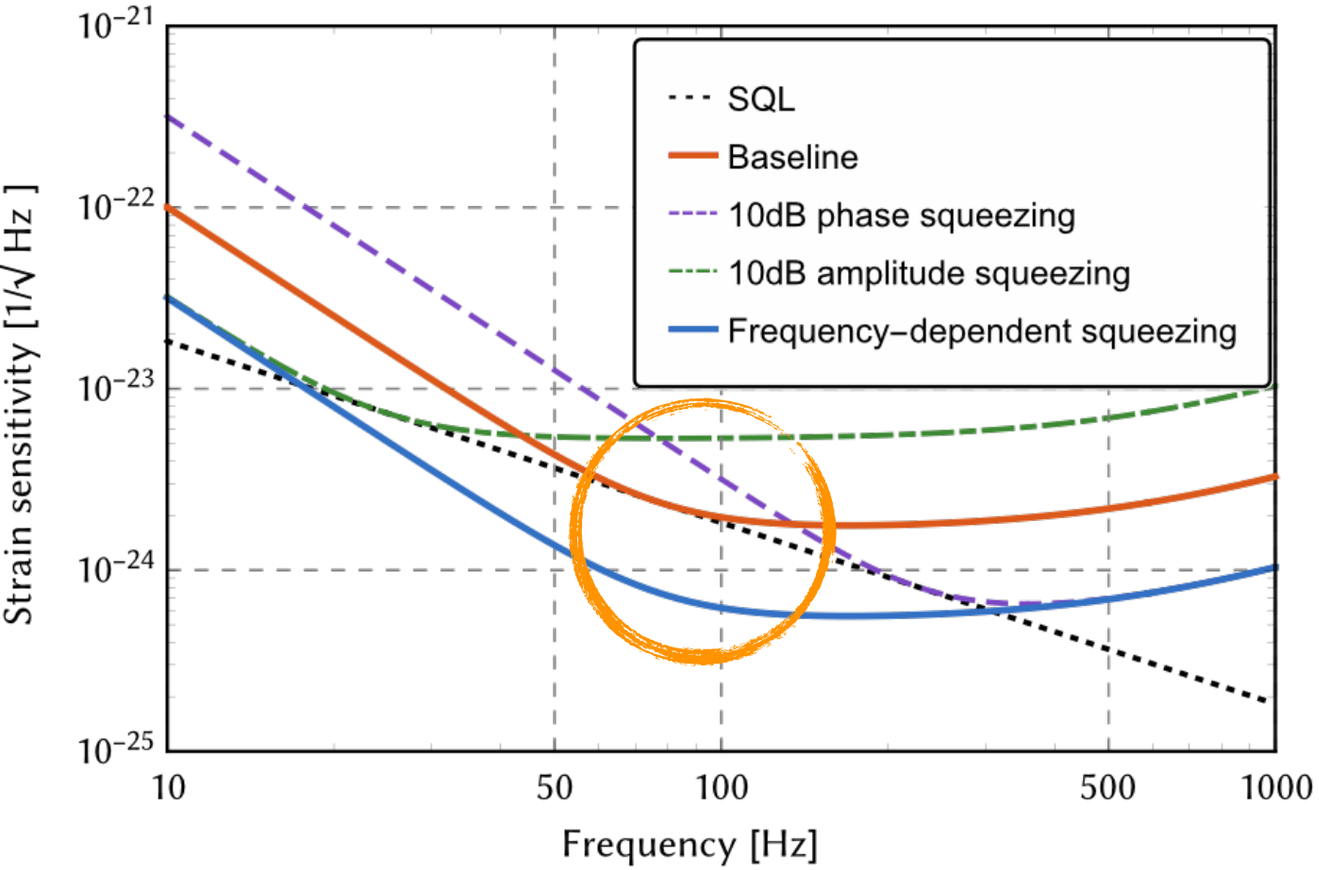
Frequency-dependent SQZ



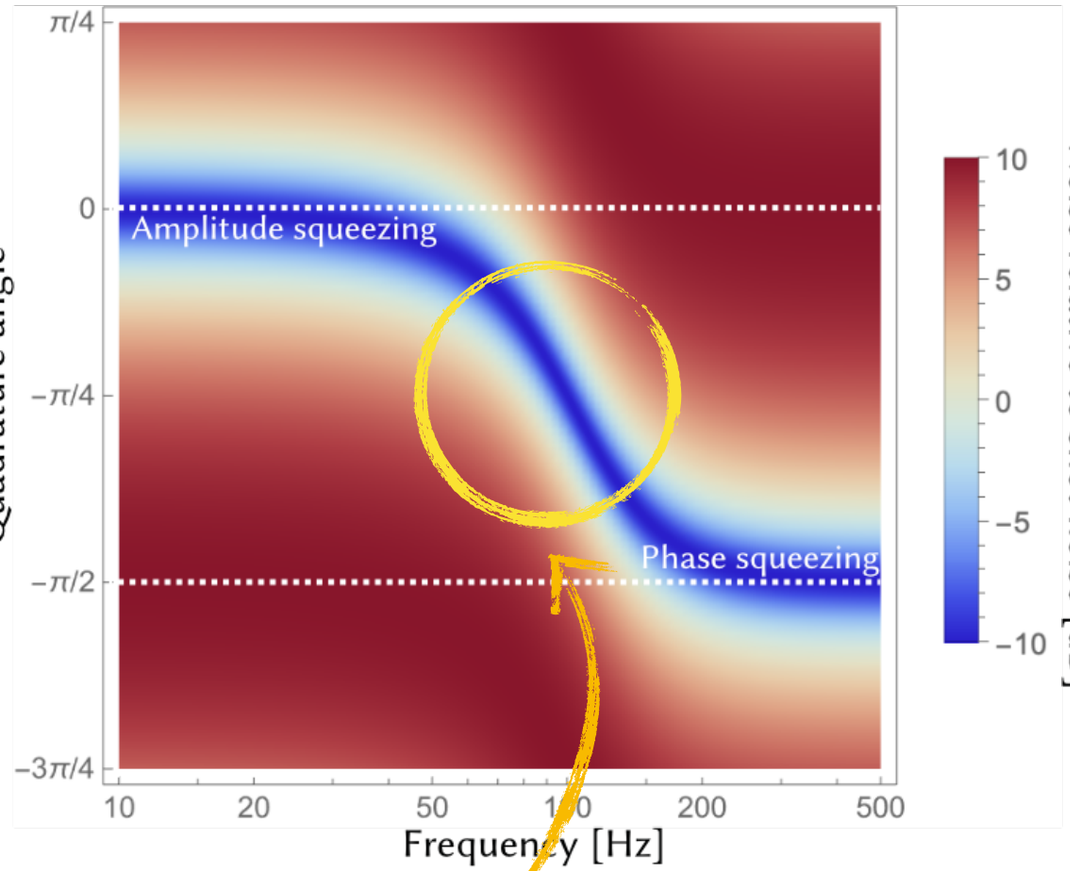


- We need frequency-dependent squeezing to suppress both shot noise and radiation-pressure noise
- For this we create frequency-dependent squeezing by reflecting the light off a single-sided cavity, detuned in a special way

Quantum noise in ET



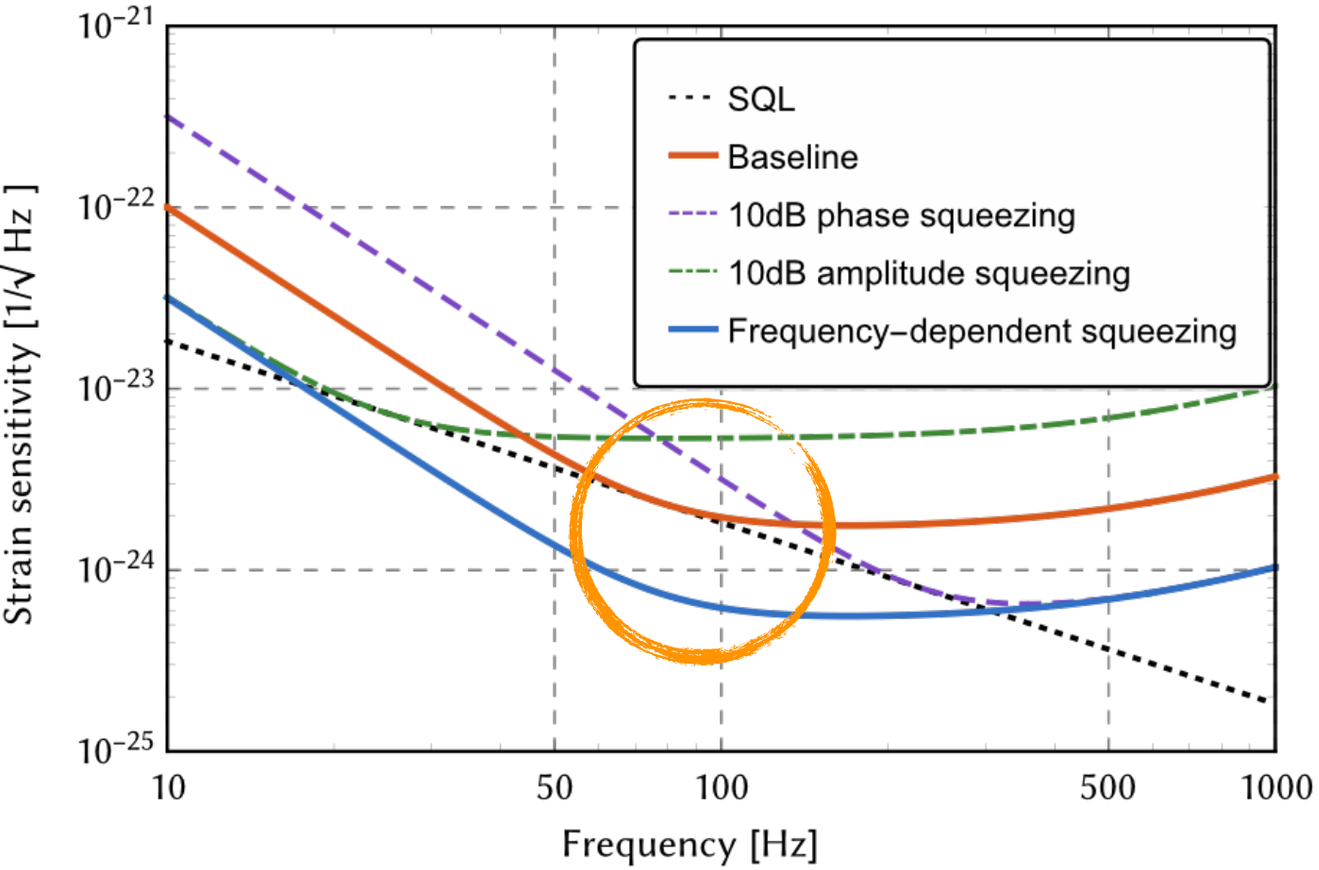
Frequency-dependent SQZ

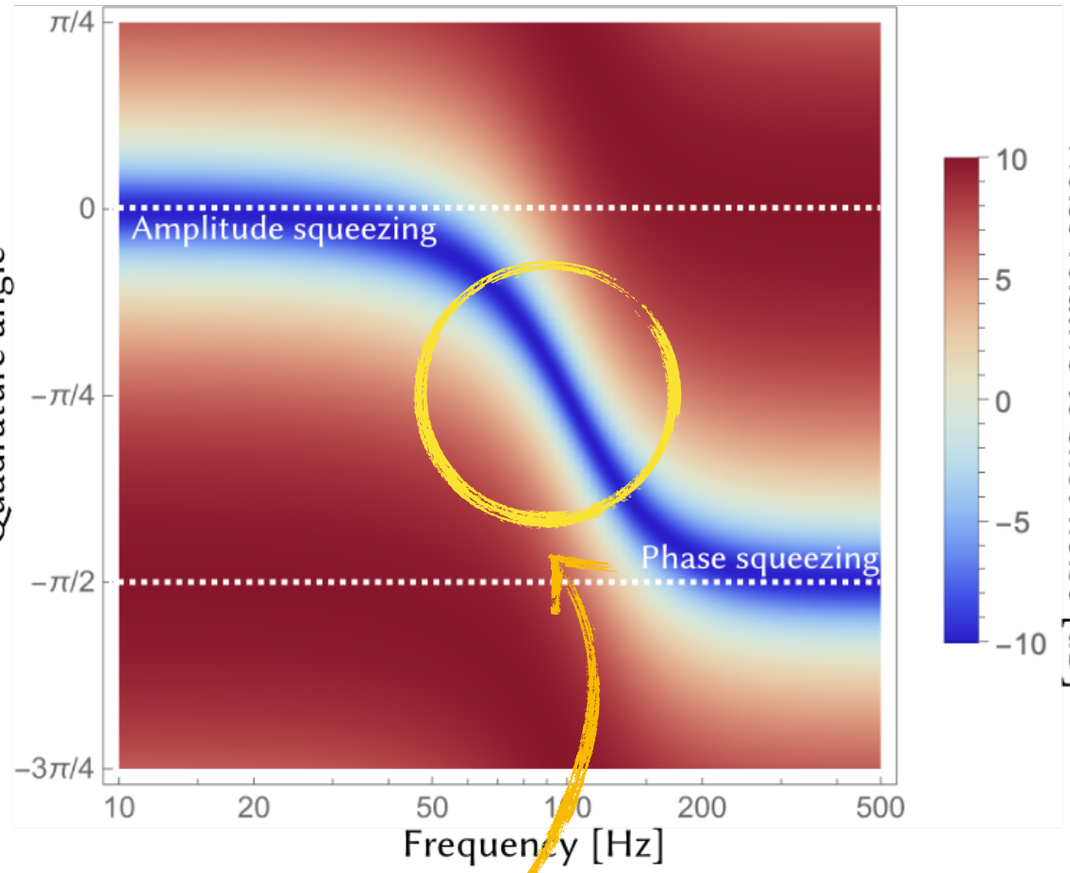


Transition frequency

Quantum noise in ET

Frequency-dependent SQZ

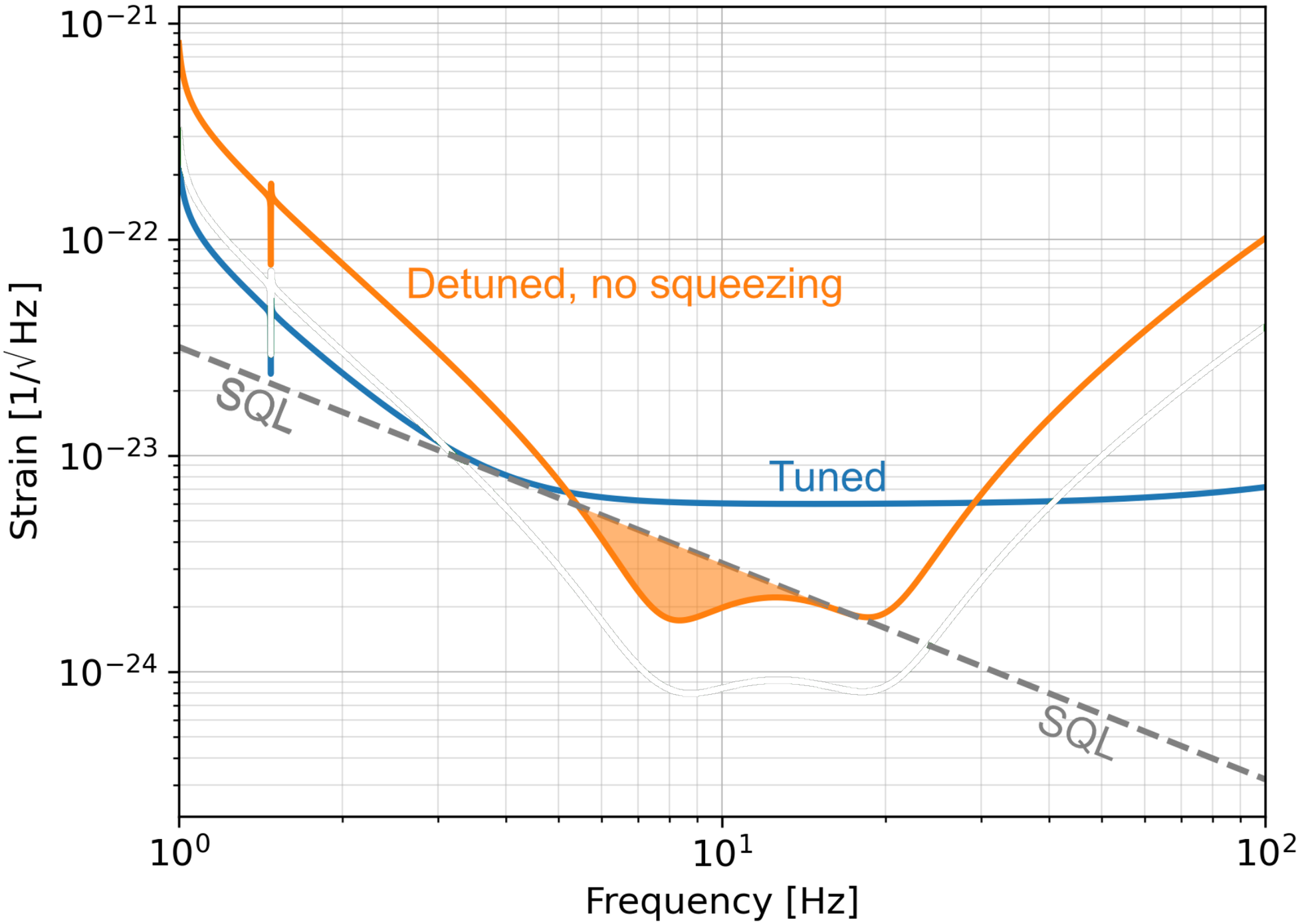




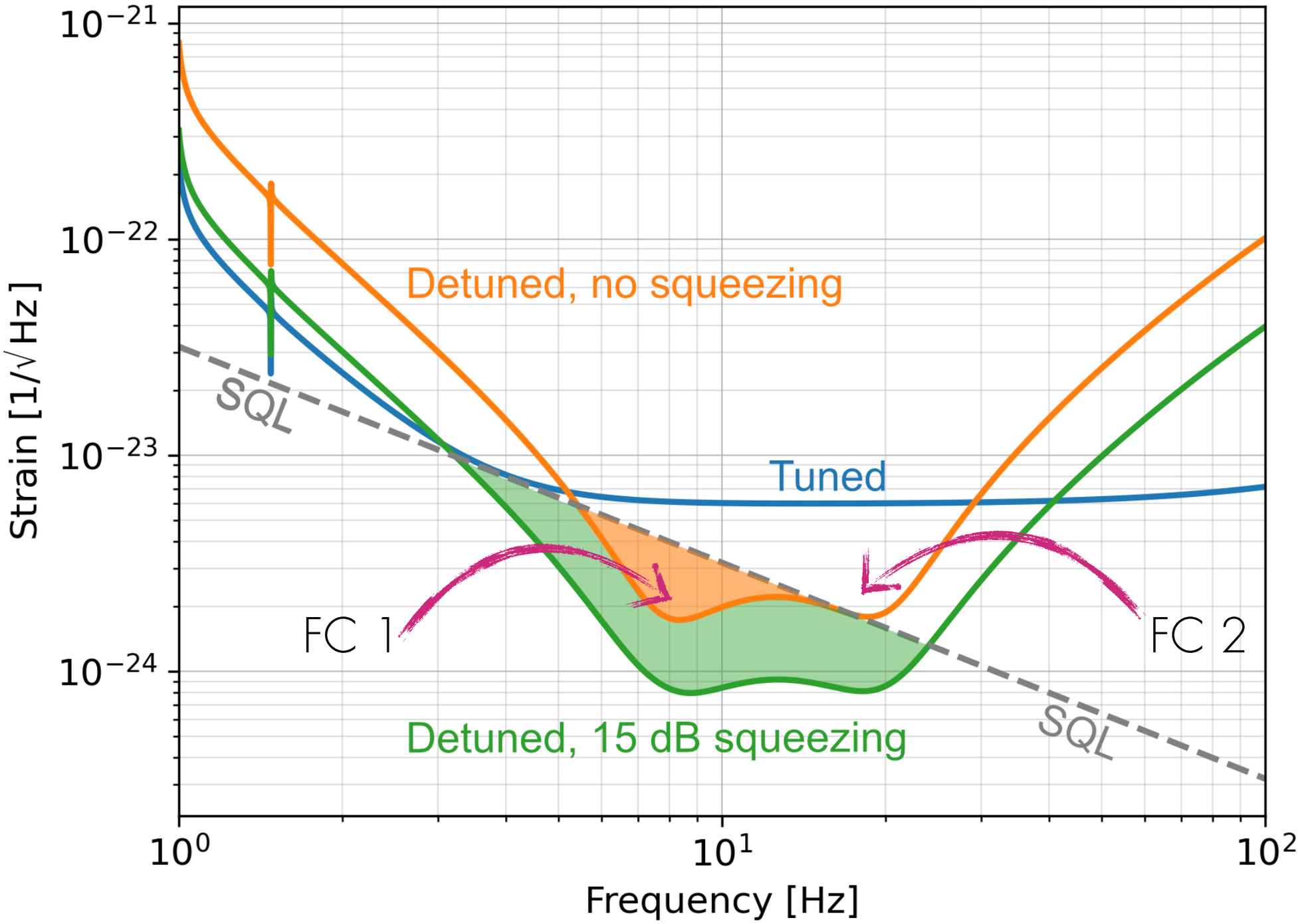
Transition frequency

- depends on FC detuning & linewidth
- changes if we change e.g. arm cavity power

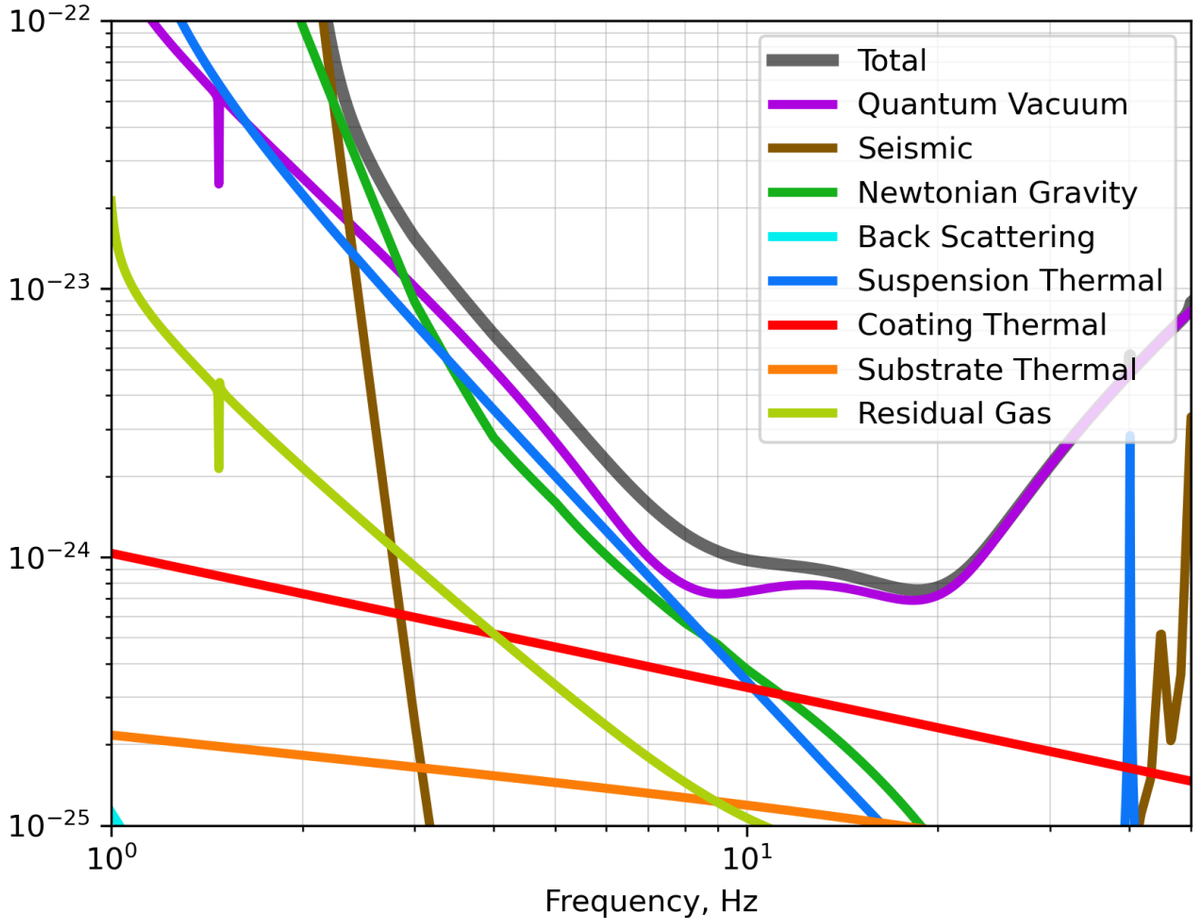
- We can use optical spring to enhance the sensitivity

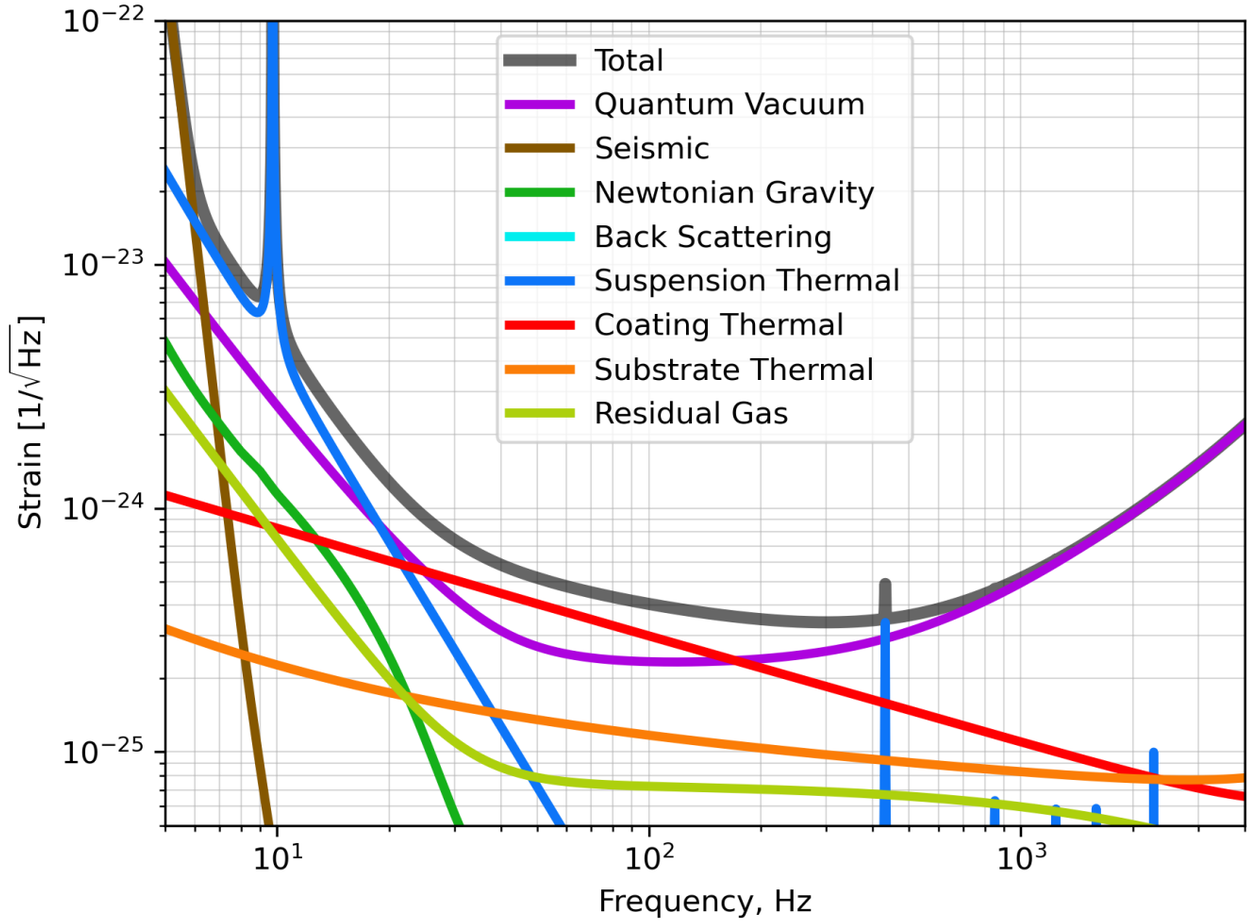


- We can use optical spring to enhance the sensitivity, but it requires 2 FCs



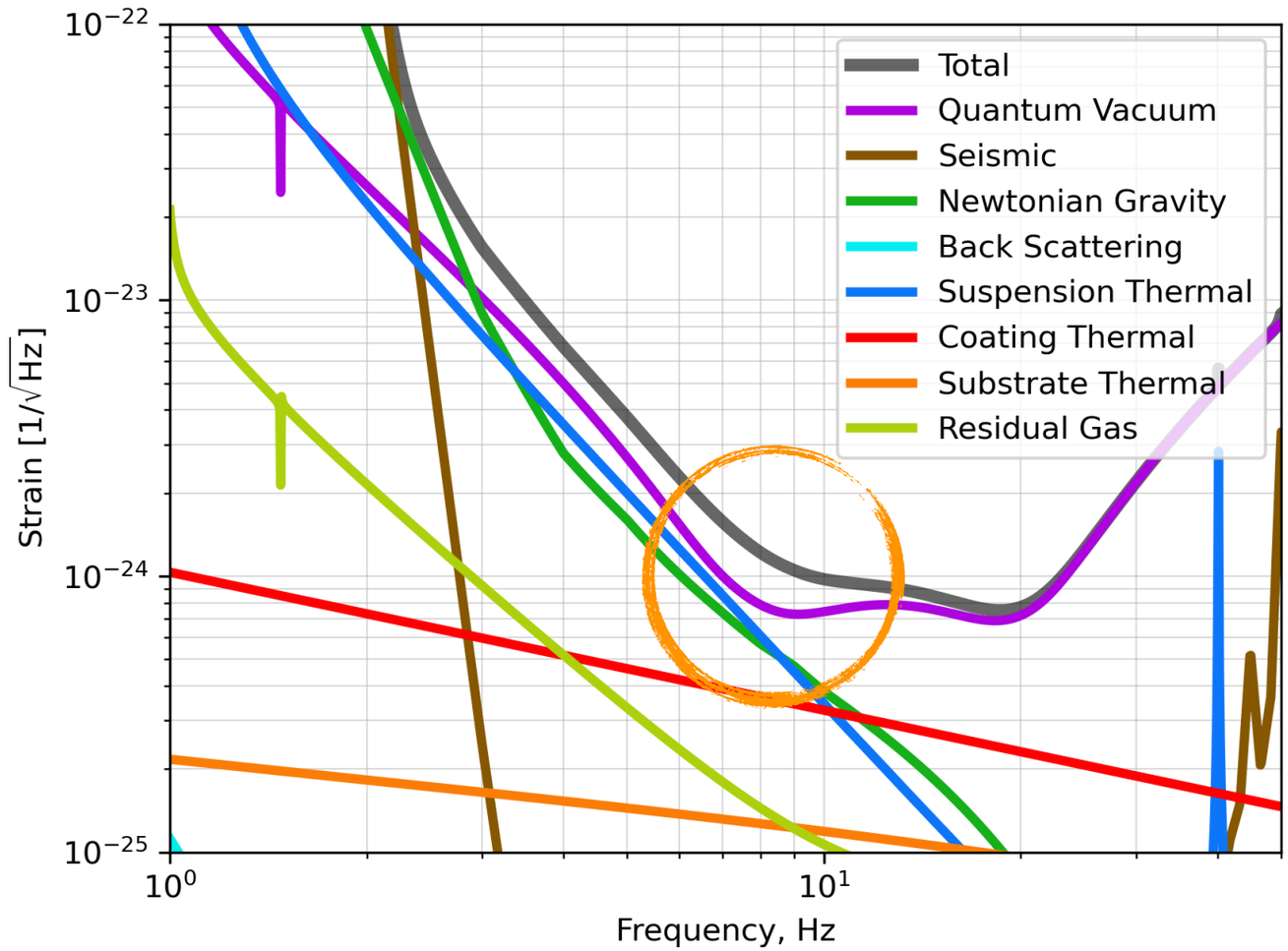
Current issues





Filter cavity loss has triple effects:

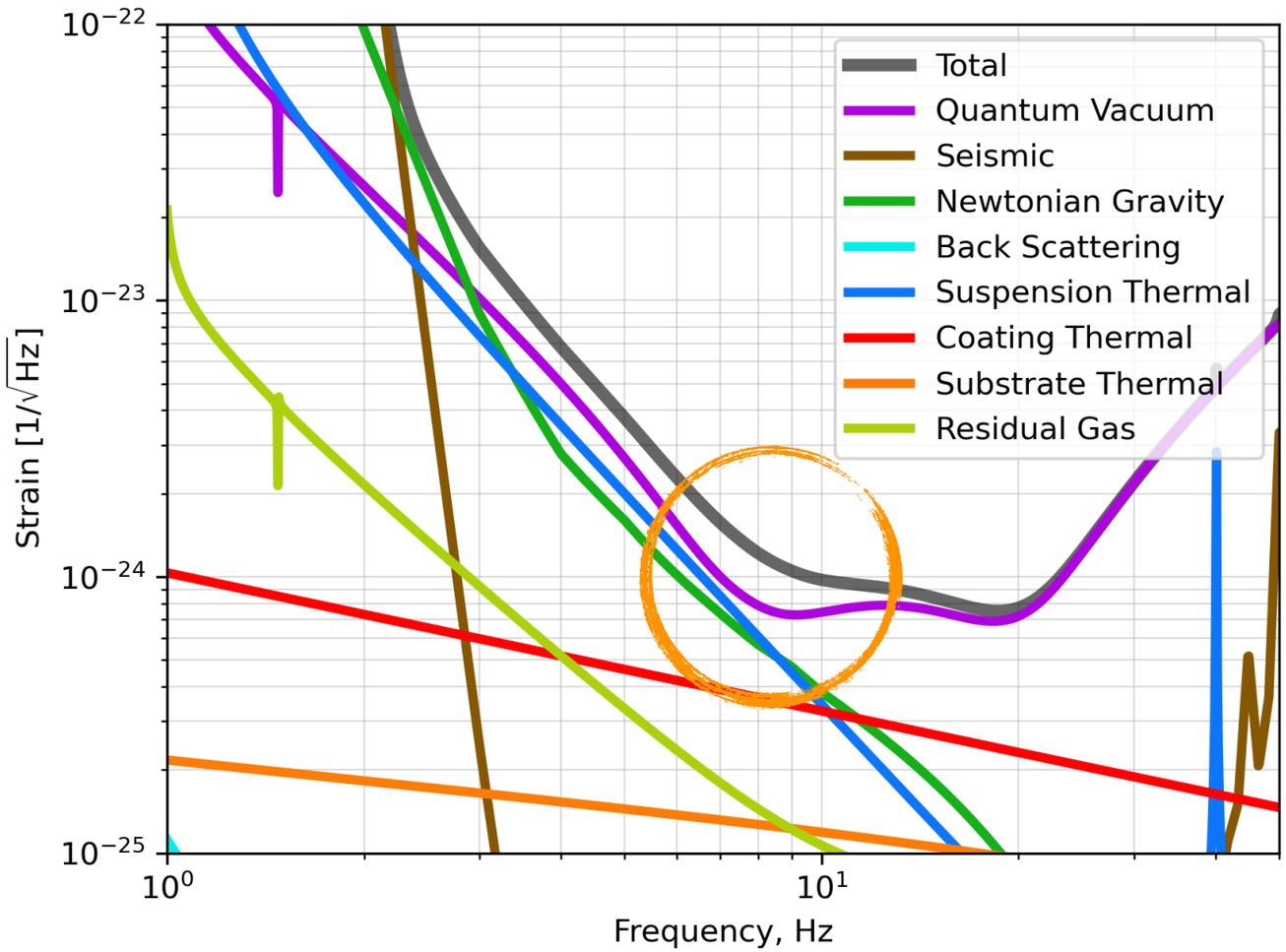
1) direct loss around detuned frequency
2) dephasing around detuned frequency (anti-squeezing couples into squeezing)
3) the need to reduce antisqueezing → reduced squeezing at all frequencies



Filter cavity loss has triple effects:

1) direct loss around detuned frequency
2) dephasing around detuned frequency (anti-squeezing couples into squeezing)
3) the need to reduce antisqueezing → reduced squeezing at all frequencies

We need lower loss in FC → make them longer



Issue 2: FC parameters

Filter cavity optimal linewidth and detuning depend on the light power in the arm cavity and its linewidth

Filter cavity optimal linewidth and detuning depend on
the light power in the arm cavity and its linewidth

We don't know what should be FC parameters before we build the detector and measure!

Also, if we change the light power in the process, we need to change the FC mirrors.

Filter cavity optimal linewidth and detuning depend on
the light power in the arm cavity and its linewidth

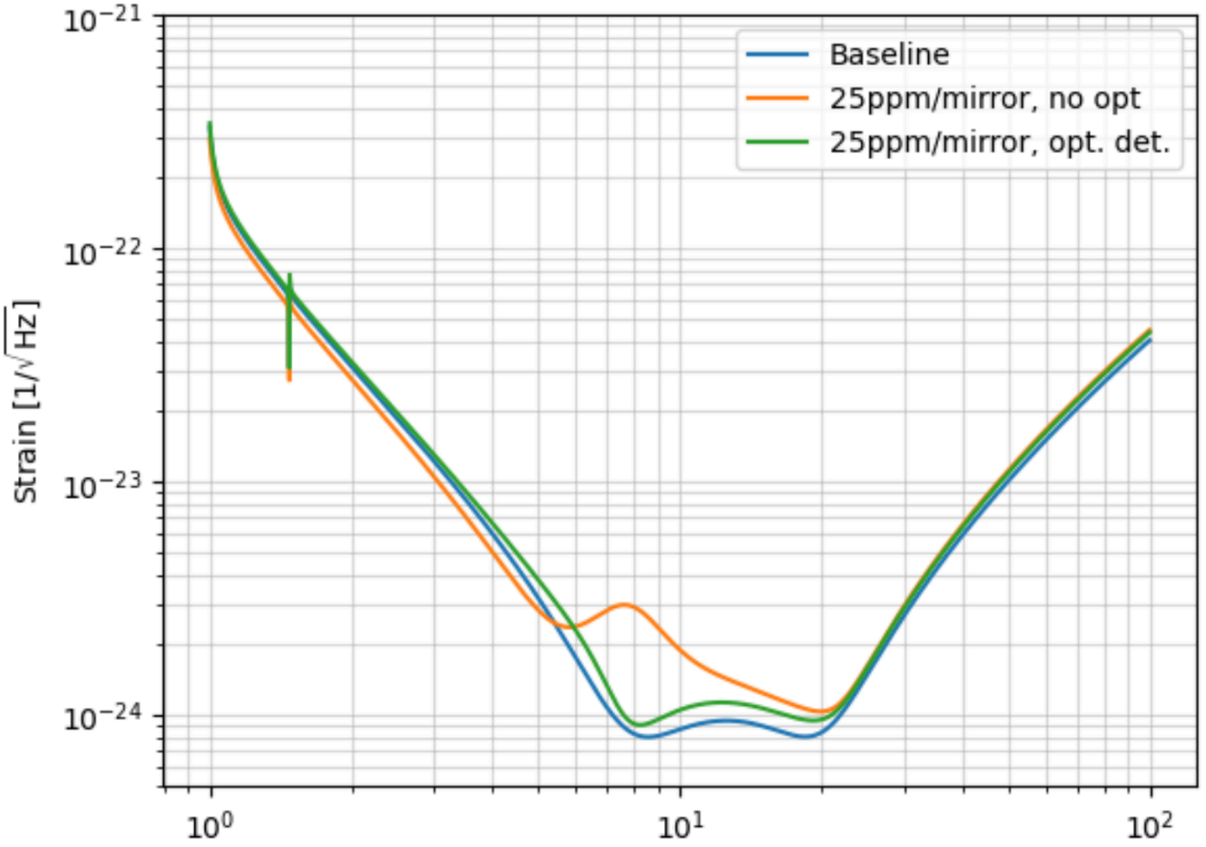
↘

We don't know what should be FC parameters before we build the detector and measure!

Also, if we change the light power in the process,
we need to change the FC mirrors.

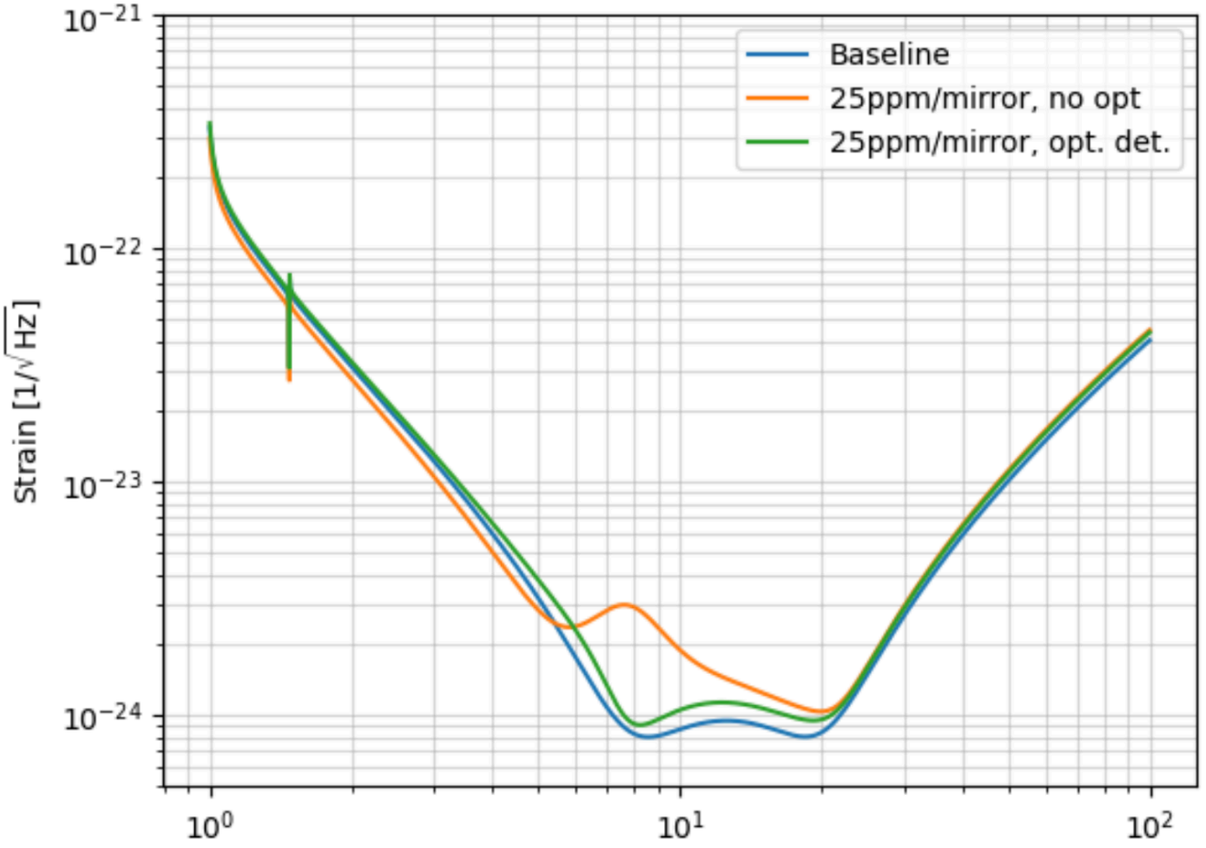
↘

Furthermore, in the cryogenic detector, ice grows
on the mirrors and changes arm cavity power & linewidth

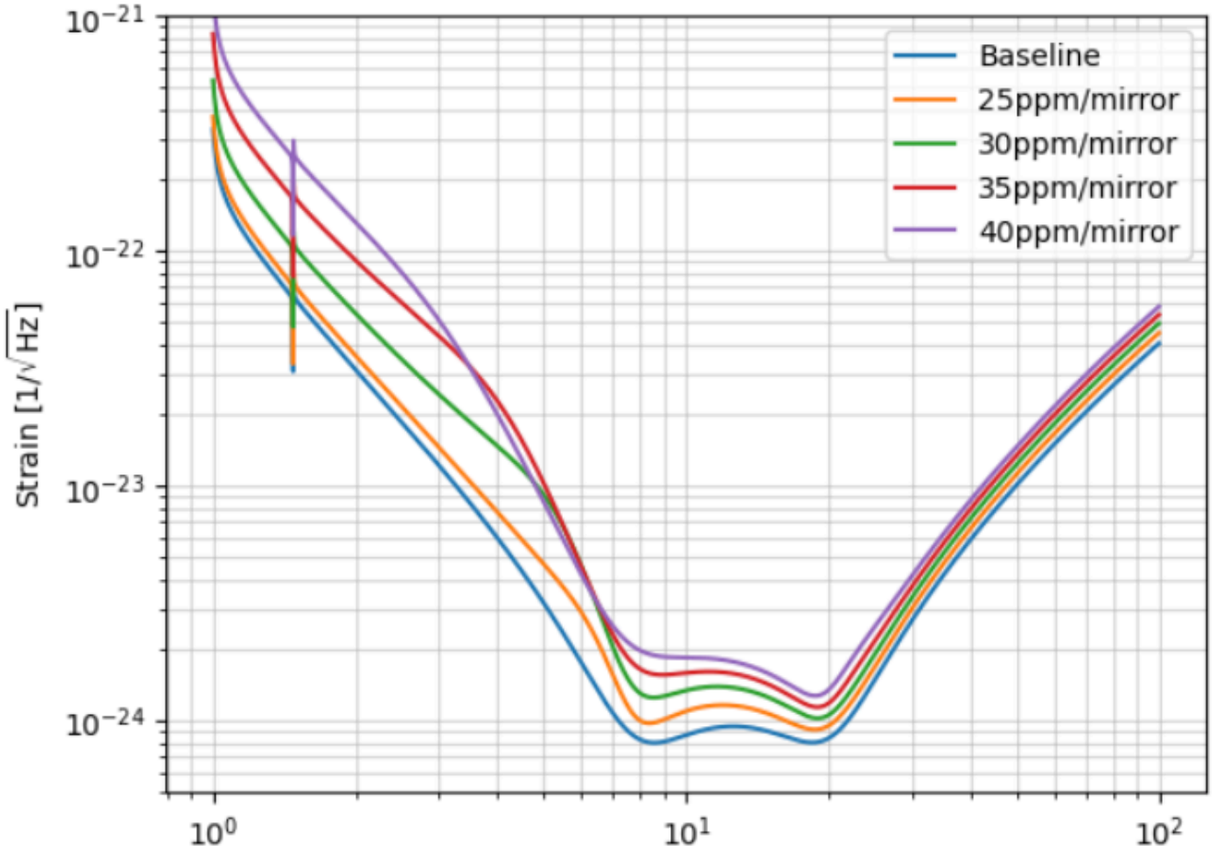


baseline: 20 ppm/mirror in the arm cavity

Current issues



FC tuning



baseline: 20 ppm/mirror in the arm cavity

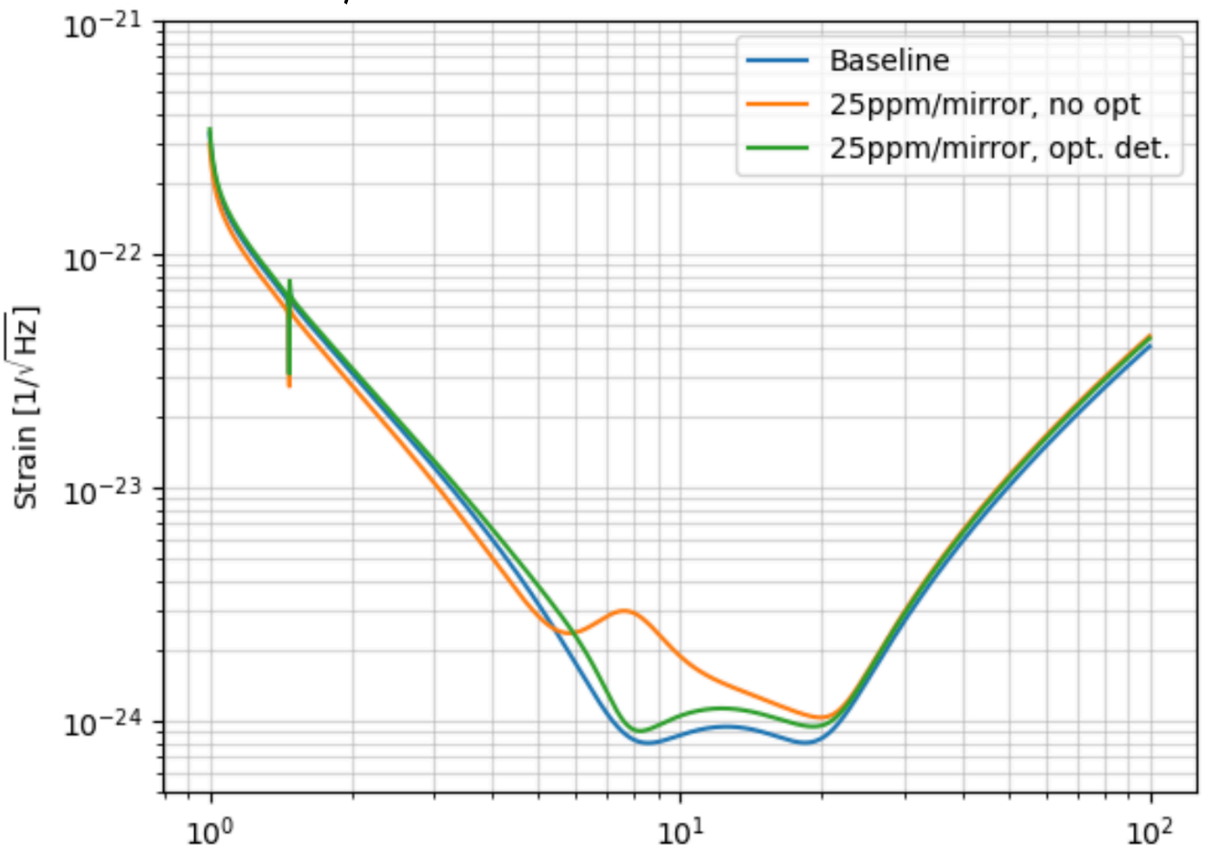
This change is more than we win by going from 1km to 5km FC

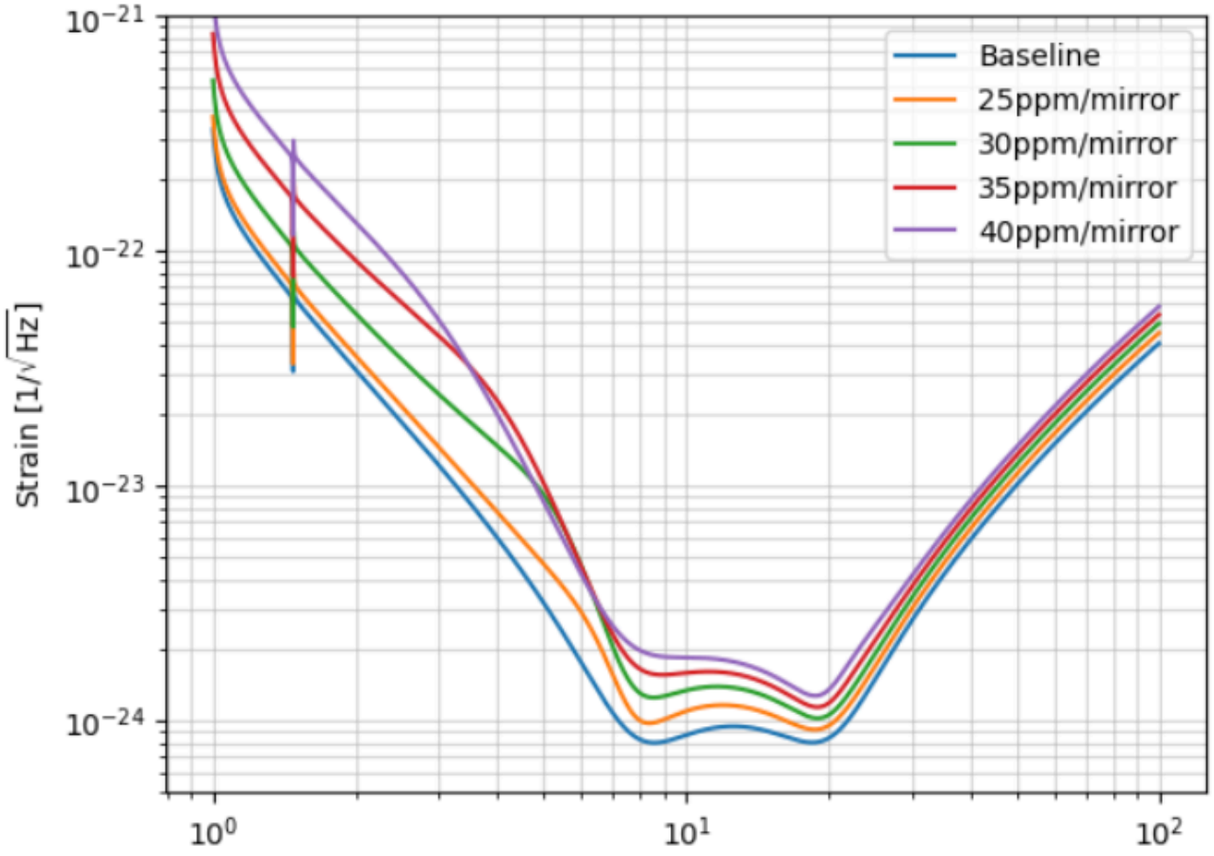
Possible solutions:

1) Exchange mirrors (expensive, long, complex)

2) Have Khalili-etalon to tune the reflectivity of the mirrors

3) ???





baseline: 20 ppm/mirror in the arm cavity

Issue 3: mode mismatch

Issue 3: mode mismatch

See my talk at the last Annual Meeting

ET-0634A-24

Alternative configurations

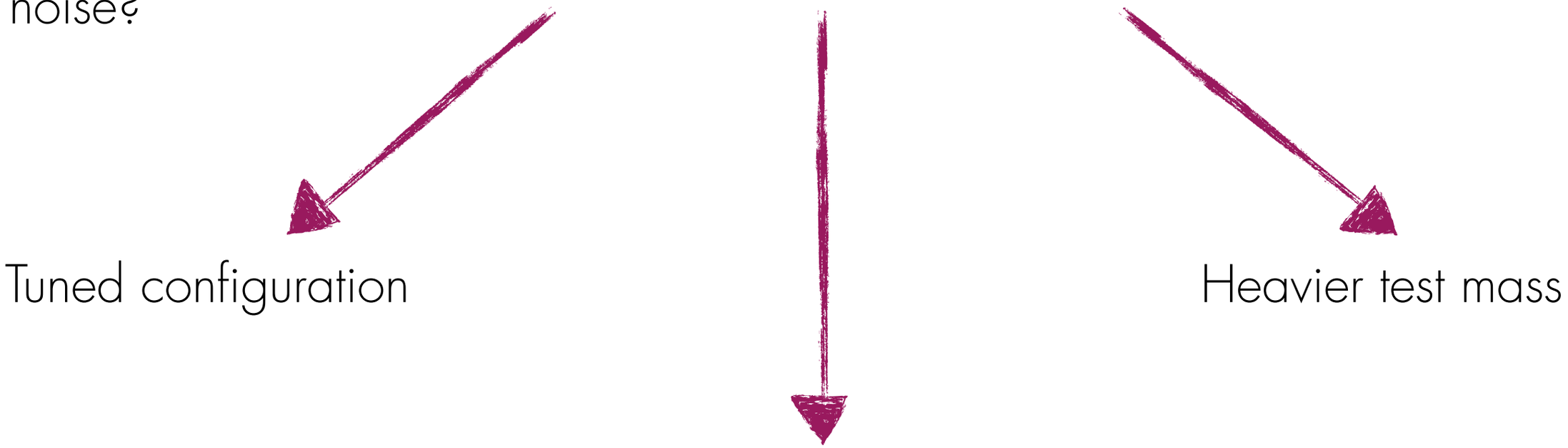
Why having alternatives?

- 5km FCs are very expensive. Could we use just one?
- We've never operated a detuned interferometer. There's no control scheme for that. How do we do it?
- We have a lot of room for improvement, could we do better with quantum noise?

Alternative configurations

Why having alternatives?

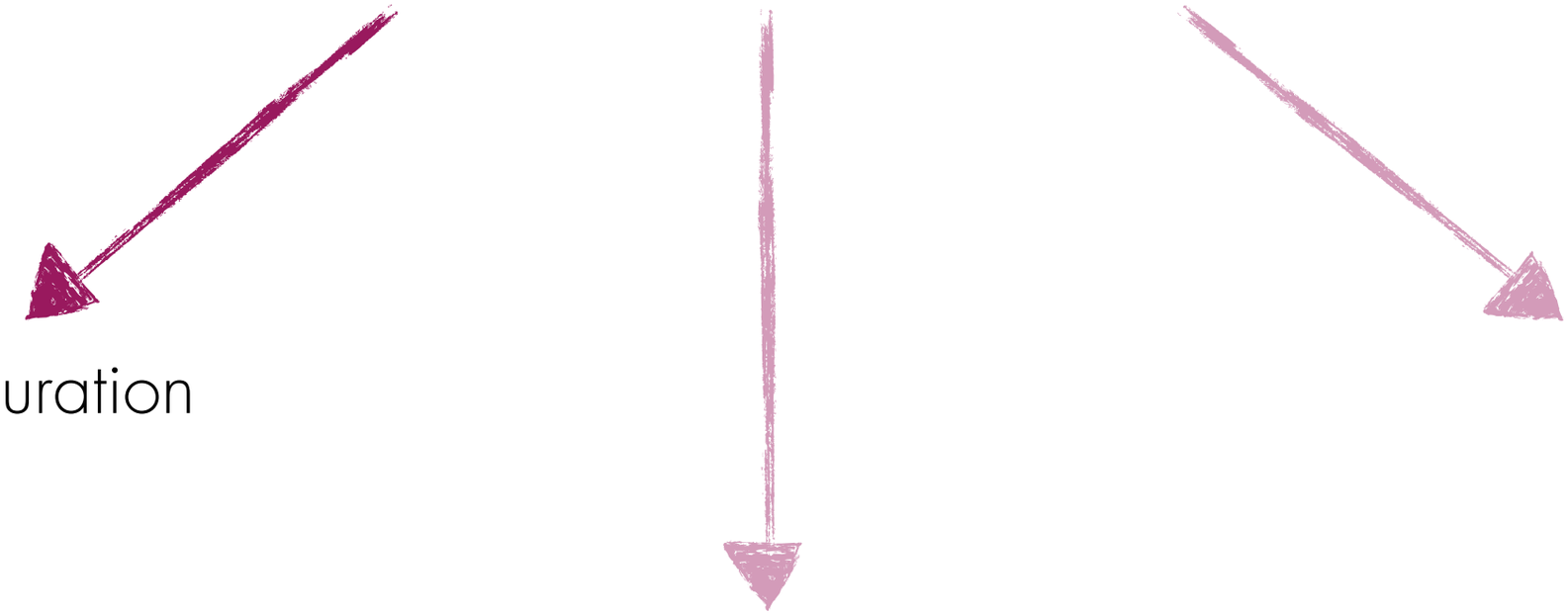
- 5km FCs are very expensive. Could we use just one?
- We've never operated a detuned interferometer. There's no control scheme for that. How do we do it?
- We have a lot of room for improvement, could we do better with quantum noise?



Alternative configurations

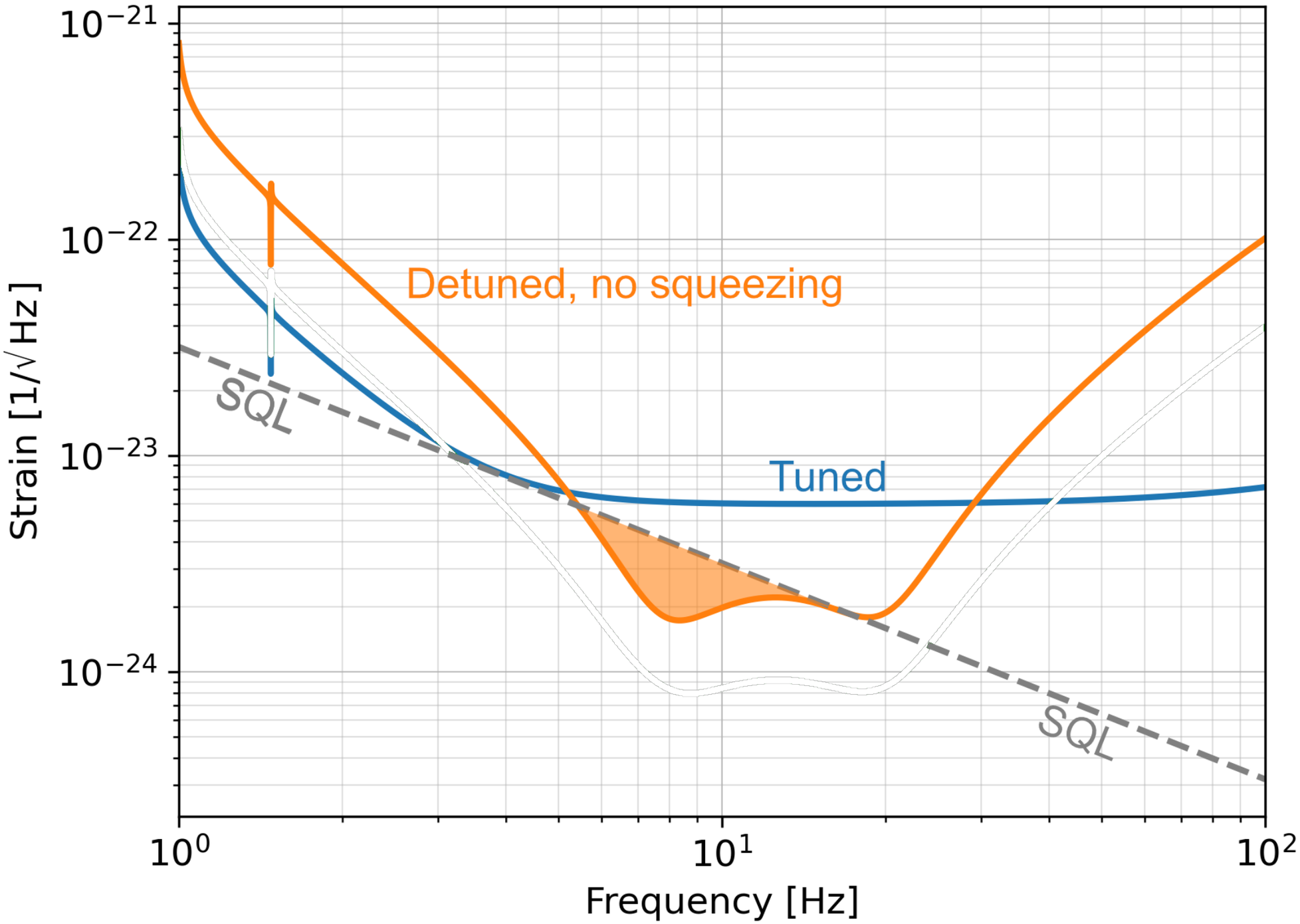
Why having alternatives?

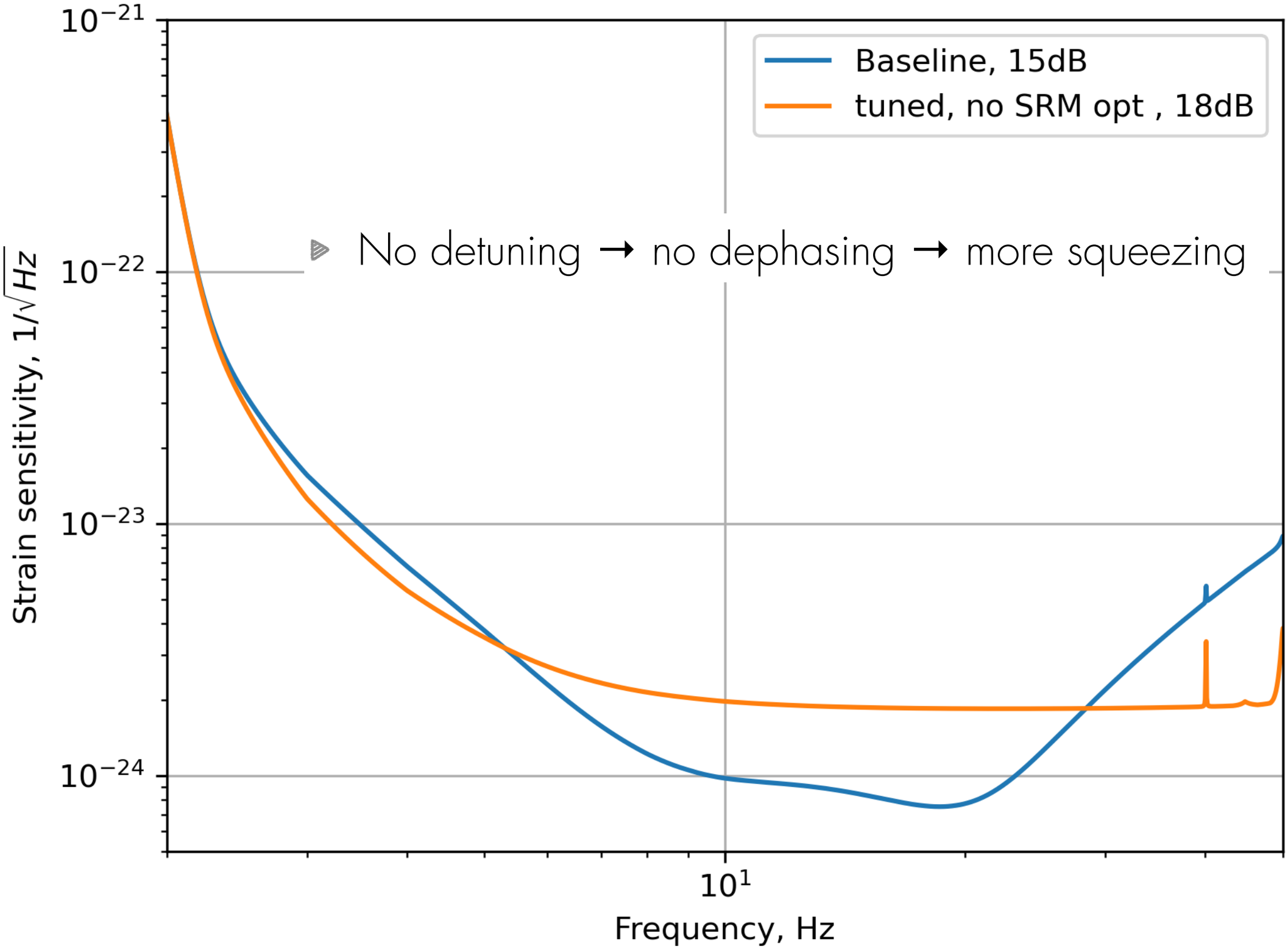
- 5km FCs are very expensive. Could we use just one?
- We've never operated a detuned interferometer. There's no control scheme for that. How do we do it?
- We have a lot of room for improvement, could we do better with quantum noise?

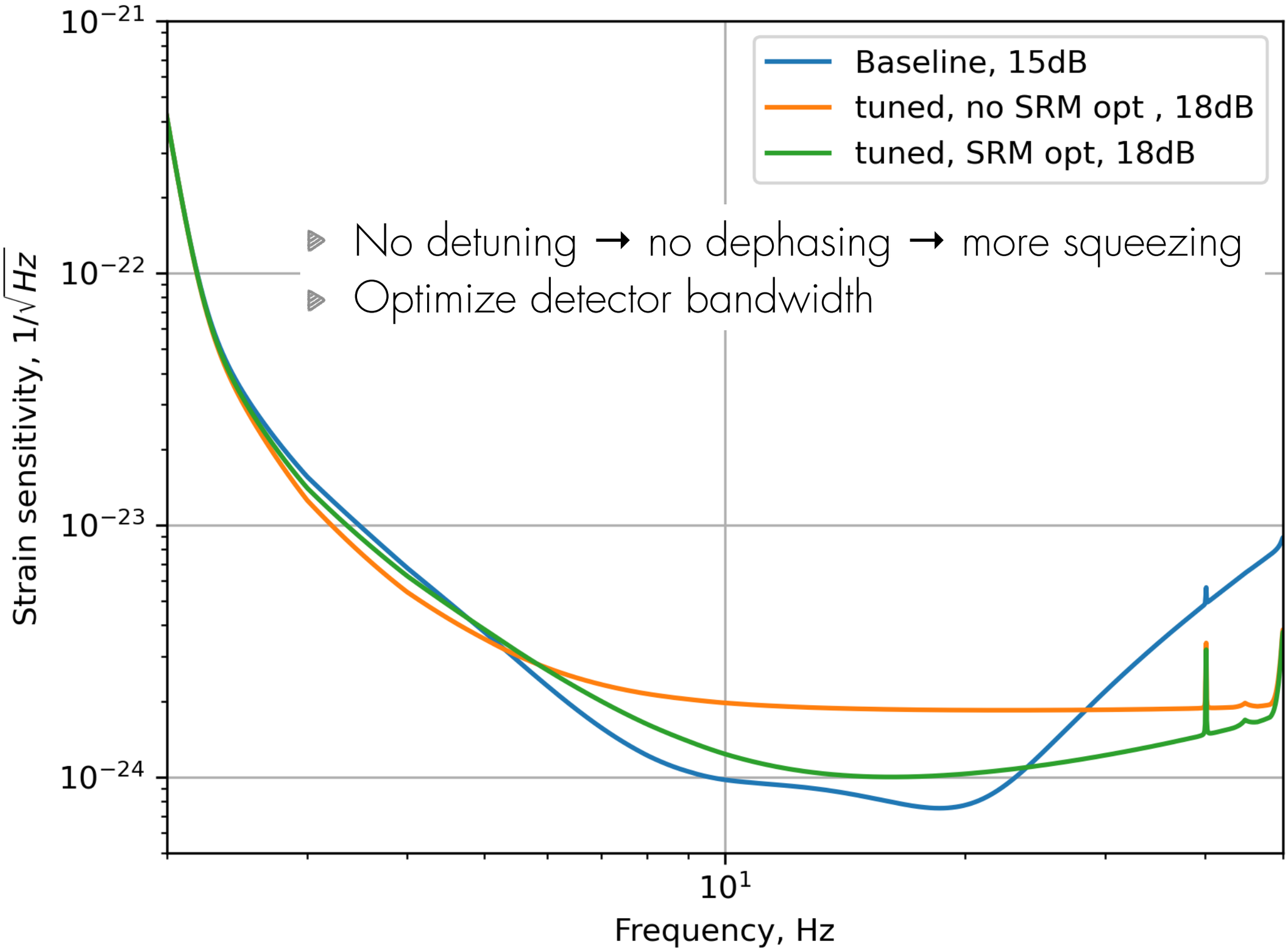


Tuned configuration

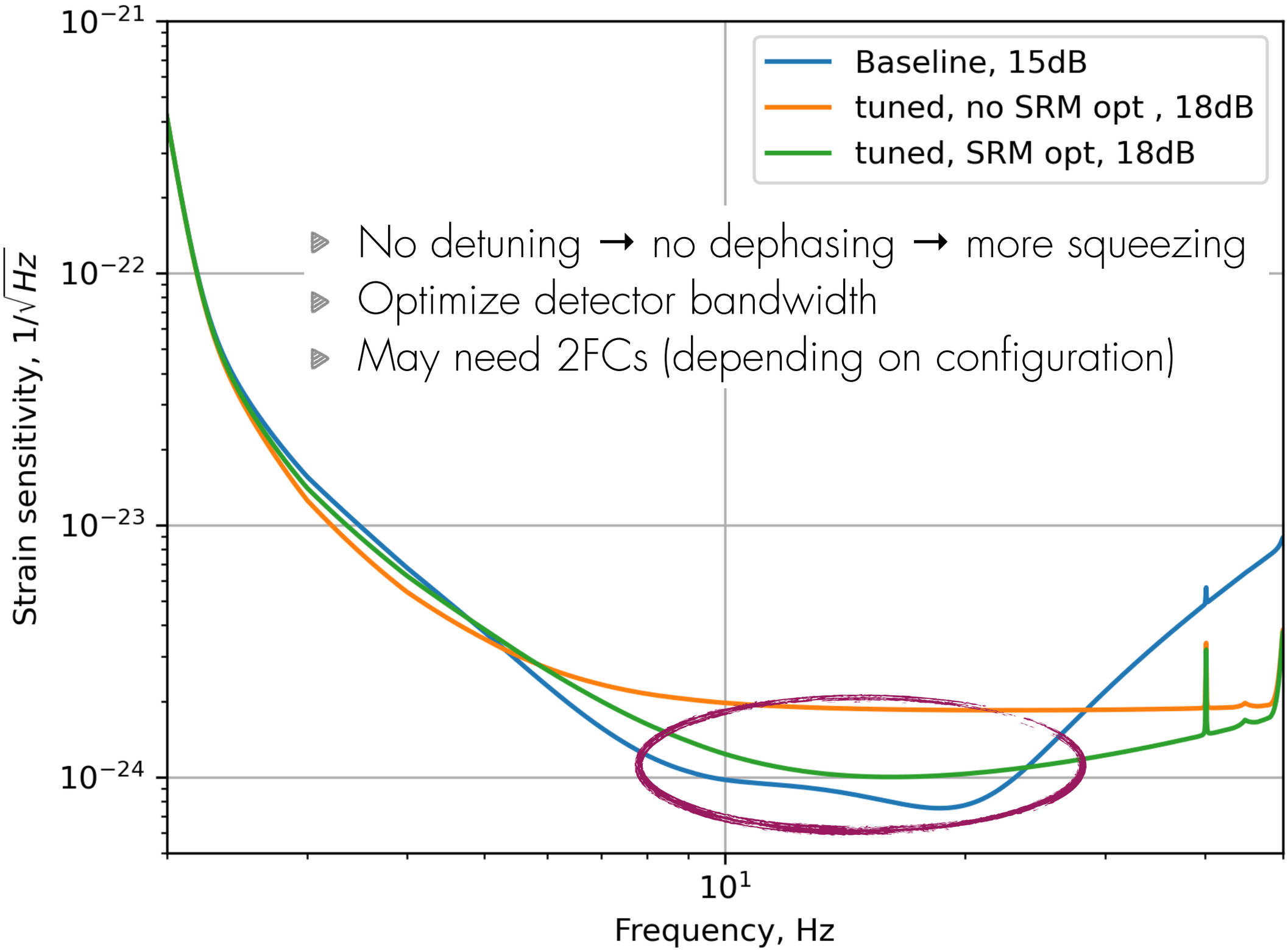
- Tuned configuration needs only 1 FC and could still have good sensitivity



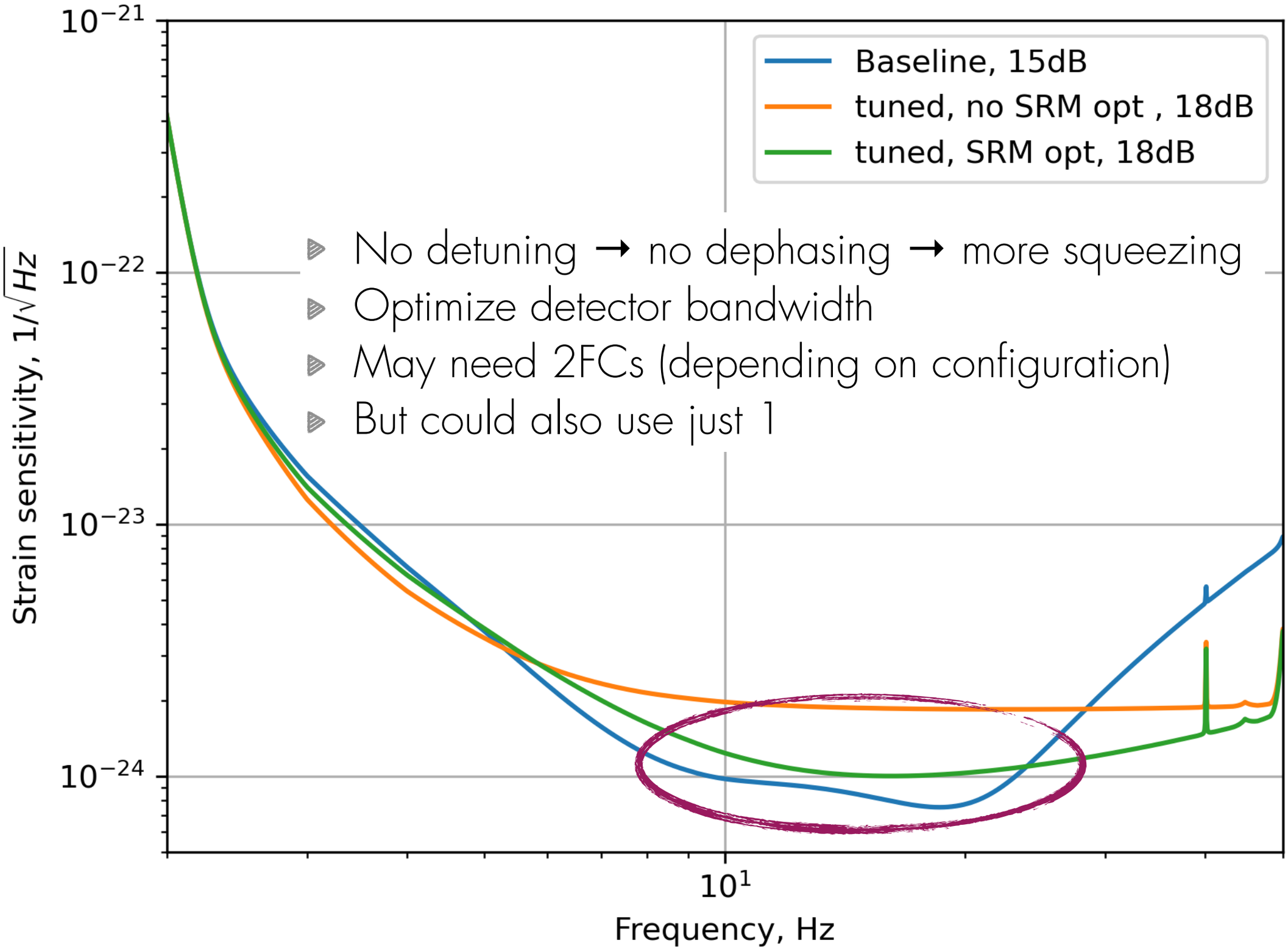

Baseline, 15dB
tuned, no SRM opt , 18dB
No detuning → no dephasing → more squeezing
Strain sensitivity, $1/\sqrt{Hz}$
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
Frequency, Hz



- No detuning → no dephasing → more squeezing
- Optimize detector bandwidth



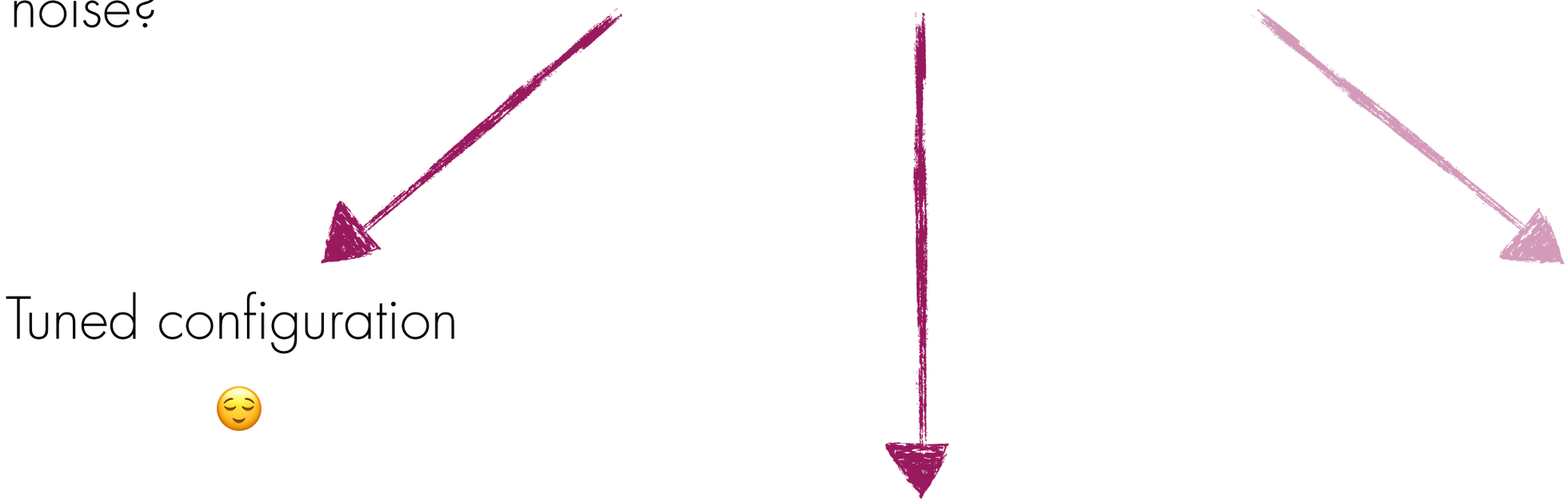
- No detuning → no dephasing → more squeezing
- Optimize detector bandwidth
- May need 2FCs (depending on configuration)



- No detuning → no dephasing → more squeezing
- Optimize detector bandwidth
- May need 2FCs (depending on configuration)
- But could also use just 1

Why having alternatives?

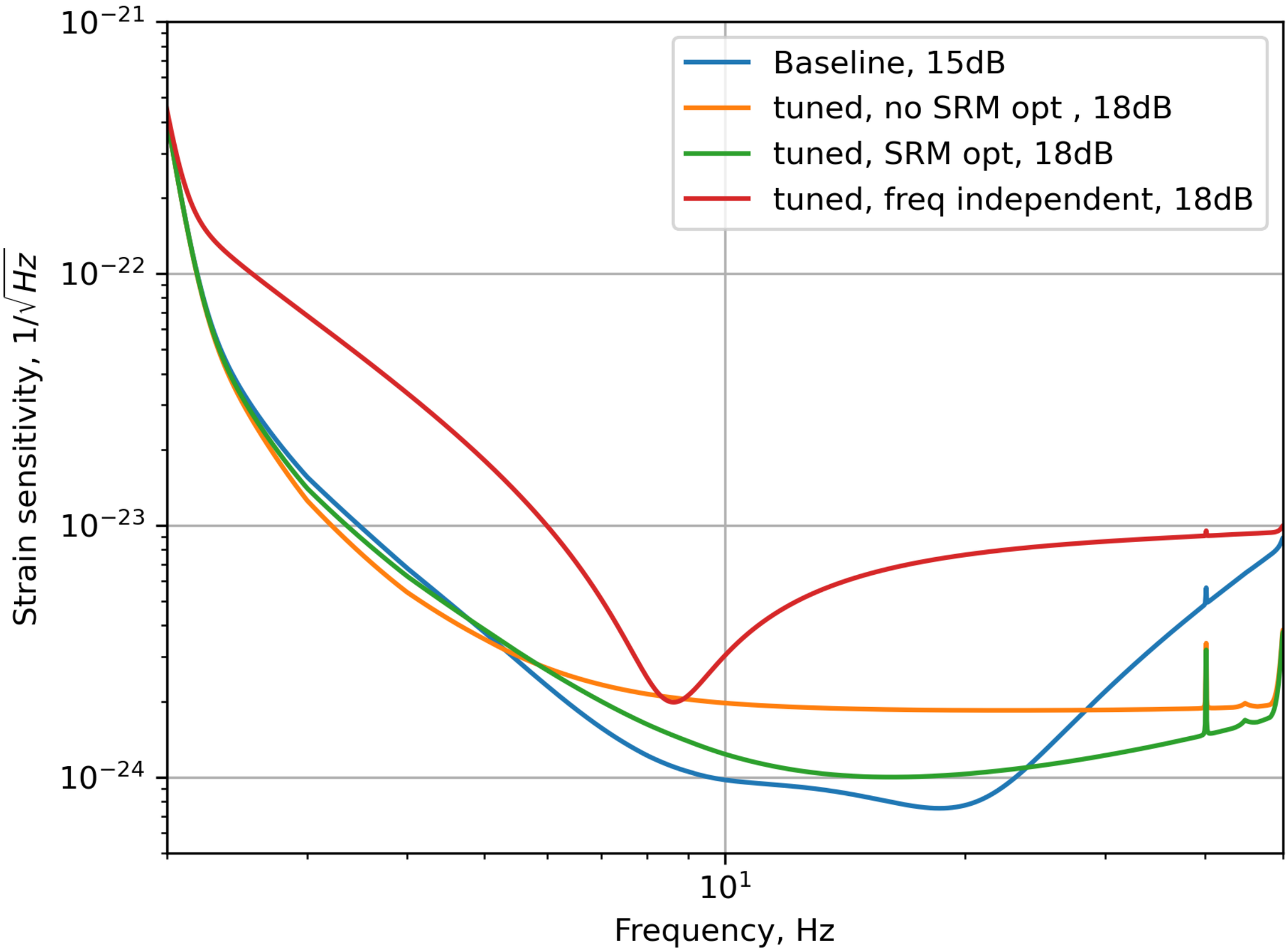
- 5km FCs are very expensive. Could we use just one?
- We've never operated a detuned interferometer. There's no control scheme for that. How do we do it?
- We have a lot of room for improvement, could we do better with quantum noise?

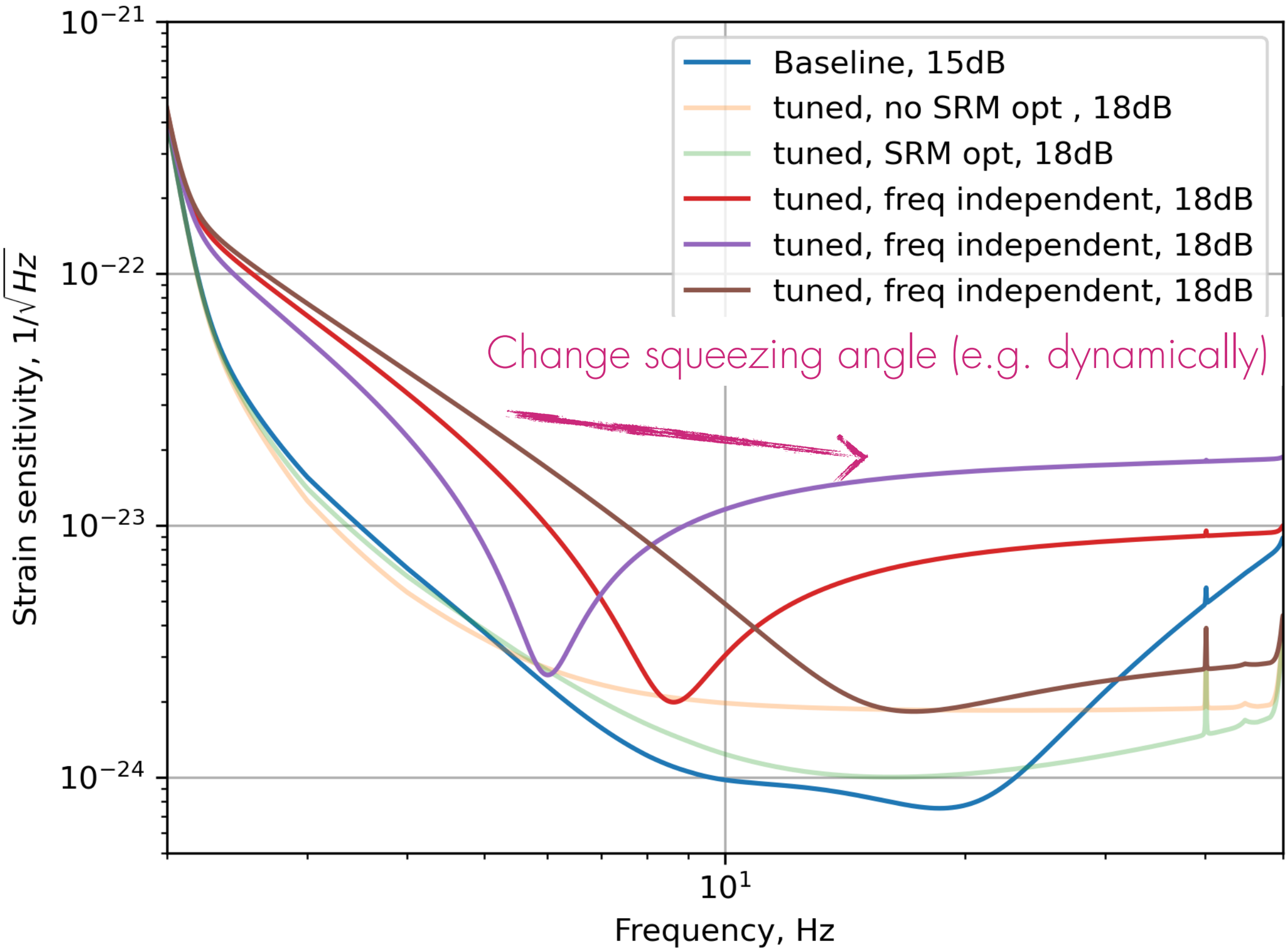


Tuned configuration

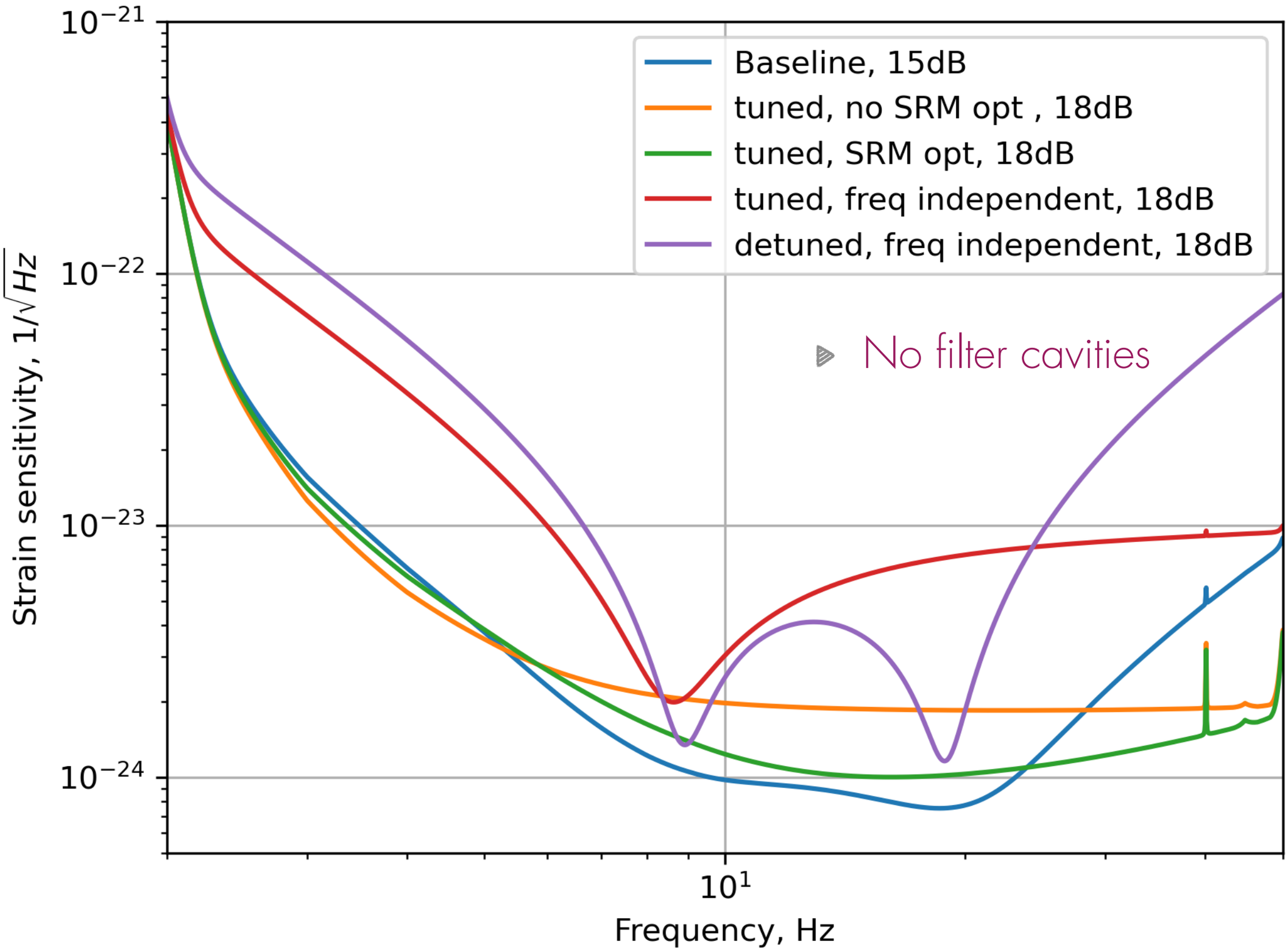
😌

Without filter cavities


Baseline, 15dB
tuned, no SRM opt , 18dB
tuned, SRM opt, 18dB
tuned, freq independent, 18dB
10^{-21}
10^{-22}
10^{-23}
10^{-24}
Strain sensitivity, $1/\sqrt{Hz}$
10^{1}
Frequency, Hz


Baseline, 15dB
tuned, no SRM opt , 18dB
tuned, SRM opt, 18dB
tuned, freq independent, 18dB
tuned, freq independent, 18dB
tuned, freq independent, 18dB
Change squeezing angle (e.g. dynamically)
Strain sensitivity, $1/\sqrt{Hz}$
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
Frequency, Hz

No FDS



- No filter cavities

Why having alternatives?

- 5km FCs are very expensive. Could we use just one?
- We've never operated a detuned interferometer. There's no control scheme for that. How do we do it?
- We have a lot of room for improvement, could we do better with quantum noise?

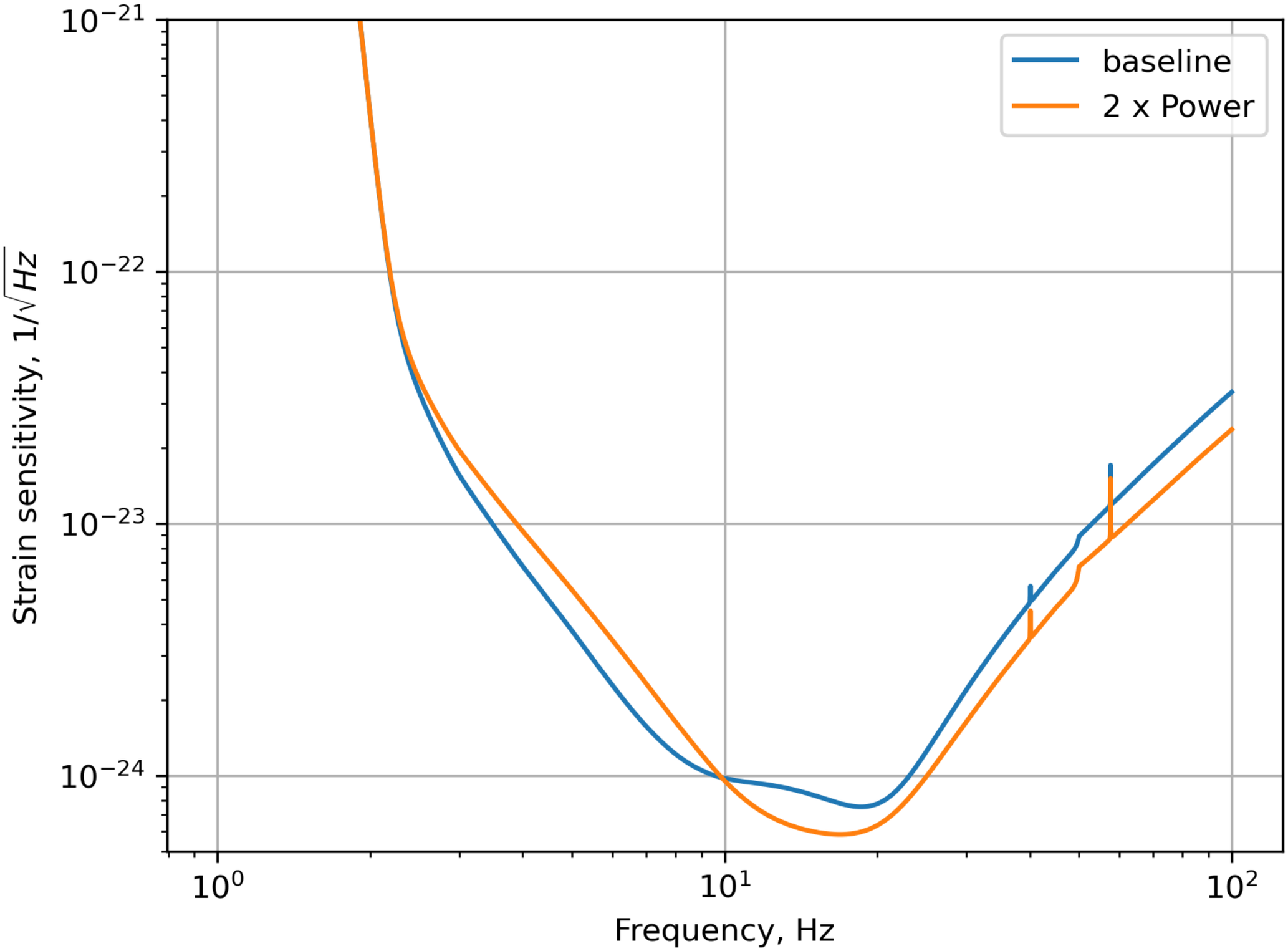
Tuned configuration

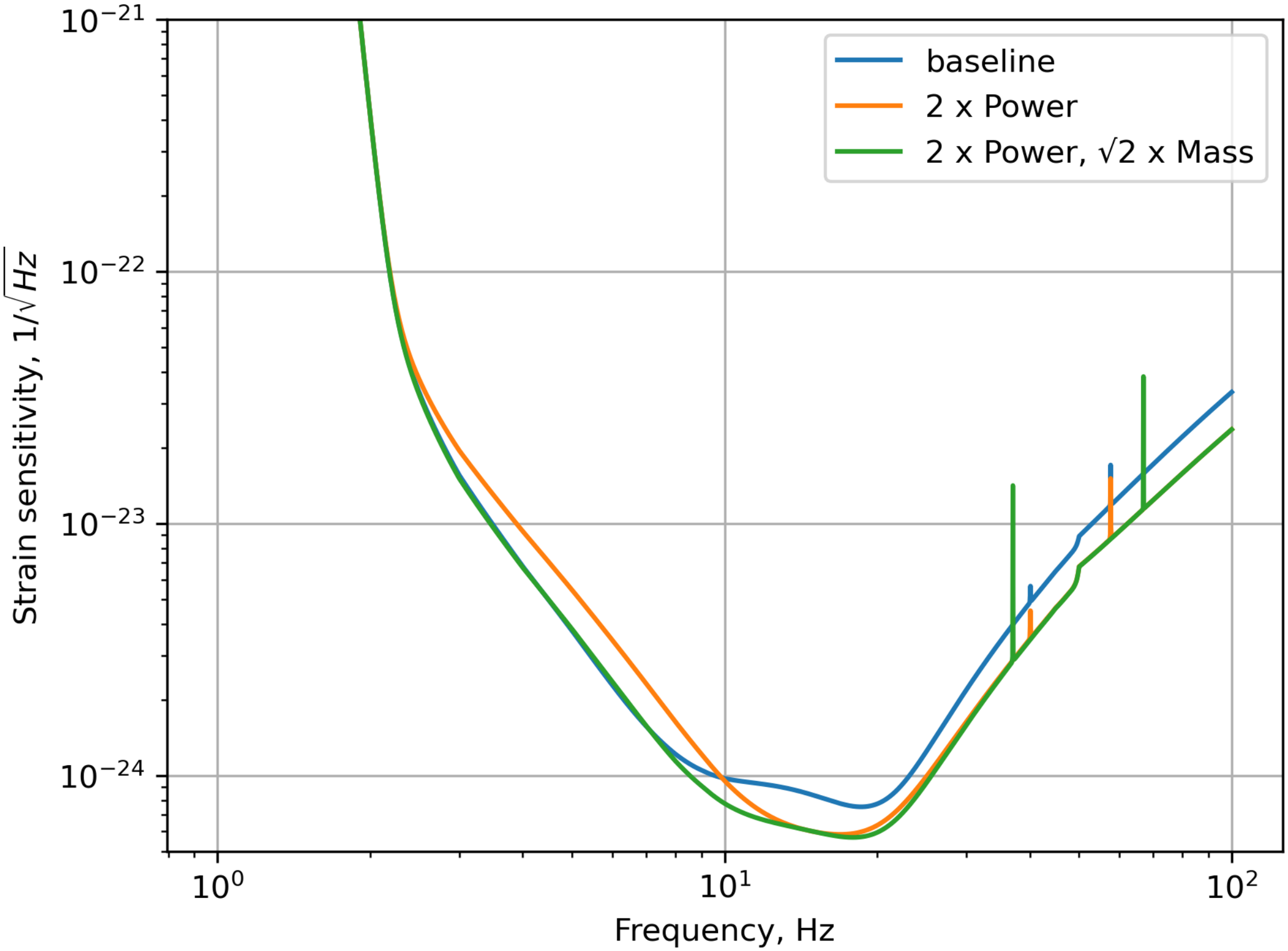
😌

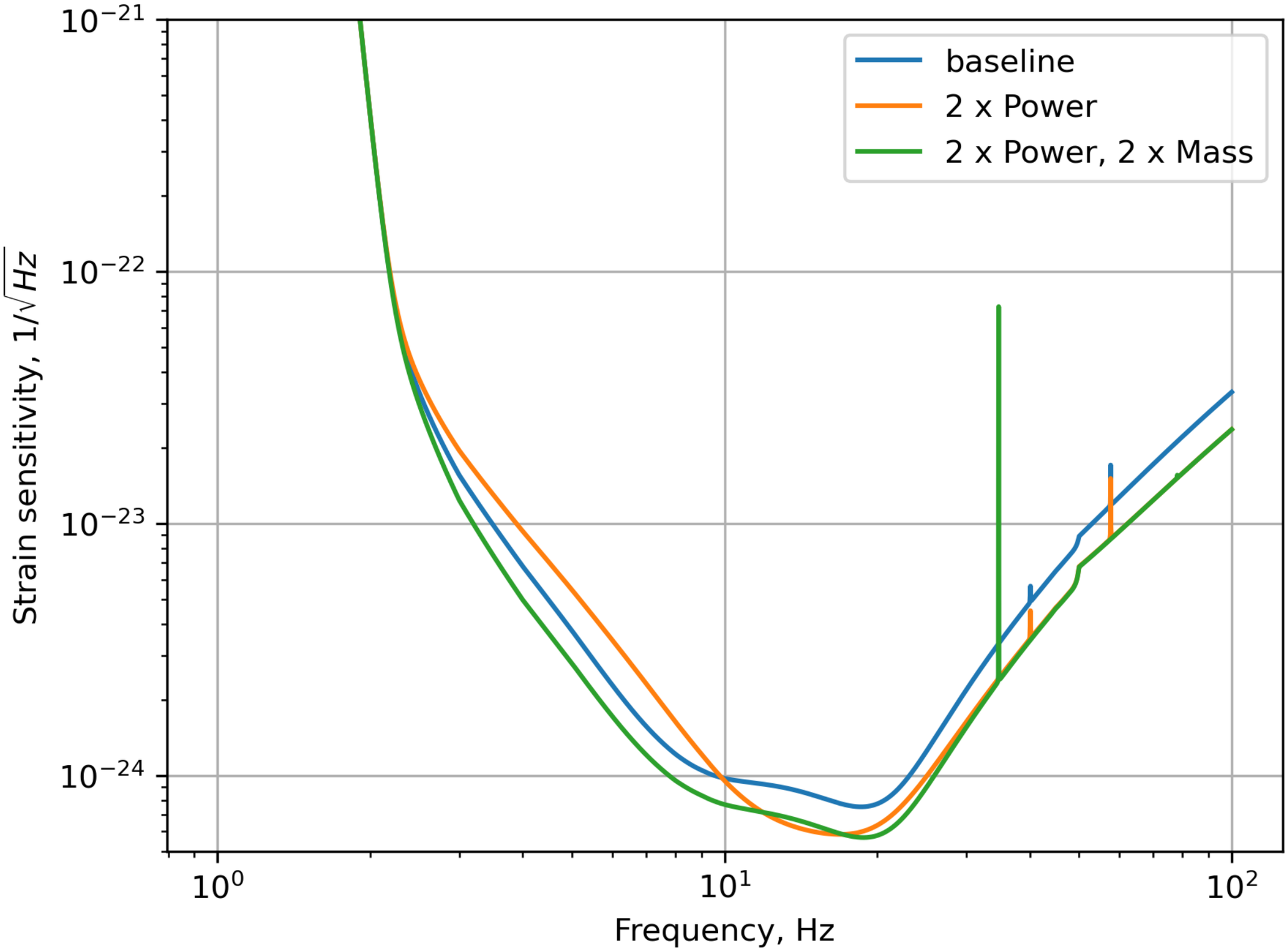
Detuned without squeezing

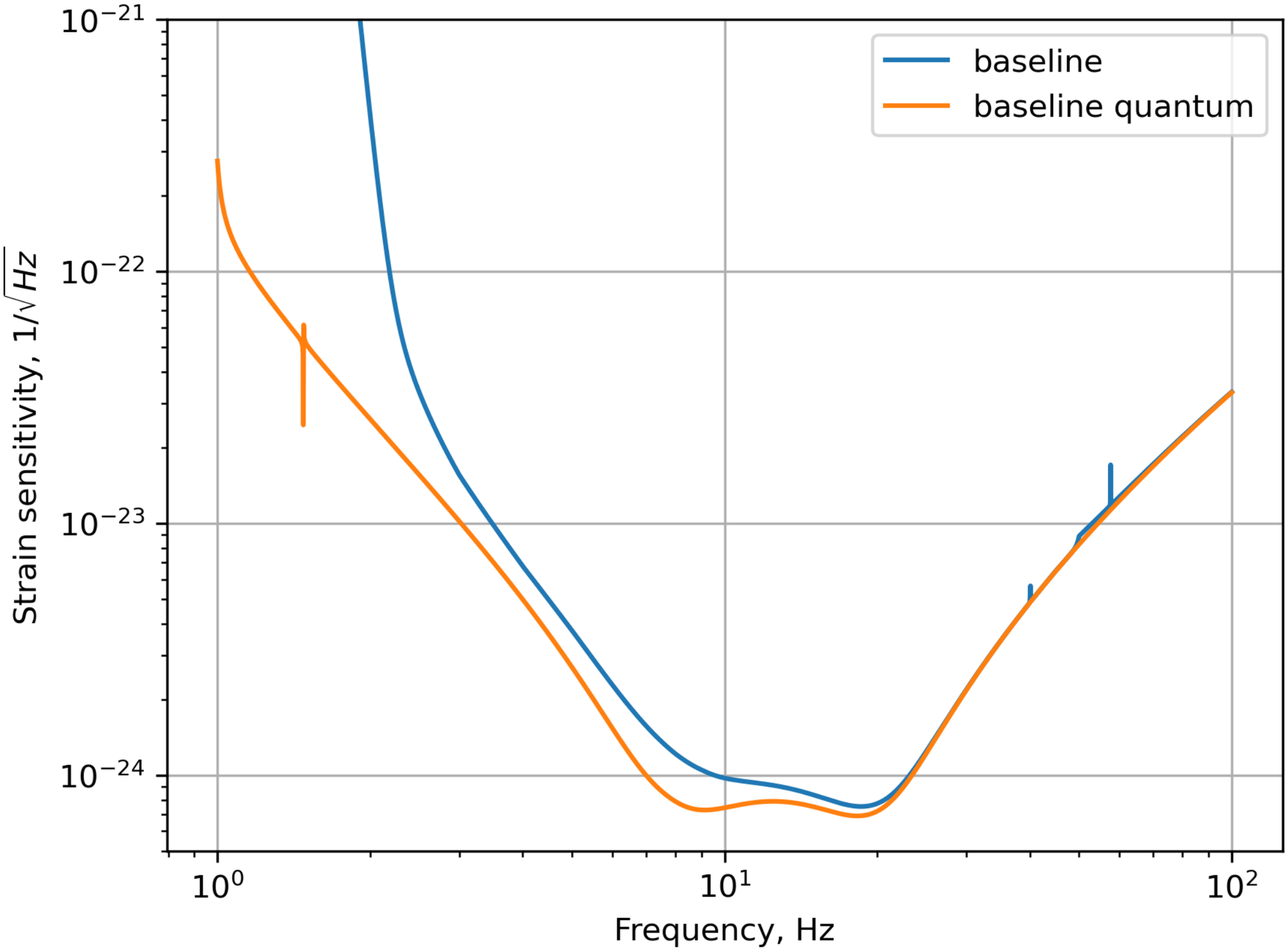
😕

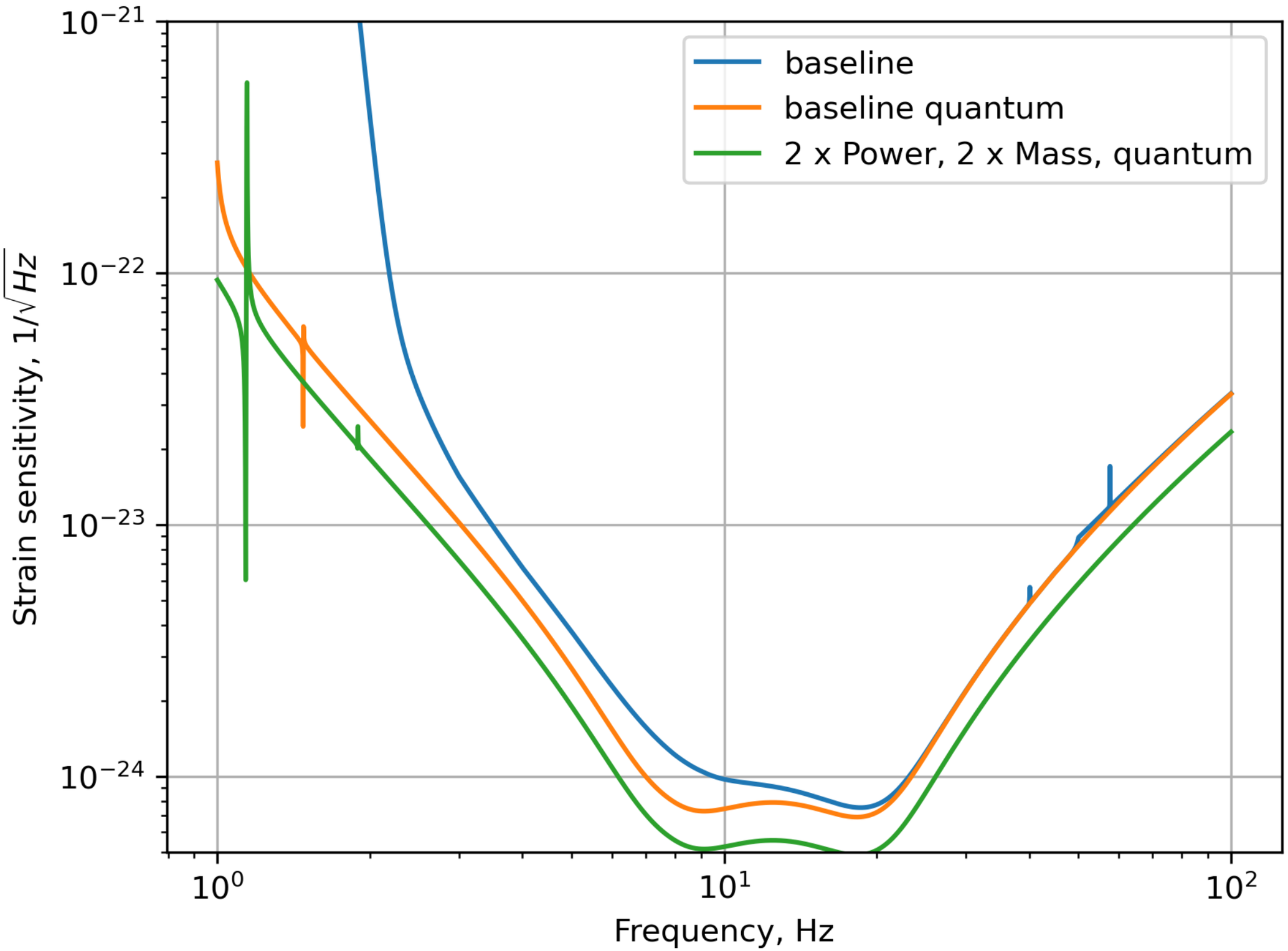
Heavier test mass

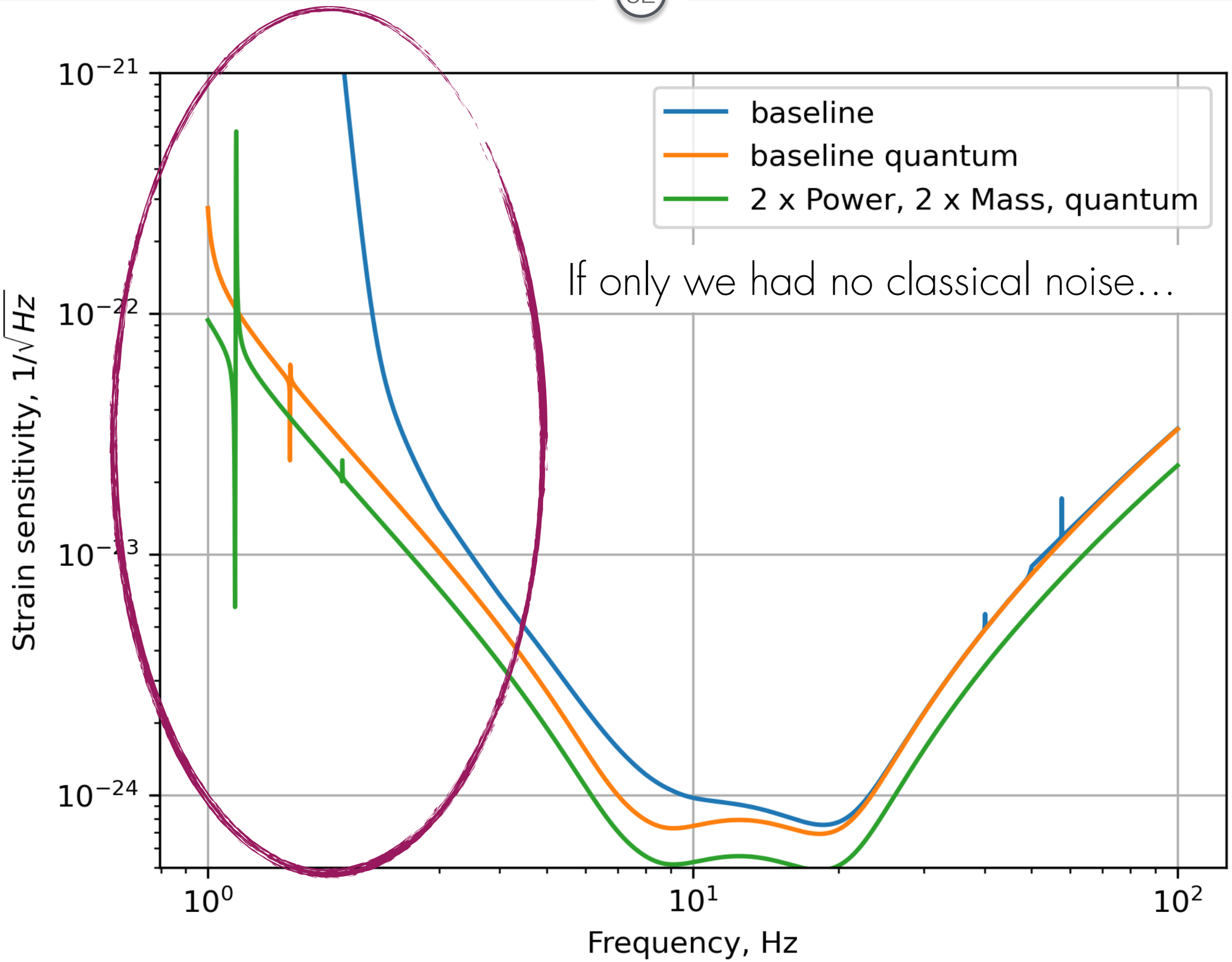

baseline
2 x Power
Strain sensitivity, $1/\sqrt{Hz}$
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{0}
10^{1}
10^{2}
Frequency, Hz


baseline
2 x Power
2 x Power, √2 x Mass
Strain sensitivity, 1/√Hz
Frequency, Hz
10^−21
10^−22
10^−23
10^−24
10^0
10^1
10^2


baseline
2 x Power
2 x Power, 2 x Mass
Strain sensitivity, $1/\sqrt{Hz}$
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{0}
10^{1}
10^{2}
Frequency, Hz


baseline
baseline quantum
Strain sensitivity, $1/\sqrt{Hz}$
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{0}
10^{1}
10^{2}
Frequency, Hz


baseline
baseline quantum
2 x Power, 2 x Mass, quantum
Strain sensitivity, $1/\sqrt{Hz}$
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{0}
10^{1}
10^{2}
Frequency, Hz


baseline
baseline quantum
2 x Power, 2 x Mass, quantum
If only we had no classical noise…
Strain sensitivity, $1/\sqrt{Hz}$
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{0}
10^{1}
10^{2}
Frequency, Hz

Why having alternatives?

- 5km FCs are very expensive. Could we use just one?
- We've never operated a detuned interferometer. There's no control scheme for that. How do we do it?
- We have a lot of room for improvement, could we do better with quantum noise?

Tuned configuration

😌

Detuned without squeezing

😕

Heavier test mass

🤩

Outlook

Hot topics:

- Better understand impact of mode mismatch
- Find practical ways to adjust FC parameters
- Look for alternative configurations (like EPR squeezing)

Outlook

Hot topics:

- Better understand impact of mode mismatch
- Find practical ways to adjust FC parameters
- Look for alternative configurations (like EPR squeezing)

But we can (and should) also look at the alternatives: both as the backup and as the new research venues…

Outlook

Hot topics:

- Better understand impact of mode mismatch
- Find practical ways to adjust FC parameters
- Look for alternative configurations (like EPR squeezing)

But we can (and should) also look at the alternatives: both as the backup and as the new research venues…

…what if one day we learn how to build an (even more) amazing suspension and to evade newtonian noise?

Outlook

Hot topics:

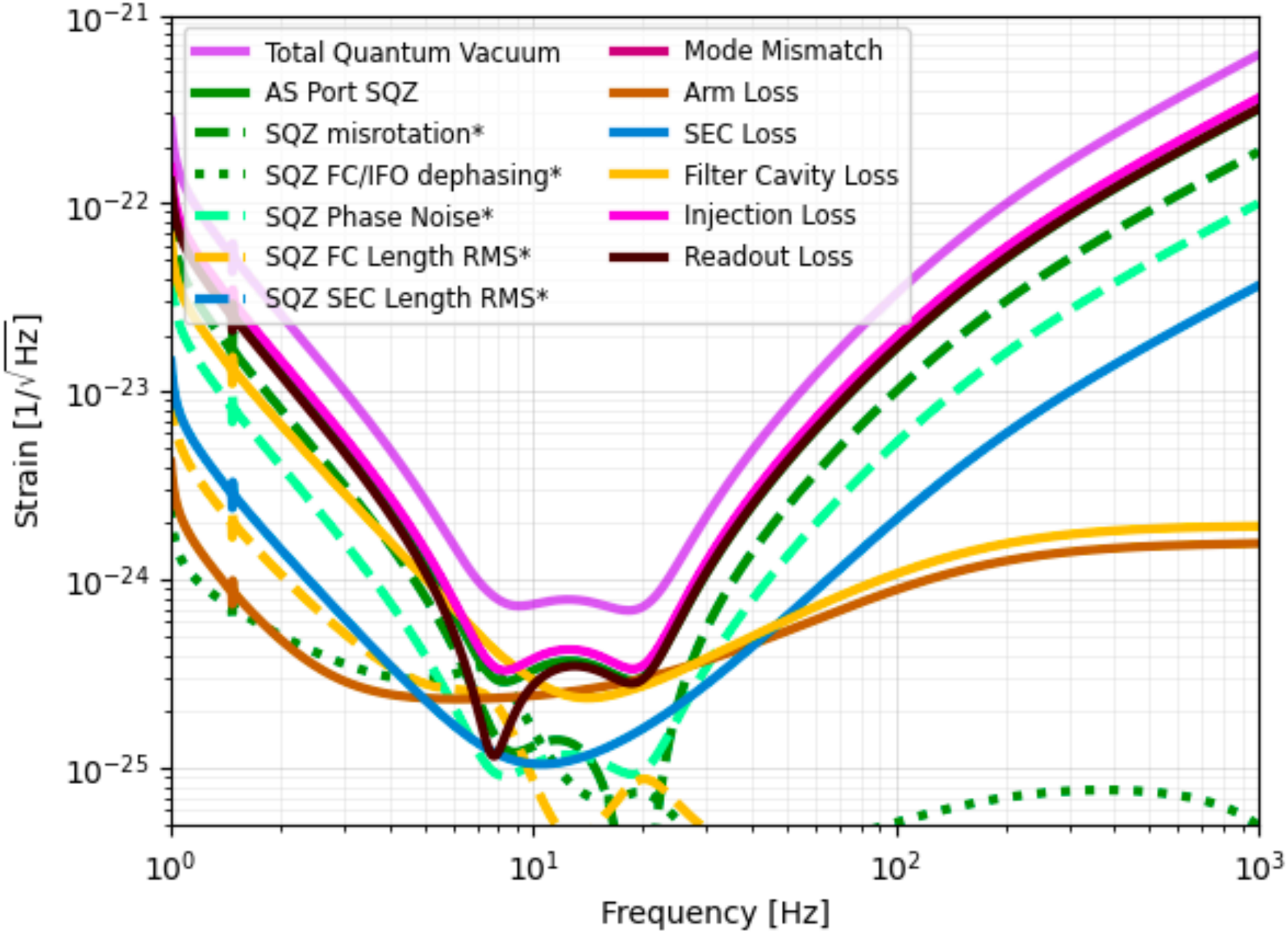
- Better understand impact of mode mismatch
- Find practical ways to adjust FC parameters
- Look for alternative configurations (like EPR squeezing)

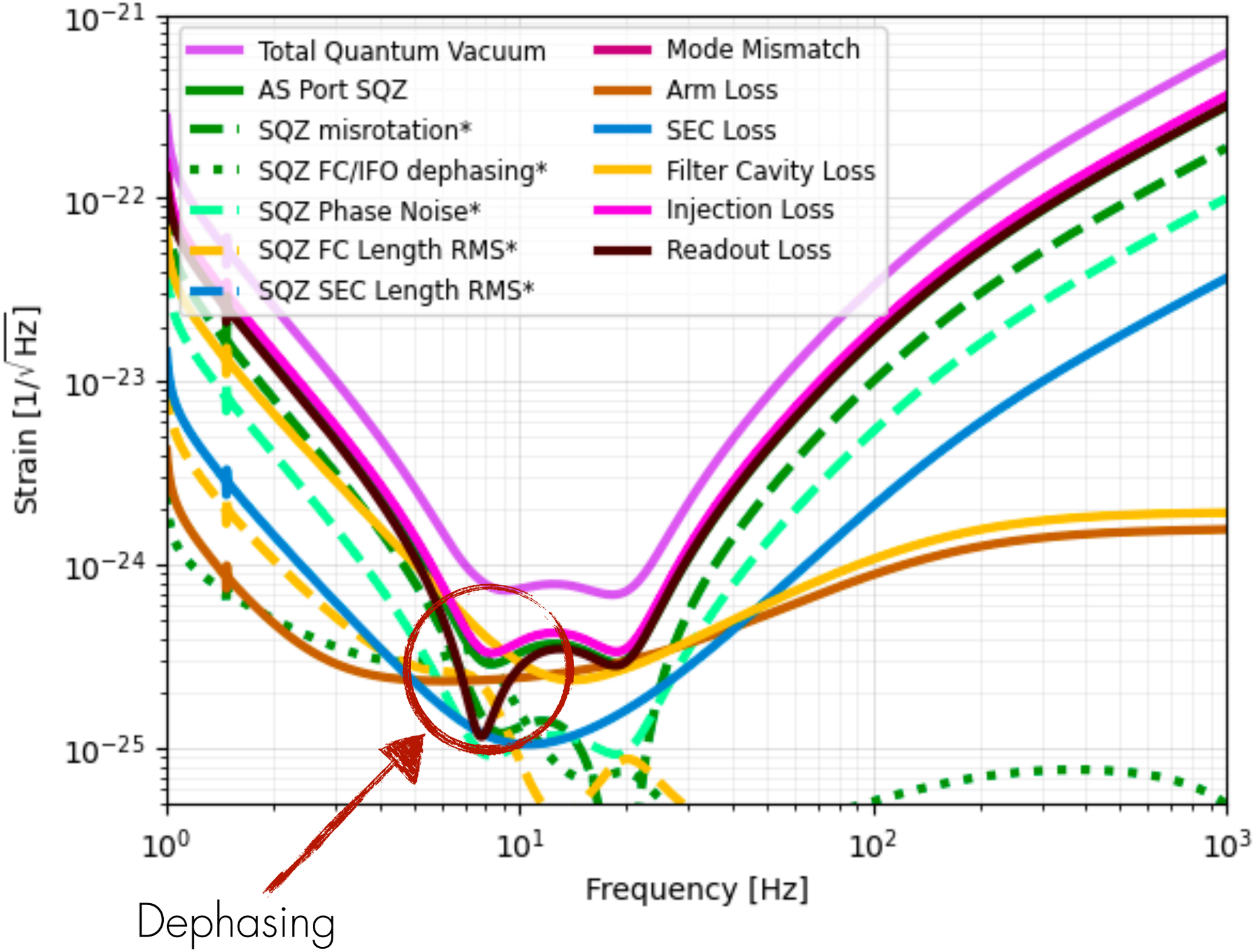
But we can (and should) also look at the alternatives: both as the backup and as the new research venues.

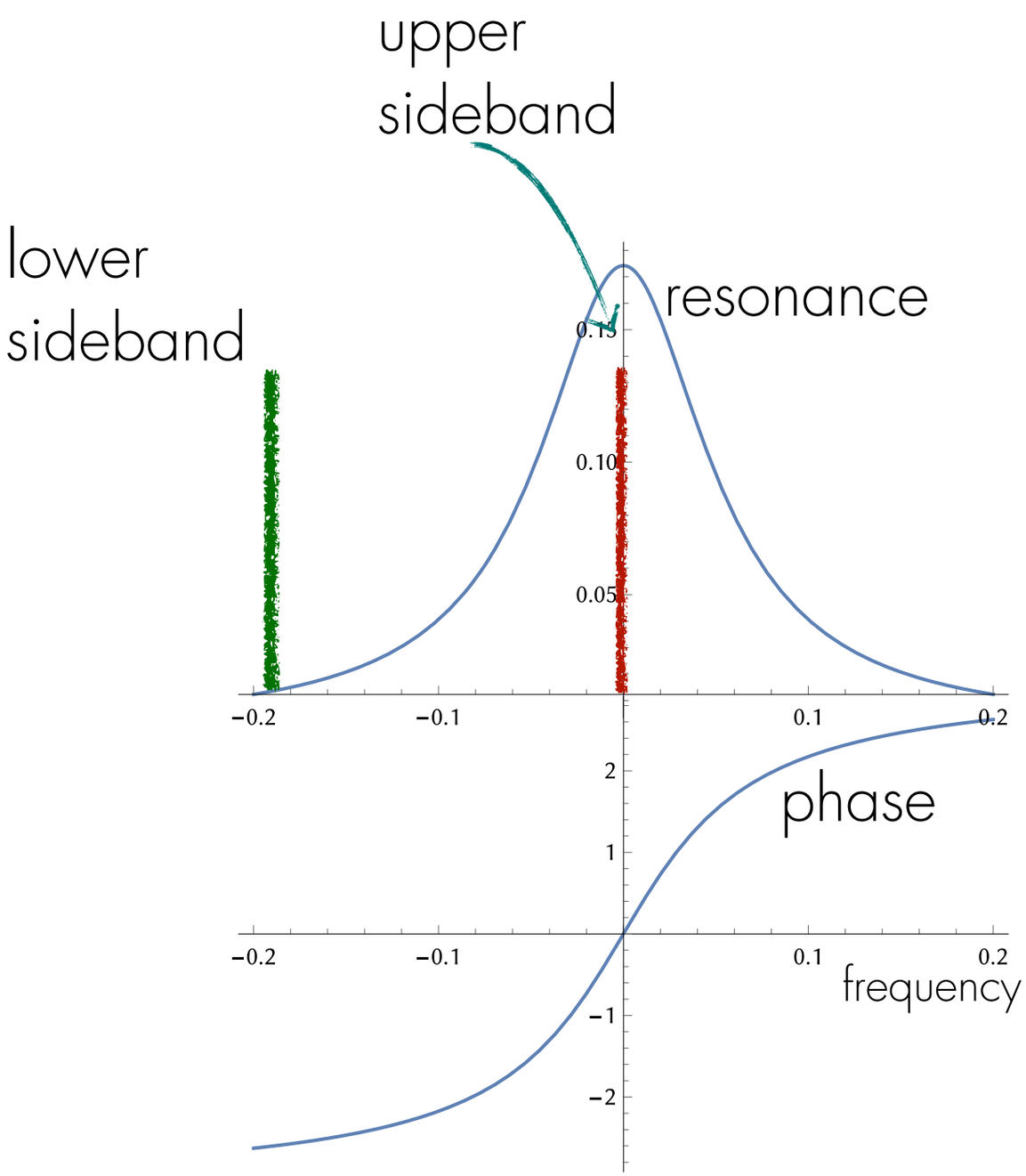
> …what if one day we learn how to build an (even more) amazing suspension and to evade newtonian noise?

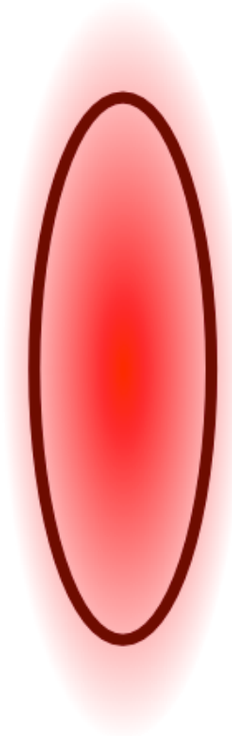
See more in my review on quantum technologies in ET:

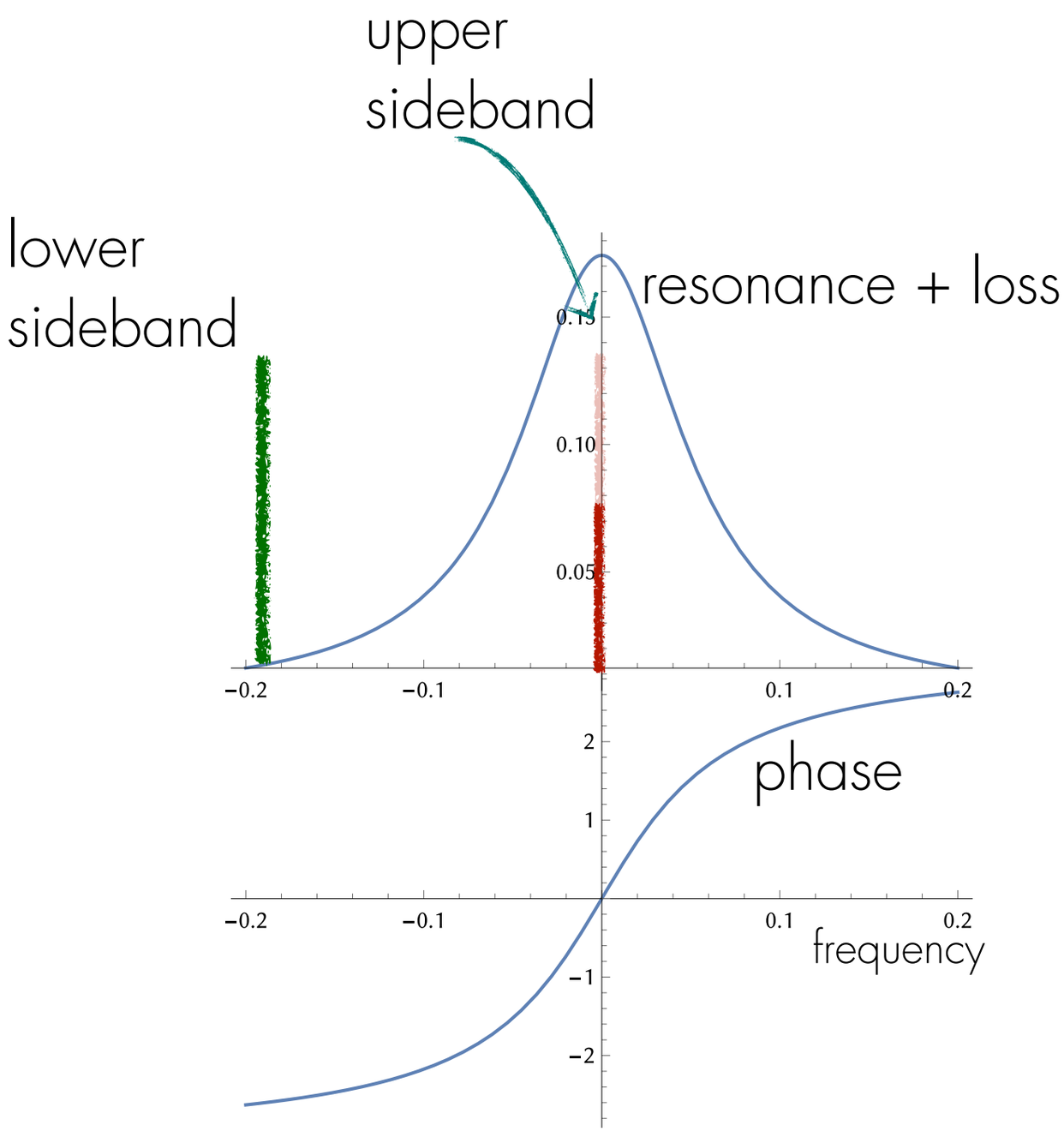
Galaxies **2025**, *13*(1), 11; https://doi.org/10.3390/galaxies13010011


Total Quantum Vacuum
AS Port SQZ
SQZ misrotation*
SQZ FC/IFO dephasing*
SQZ Phase Noise*
SQZ FC Length RMS*
SQZ SEC Length RMS*
Mode Mismatch
Arm Loss
SEC Loss
Filter Cavity Loss
Injection Loss
Readout Loss
Strain [1/√Hz]
Frequency [Hz]
10^−21
10^−22
10^−23
10^−24
10^−25
10^0
10^1
10^2
10^3

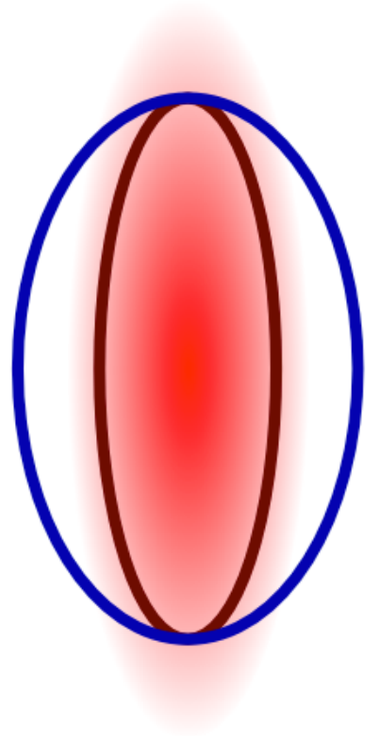

Total Quantum Vacuum
AS Port SQZ
SQZ misrotation*
SQZ FC/IFO dephasing*
SQZ Phase Noise*
SQZ FC Length RMS*
SQZ SEC Length RMS*
Mode Mismatch
Arm Loss
SEC Loss
Filter Cavity Loss
Injection Loss
Readout Loss
Strain [1/√Hz]
Frequency [Hz]
Dephasing


upper
sideband
lower
sideband
resonance
0.15
0.10
0.05
−0.2
−0.1
0.1
0.2
2
1
−1
−2
phase
frequency





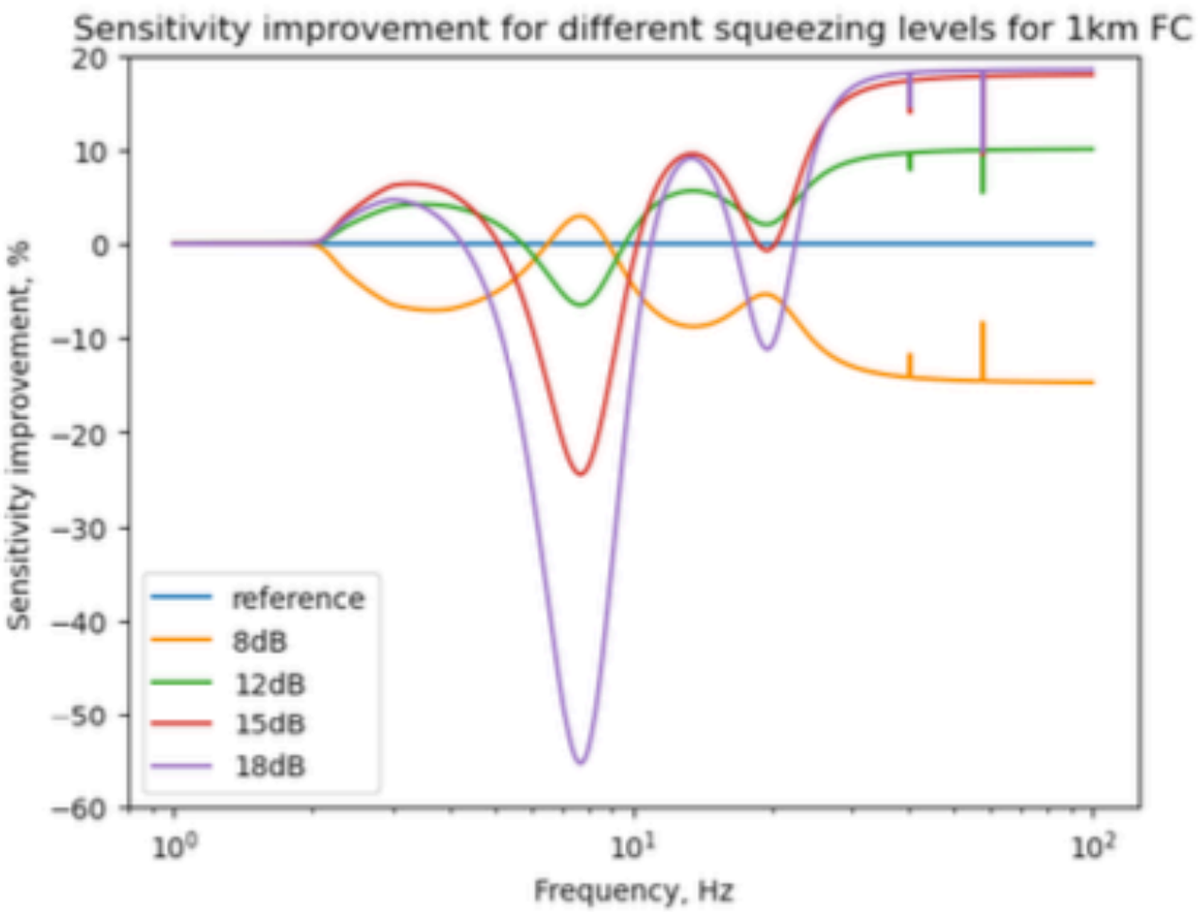
Dephasing

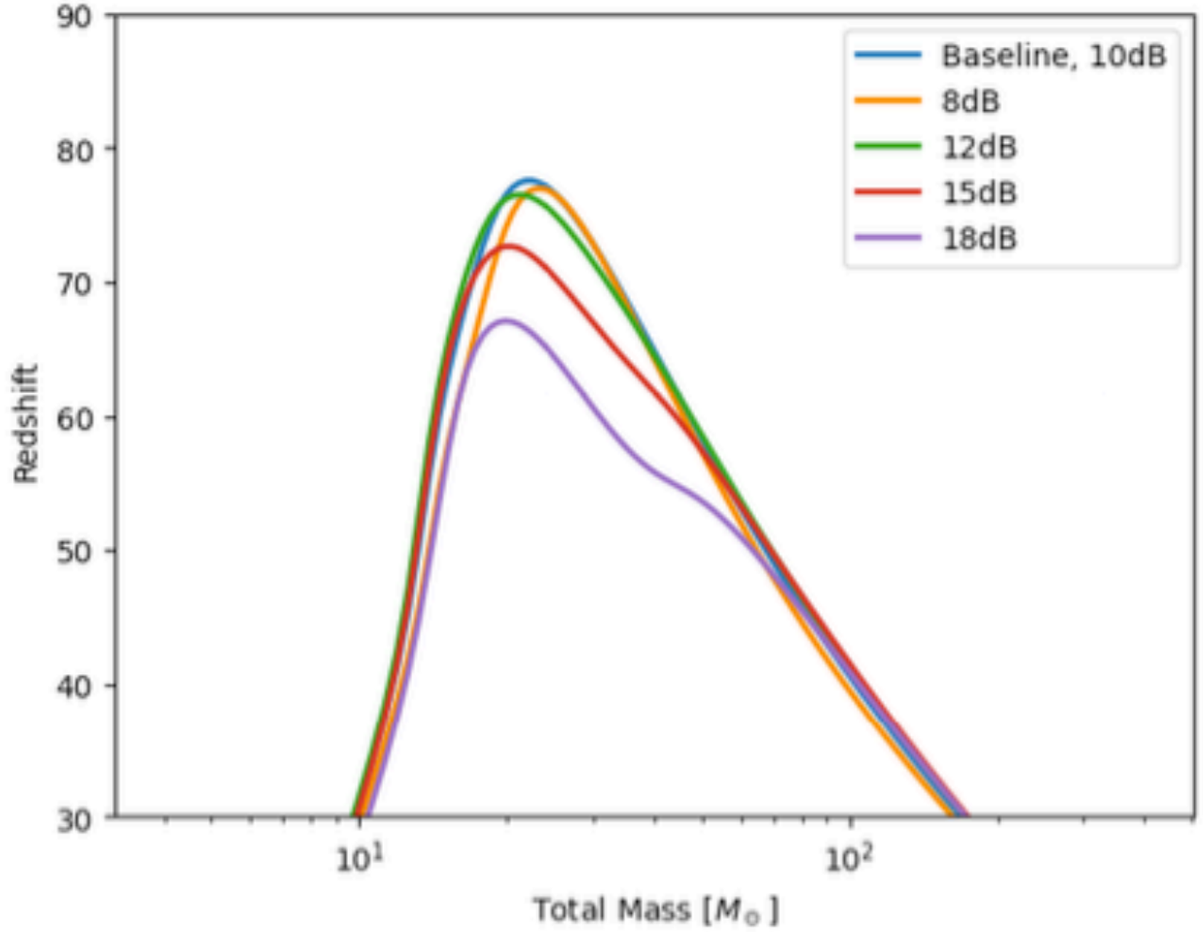


Anti-squeezing couples
into a squeezed quadrature

Filter cavity loss has triple effects:

1) direct loss around detuned frequency
2) dephasing around detuned frequency
3) the need to reduce antisqueezing → reduced squeezing at all frequencies

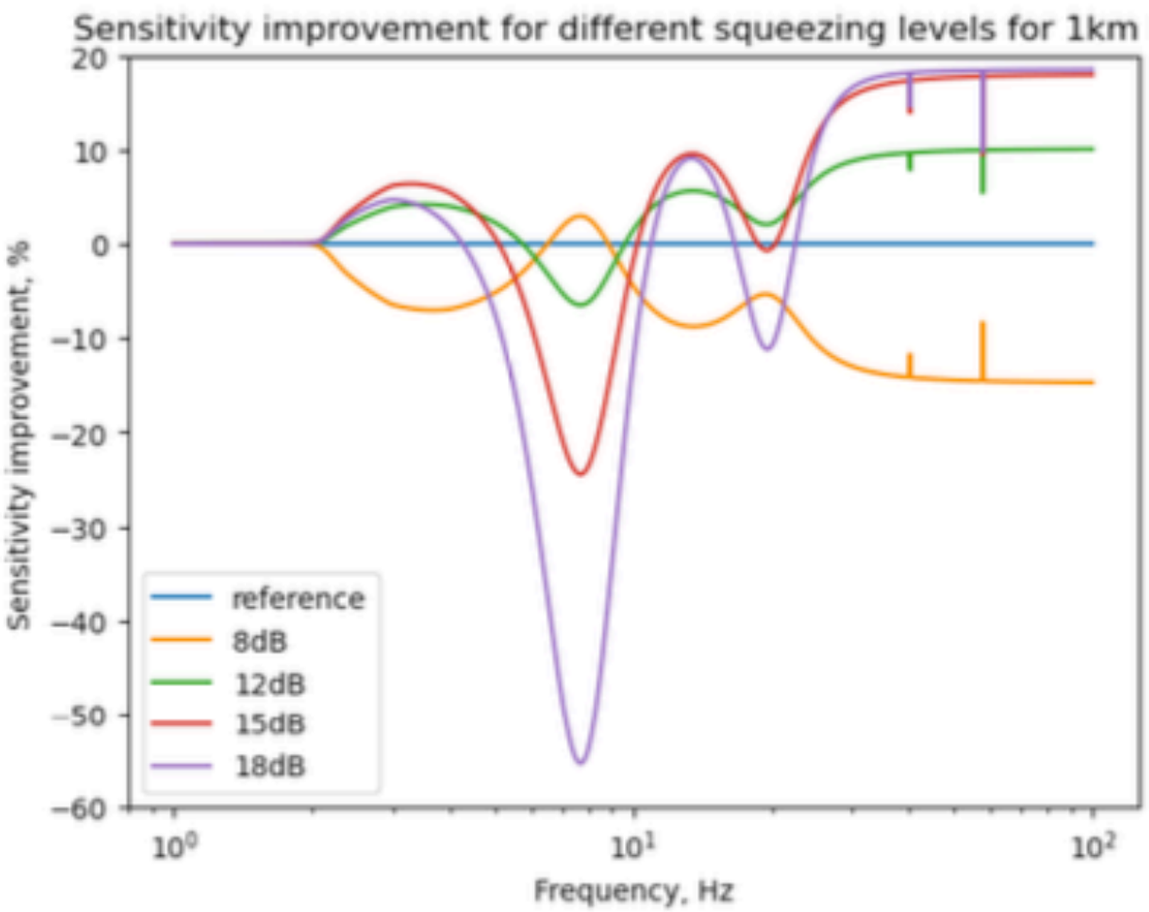


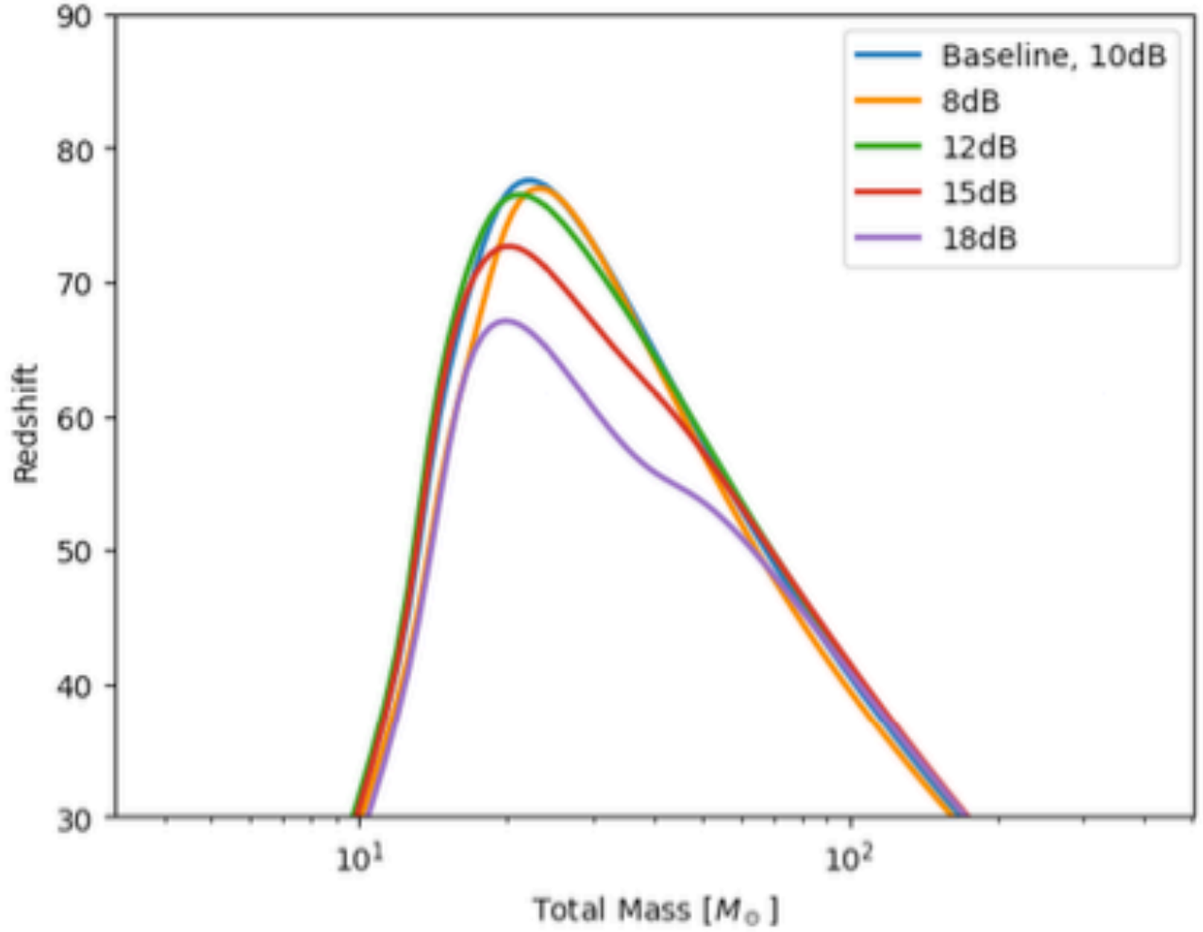


Filter cavity loss has triple effects:

1) direct loss around detuned frequency
2) dephasing around detuned frequency
3) the need to reduce antisqueezing → reduced squeezing at all frequencies

We need lower loss in FC → make them longer





Filter cavity loss has triple effects:

1) direct loss around detuned frequency
2) dephasing around detuned frequency
3) the need to reduce antisqueezing → reduced squeezing at all frequencies

$$\sqrt{S_h / S_h^{\mathrm{SQL}}} \geq \left(\frac{\lambda c}{\beta \gamma L} \right)^{1/4}.$$

We need lower loss in FC → make them longer