Quantum noise reduction goals for Virgo upgrades and Einstein Telescope

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Workshop R&Ds - développements instrumentaux pour Virgo et ET

Marseille, 6 mars 2024

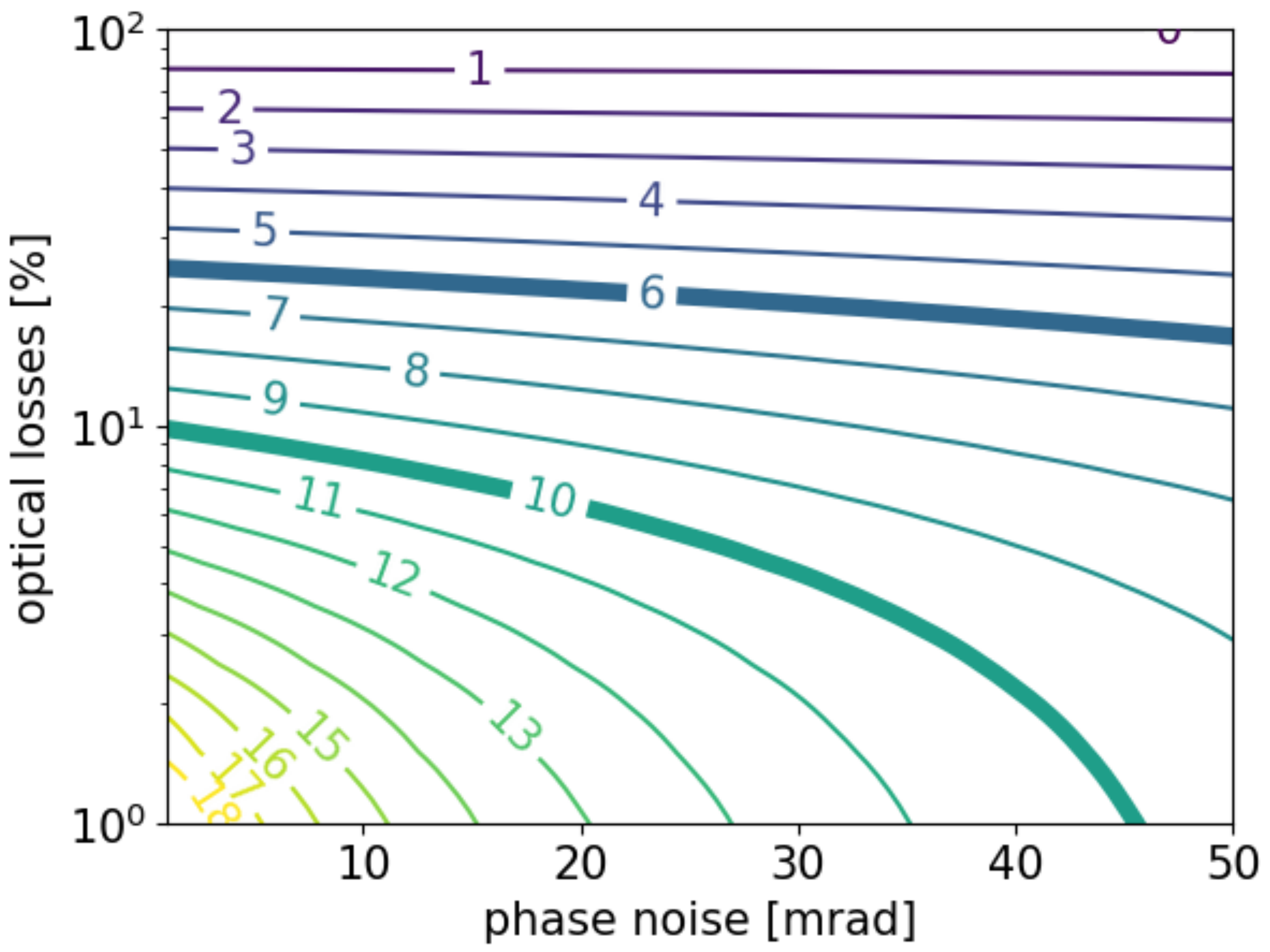
Squeezing target: 10 dB

- Same target as A#, Voyager, Virgo_nEXT, Cosmic Explorer
  - Phase noise ~ 10 mrad
  - Total losses ~ 8%

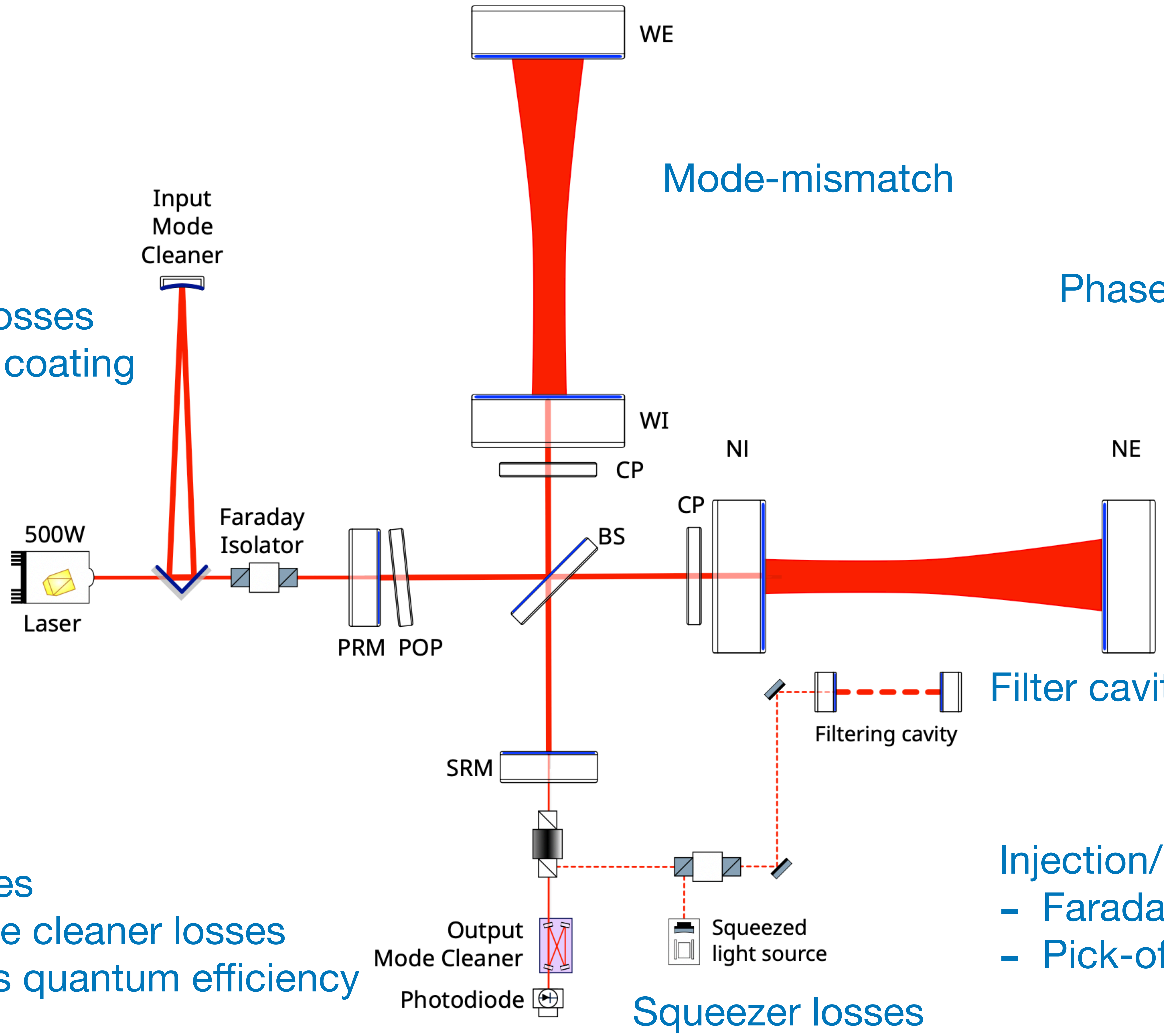
- Current results

LIGO: losses: 25% Phase noise: < 20 mrad

Virgo (O3): losses: 32-41% Phase noise: 40 mrad



Squeezing degradation sources



Mode-mismatch

Phase noise

SEC (signal extraction cavity) losses
- Scattering and antireflective coating
- Pick-off for controls

Filter cavity losses

Injection/propagation losses
- Faraday isolators
- Pick-off for controls

Readout losses
- Output mode cleaner losses
- Photodiodes quantum efficiency

Squeezer losses

Quantum noise relevant parameters

Einstein Telescope

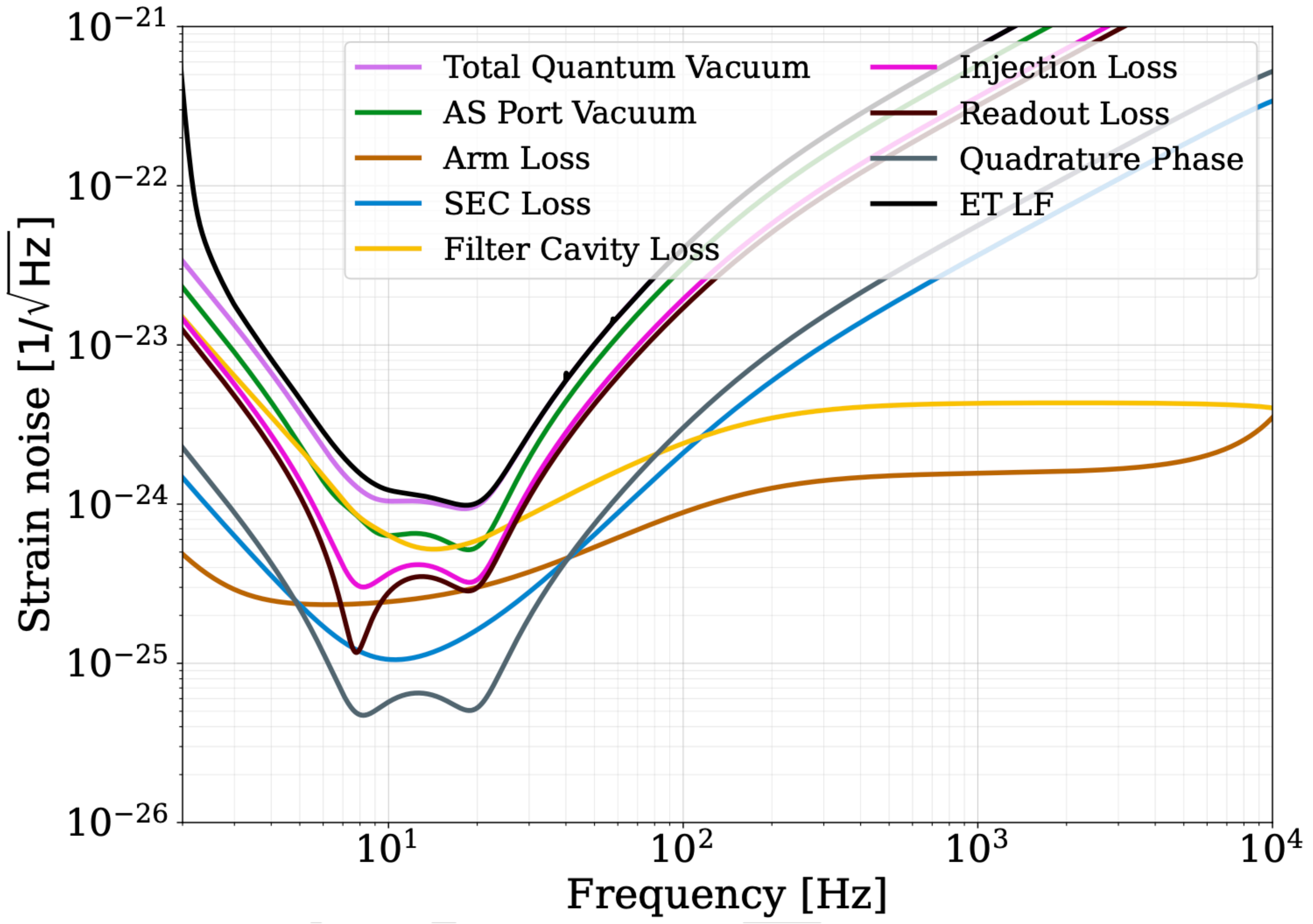
Parameter	Units	HF Detector	LF Detector
Interferometer configuration	Tuned dual-recycled Fabry-Perot-Michelson		
Laser wavelength	nm	1064	1550
Laser power	W	500.0	1.7
Arms length	km	10	10
Arms circulating power	kW	3000	18
ITM transmissivity	%	0.7	0.7
Arm finesse		888	888
Arm half-bandwidth	Hz	8.3	8.3
Signal extraction cavity (SEC)			
SEM transmissivity	%	5.0	20
SEC tunephase	rad	0.0	0.75
SEC length	m	100	100
Squeezing injection			
Squeezing type	Frequency-dependent squeezing		
Injected squeezing	dB	18	10
Injected squeezing angle	rad	0.00	0.3
Filter cavity length	m	1000	1000/1000
Filter cavity input transmissivity	ppm	1773	357.1/ 138
Filter cavity half-bandwidth	Hz	21.16	4.26/1.65
Filter cavity detuning	Hz	-21.15	19.51/-7.65
Readout loss			
Photodetector Inefficiency	%	1	1
Faraday isolator	%	1	1
Output mode cleaner	%	1	1
Internal loss of interferometer			
ETM transmissivity	ppm	5.0	5
Arm Loss per mirror	ppm	37.5	20
Arm round trip loss	ppm	80	45
SEC loss	ppm	1000.0	1000
Squeezing injection loss			
OPA cavity	%	1.0	1
Faraday isolators	%	2	3
FC end mirror transmittance	ppm	5	5
FC round-trip loss	ppm	45	20

Virgo n_EXT

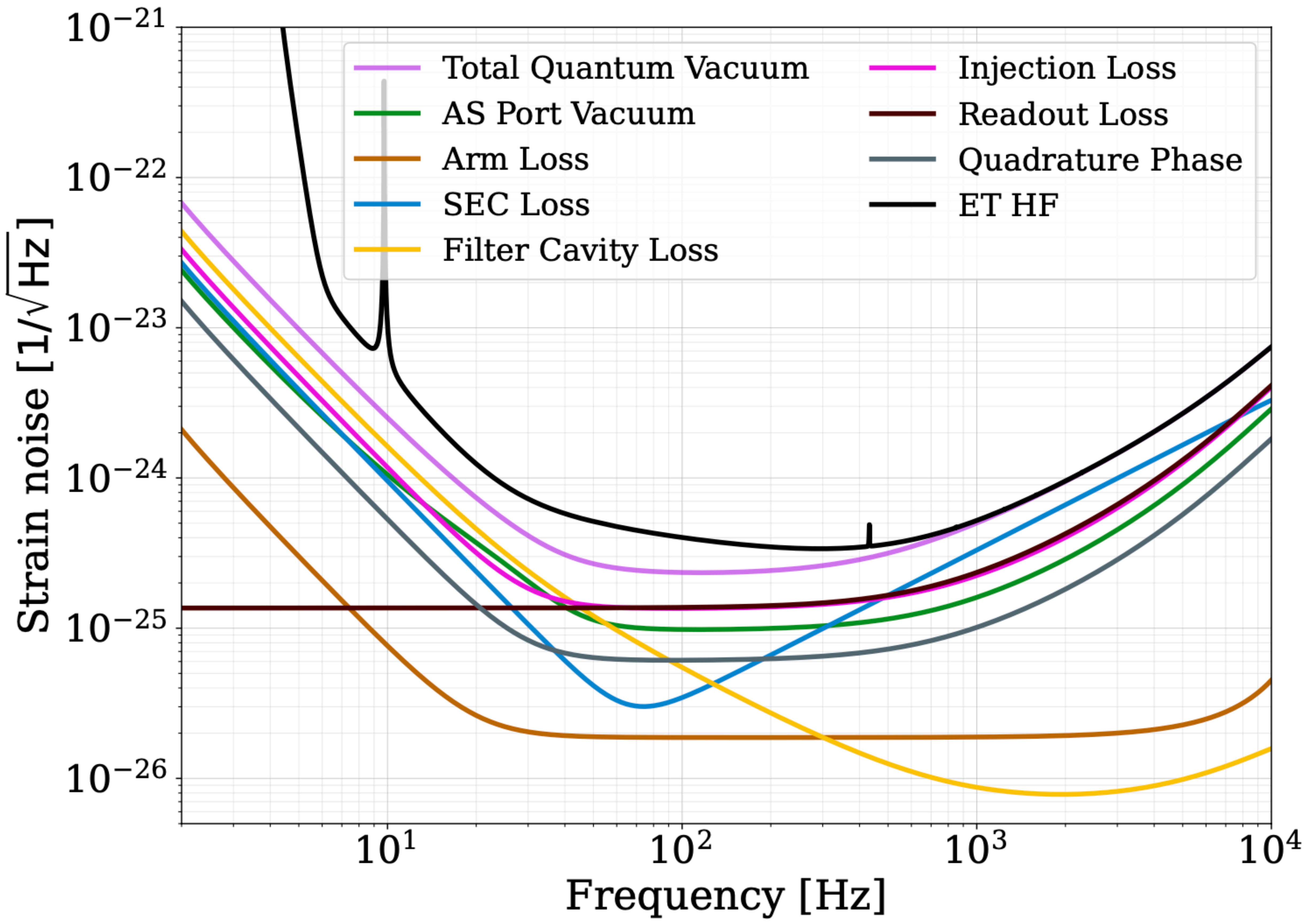
Parameter	O5	Initial post-O5	VnEXT
Injected squeezing	12 dB	12 dB	15 dB
injection losses	6.5%	5.5%	1.8%
FC losses	30 ppm	30 ppm	20 ppm
Readout losses	6%	4.5%	2.5 %
Arm-cavity roundtrip losses	75 ppm	75 ppm	75 ppm
Signal extraction cavity (SEC) roundtrip losses	1000 ppm	1000 ppm	500 ppm
Phase noise	25 mrad	15 mrad	10 mrad
Mismatching squeezing - filter cavity	0.5%	0.5%	0.25%
Mismatching squeezing - interferometer	2%	1%	0.5%
Measured squeezing at high-frequency	**5.5 dB**	**7.5 dB**	**10.5 dB**

Target squeezing degradation budget

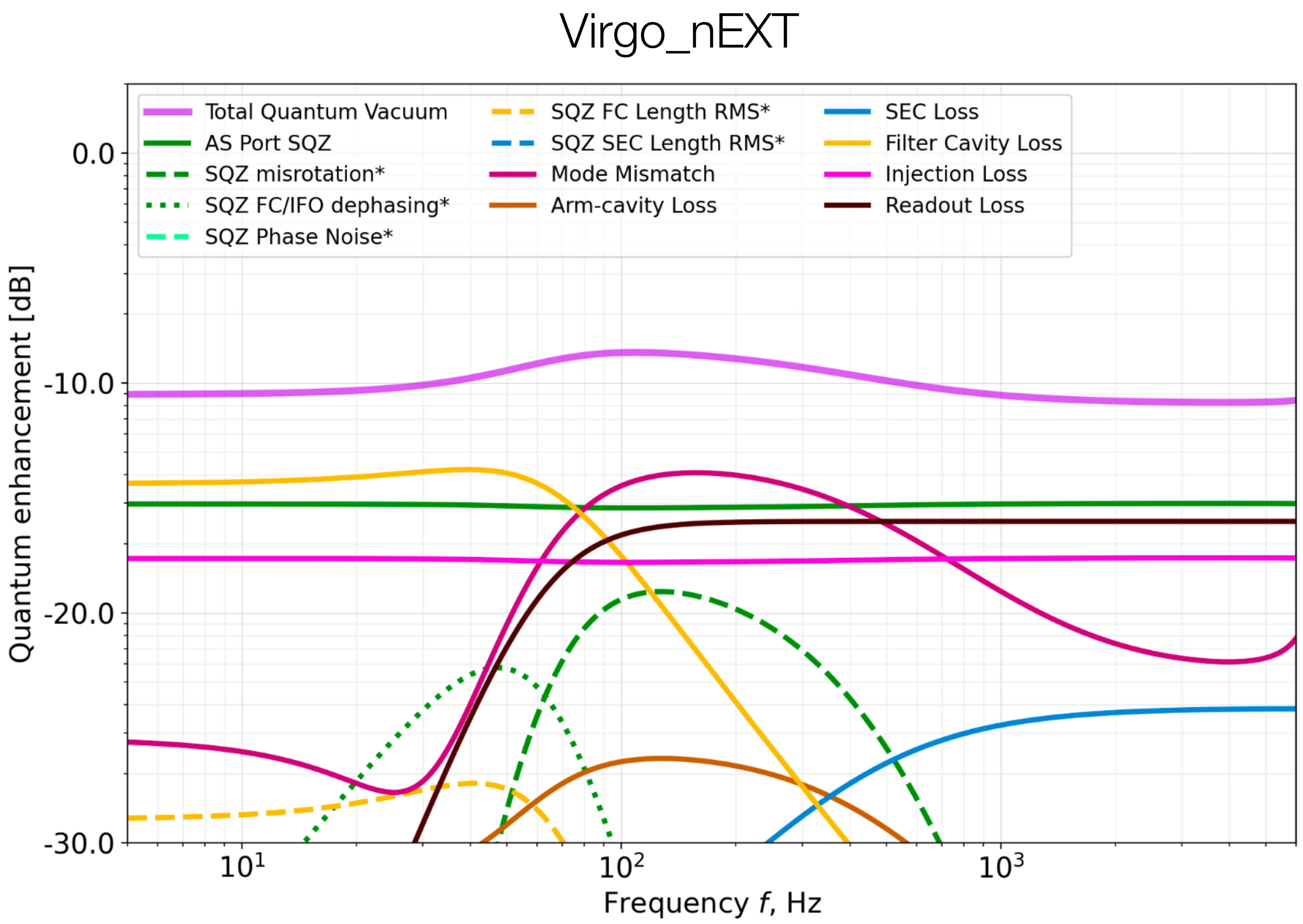
ET - low frequency



ET - high frequency



Target squeezing degradation budget



Squeezer and injection losses

- Total Injection loss target 3%
  - 1% OPA
  - 2% Faraday Isolator (several passes)

R&D

- Development and characterisation of a vacuum squeezing source in synergy with Virgo_nEXT, as a continuation of the ANR Exsqueez project (**IJCLab**):
  - comparative measurements with the OPO in air and in vacuum (and homodyne photodiodes in vacuum in an enclosure currently under construction)
  - The first squeezing measurements expected by the end of the year
- Faraday isolation loss reduction: current 1% -> goal 0.35%

Interferometer core optics losses

- Arm cavity round trip losses (75 ppm) already compliant with requirement
- SEC losses are more critical
  - Theoretical budget for Virgo: 1000 ppm but current value is much larger (few %?)

BS antireflective (round trip) - pick off for control	600 ppm
Compensating plate antireflective (round trip)	200 ppm
Optics scattering	200 ppm
Total	**1000 ppm**

- Measured LIGO value 6000 ppm
- **10dB goal -> 500/1000 ppm**

R&D

- Reduction of Anti-reflecting coating to 50 ppm through a better control of the deposition system (**LMA**)

SEC Losses in 3G detectors

- Interesting discussion in [XGCD (Next-Generation collaborative design) meeting]
- CE SEC loss target of 500 ppm seems very critical and it is being carefully considered in the design
    - Alternative to compensation plates
    - BS thermal lenses issue

Achieving 500 ppm SEC loss: Eliminate compensation plates

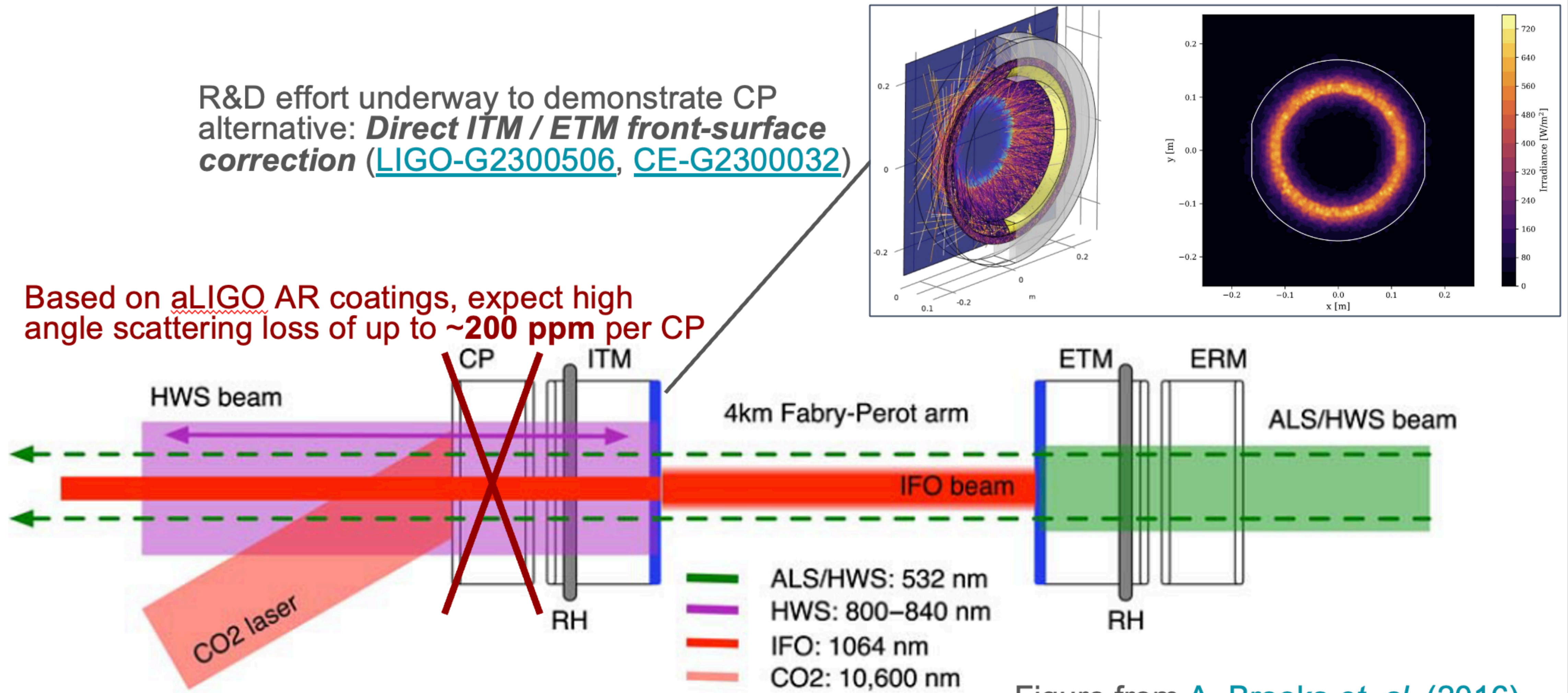
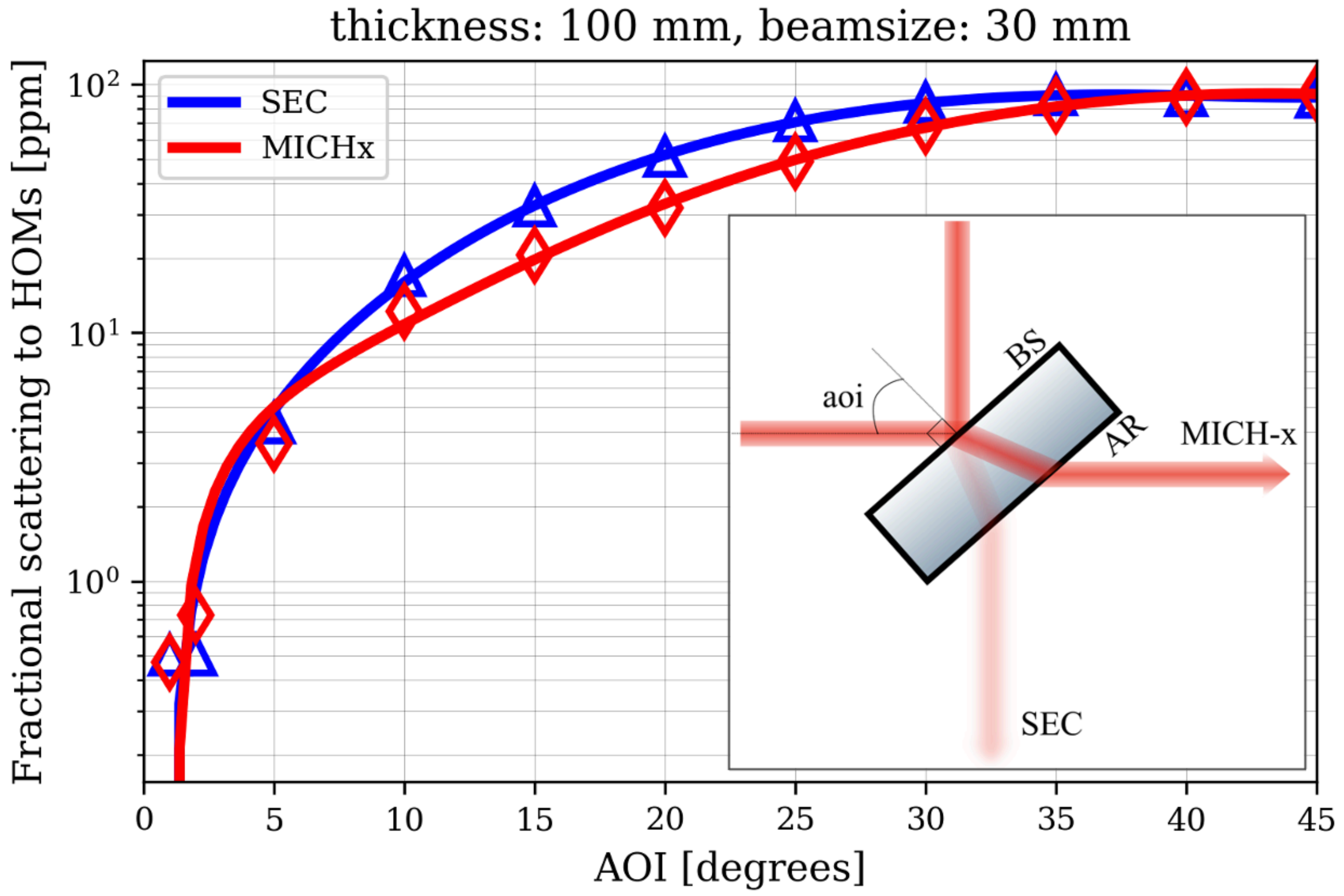


Figure from A. Brooks *et. al.* (2016)

Achieving 500 ppm SEC loss: Control beamsplitter thermal lensing

Beamsplitter HOM scattering loss versus AOI, *with* optimal thermal compensation applied (by H.T. Cao)



- Expect ~1 ppm total absorption by beamsplitter (dominated by HR and AR coating absorption)
- Thermo-refractive substrate lensing is dominant effect
- Initial modeling shows HOM scattering losses **as high as 100s of ppm**, depending on AOI, thickness, and absorption (ongoing analysis by H. T. Cao)
- **Thermal compensation of beamsplitter requires low AOI to be effective**
  (due to divergence of MICH-x and SEC paths inside substrate)

Highlights from CE optical design
Jon Richardson (University of California, Riverside), Paul Fulda (University of Florida)
https://indico.gssi.it/event/621/

Readout chain losses

- Photodiode efficiency (>99%) should be compliant with requirements
- Replace monolithic OMC cavity by an open cavity or a hollow cavity to remove absorption losses and Rayleigh scattering losses inside the cavity medium.

R&D

- Design and test of a reduced loss output mode cleaner (**LAPP**)

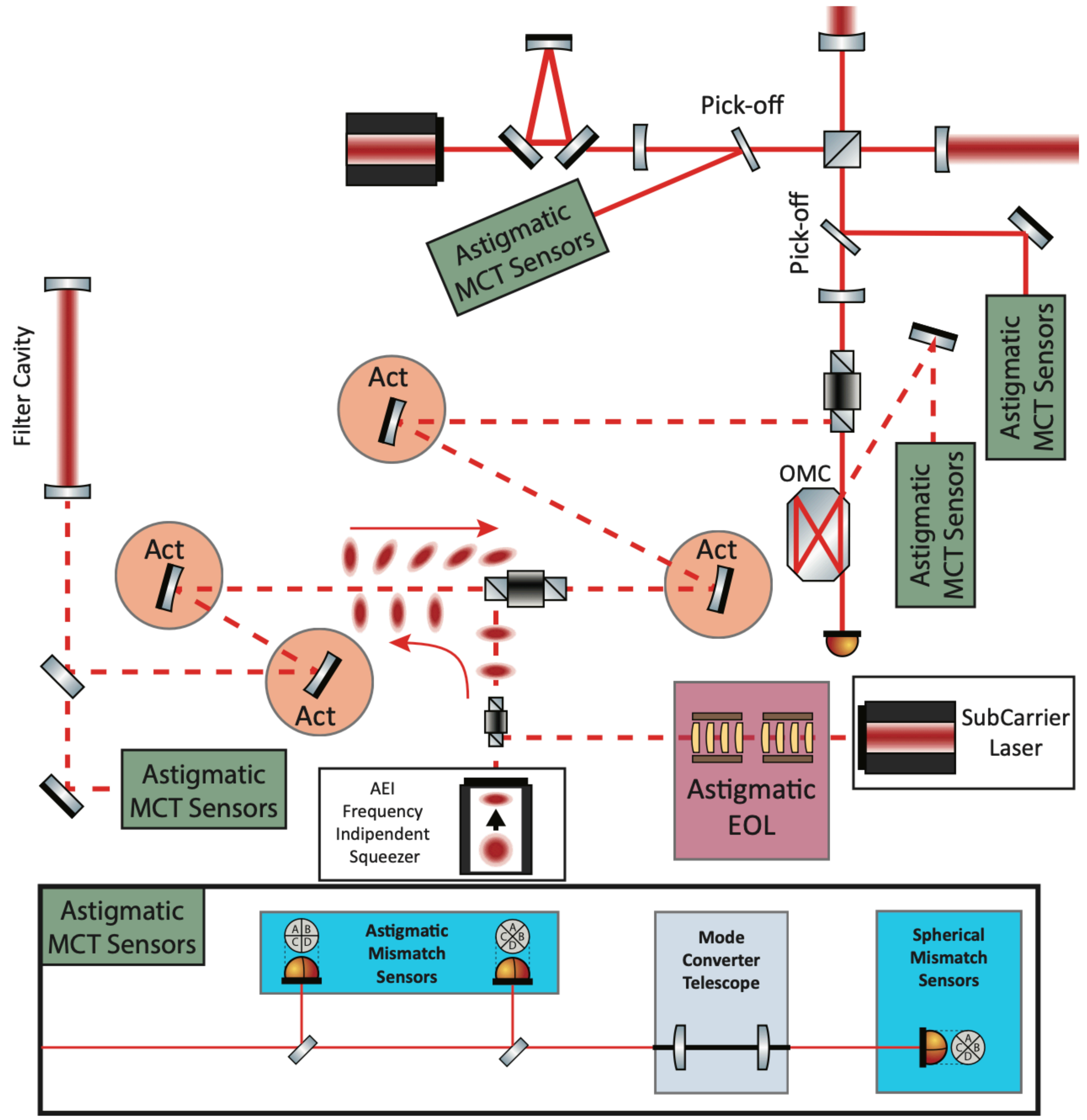
Mode-mismatching

- Several cavities to be matched: important source of losses
- Frequency dependent degradation effect. Some uncertainties in the modelling.
- Goal: <1%
- Not only curvature mismatch correction, but also astigmatism and higher order aberrations.

R&D

- Adaptive matching telescopes, developing new mismatching sensing scheme (**APC**)

- Higher order mismatches between the arms and the SEC due to optical path length distortions in the ITMs with high power: can TCS compensate ?



Scheme of possible mode matching sensors and actuators implementation for VnEXT.

Mode-mismatching for Cosmic Explorer

Precision mode-matching is a central design driver

Example of “anti-squeezing” around HOM resonances in DARM spectrum

Model assumes a 1% SEC mode-mismatch with arms

Effective rotation of SQZ angle via mode scattering process:

TEM00 → LG10 → TEM00*

*having accumulated *different* phase relative to the unscattered TEM00 field

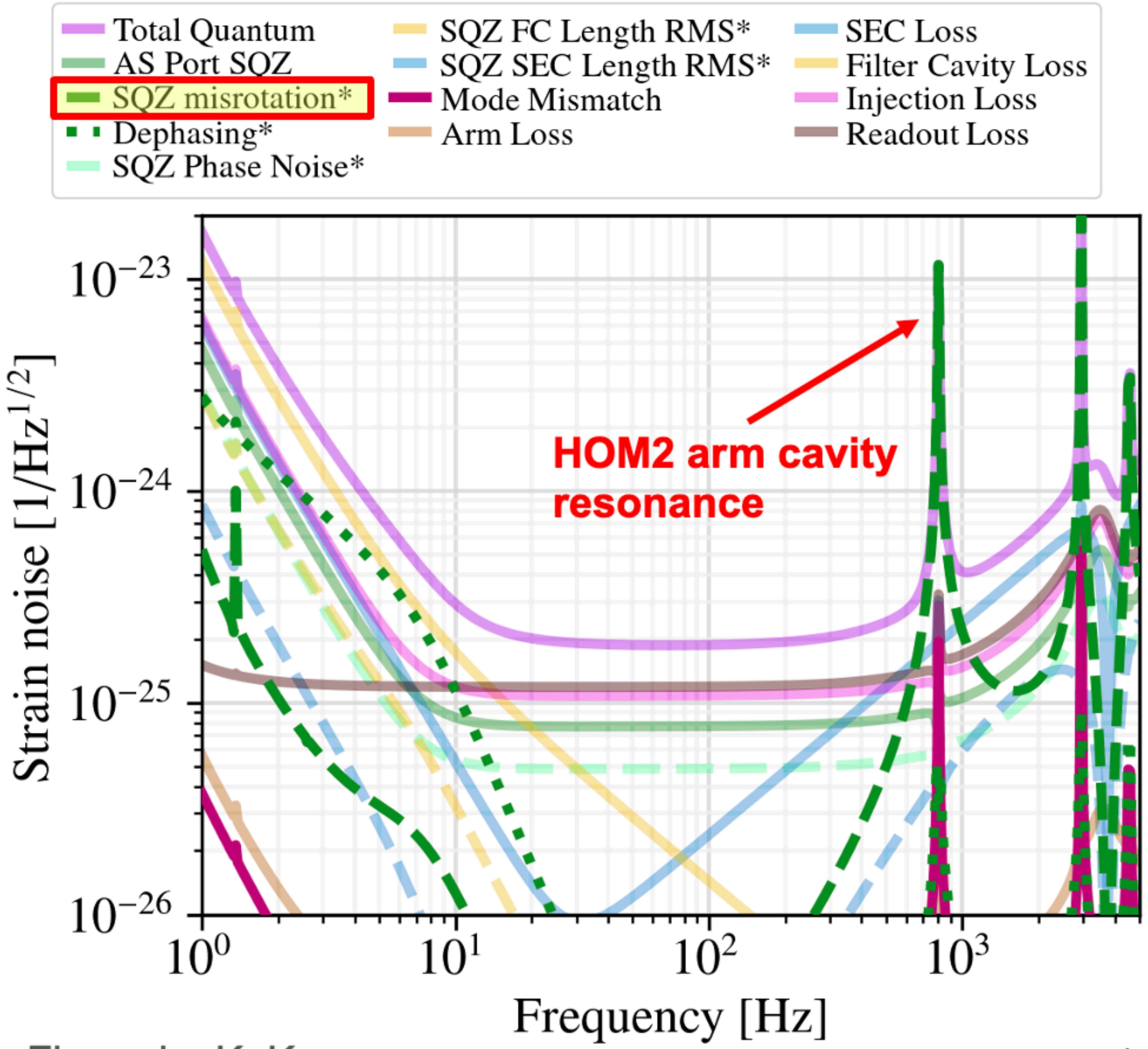


Figure by K. Kuns

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Filter cavity: losses

- Currently 50-90 ppm of round trip losses -> target 20 ppm
- Measured losses systematically higher than expected. Loss budget not fully understood

R&D

- Reduce scattering from mirrors (20 ppm RTL target):
  - Optimisation of the coating process to reduce the point defect density: study impact of the process parameters (IBS source parameters, post-annealing) (**LMA**)
  - Implement an in-situ monitoring system to study the contaminant in the Grand Coater machine (**LMA**)

Filter cavity: design and operation

R&D:

- Filter cavity with adaptive finesse (**IJCLAB** in collaboration with **LKB, LAPP, LMA** - ANR QFilter):
  - Simulation activity on going
  - Possible implementation on CALVA

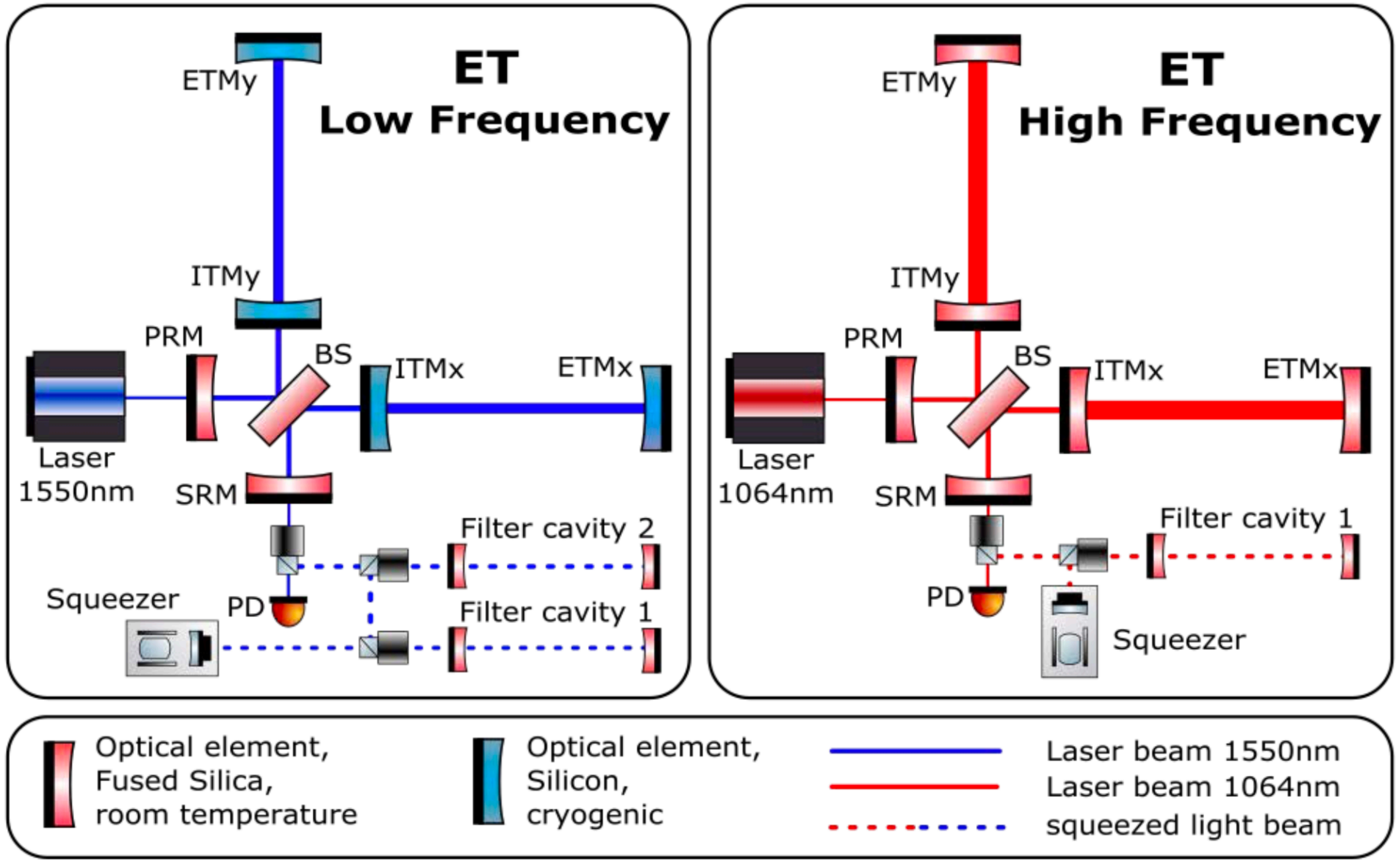
- Filter cavity topology study for optimal quantum noise in a detuned interferometer (**APC** - ANR quantum-FRESCO):
  - On-going simulation to find the best design to perform a non-trivial phase rotation (2 filter cavities, coupled cavity)
  - Table top experiment under development

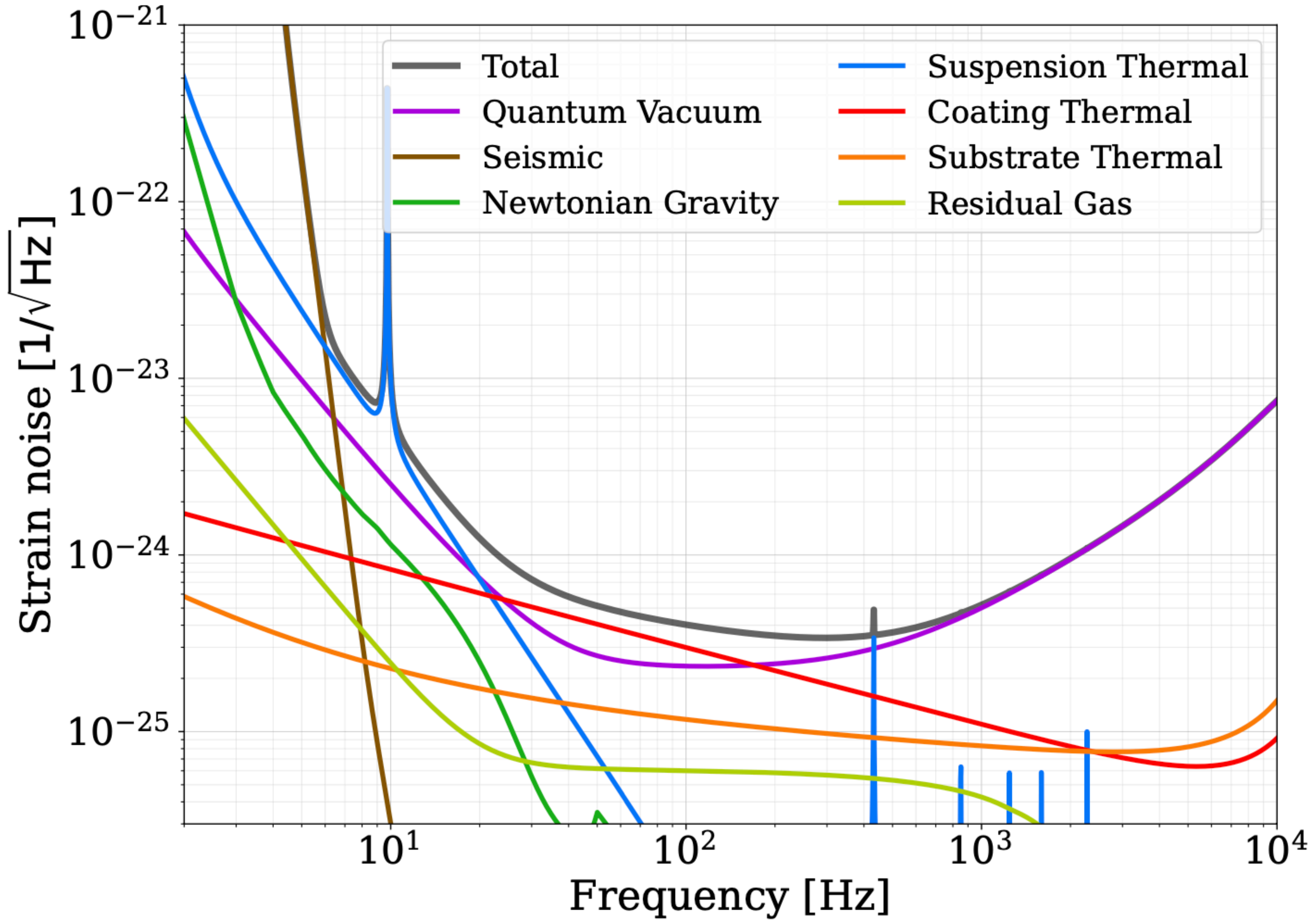
Summary

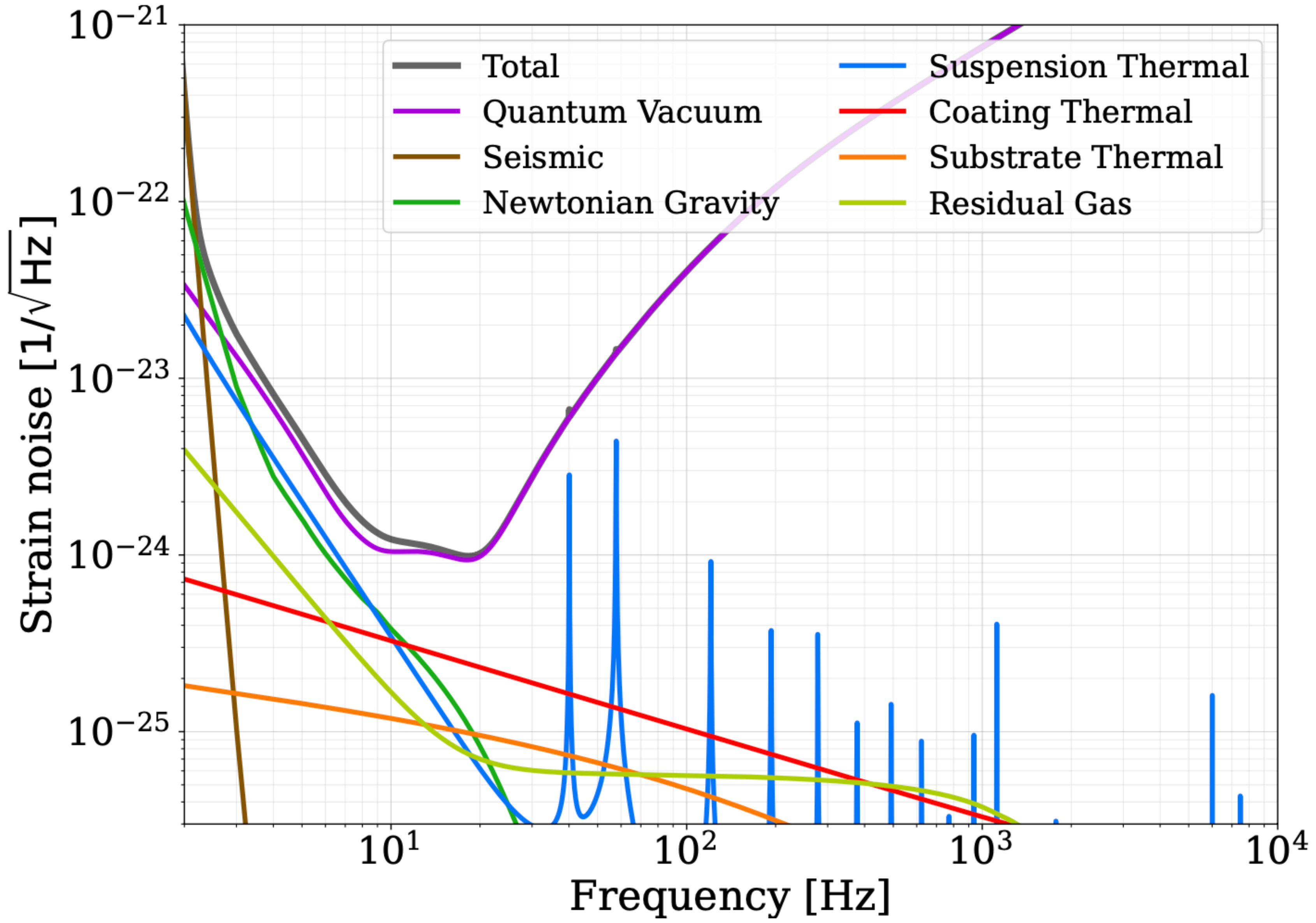
- ET/Virgo n_EXT are targeting 10 dB of quantum noise reduction
  - Well established technology: frequency dependent squeezing with filter cavities.
- Main challenges:
  - Total loss reduction below 8%
  - Thermal effect from high power
  - ET-LF cavity needs 2 filter cavities with very narrow bandwidth
- Strong synergy with Virgo_nEXT, A#, CE (same 10dB target and same technologies)

Back up

ET configuration and noise budget







- Quantum noise: main limitation

Virgo_nEXT parameters

Parameter	O4 high	O4 low	O5 high	O5 low	VnEXT_low
Power injected	25 W	40 W	60 W	80 W	277 W
Arm power	120 kW	190 kW	290 kW	390 kW	1.5 MW
PR gain	34	34	35	35	39
Finesse	446	446	446	446	446
Signal recycling	Yes	Yes	Yes	Yes	Yes
Squeezing type	FIS	FDS	FDS	FDS	FDS
Squeezing detected level	3 dB	4.5 dB	4.5 dB	6 dB	10.5 dB

- Technology : frequency dependent squeezing with filter cavities for post O5 and 3G
  - Successfully demonstrated in A+
- Incremental approach to reduce optical losses and phase noise to target value

*Note that Virgo_nEXT will use stable cavities

Quantity	LIGO A+	CE	ET_HF
Arm length (km)	4	20/40	10
Laser wavelength (um)	1064	1064	1064
Arm power (MW)	0.75 (~0.35)	1.5	3
Squeezing (dB)	6	10	10
Mirror mass (kg)	40	320	200
Arm cavity loss (round trip, ppm)	75	40	75
Signal Extraction Cavity loss (round	5000	500	1000

For comparison: Virgo_nEXT parameters

Parameter	O4 high	O4 low	O5 high	O5 low	VnEXT_low
Power injected	25 W	40 W	60 W	80 W	277 W
Arm power	120 kW	190 kW	290 kW	390 kW	1.5 MW
PR gain	34	34	35	35	39
Finesse	446	446	446	446	446
Signal recycling	Yes	Yes	Yes	Yes	Yes
Squeezing type	FIS	FDS	FDS	FDS	FDS
Squeezing detected level	3 dB	4.5 dB	4.5 dB	6 dB	10.5 dB
Payload type	AdV	AdV	AdV	AdV	Triple pendulum
ITM mass	42 kg	42kg	42 kg	42 kg	105 kg
ETM mass	42 kg	42kg	105 kg	105 kg	105 kg
ITM beam radius	49 mm	49 mm	49 mm	49 mm	49 mm
ETM beam radius	58 mm	58 mm	91 mm	91 mm	91 mm
Coating losses ETM	2.37e-4	2.37e-4	2.37e-4	0.79e-4	6.2e-6
Coating losses ITM	1.63e-4	1.63e-4	1.63e-4	0.54e-4	6.2e-6
Newtonian noise reduction	None	1/3	1/3	1/5	1/5
Technical noise	“Late high”	“Late low”	“Late low”	None	None
BNS range	90 Mpc	115 Mpc	145 Mpc	260 Mpc	500 Mpc