Squeezing in the post-O5 era and synergies with third generation detectors

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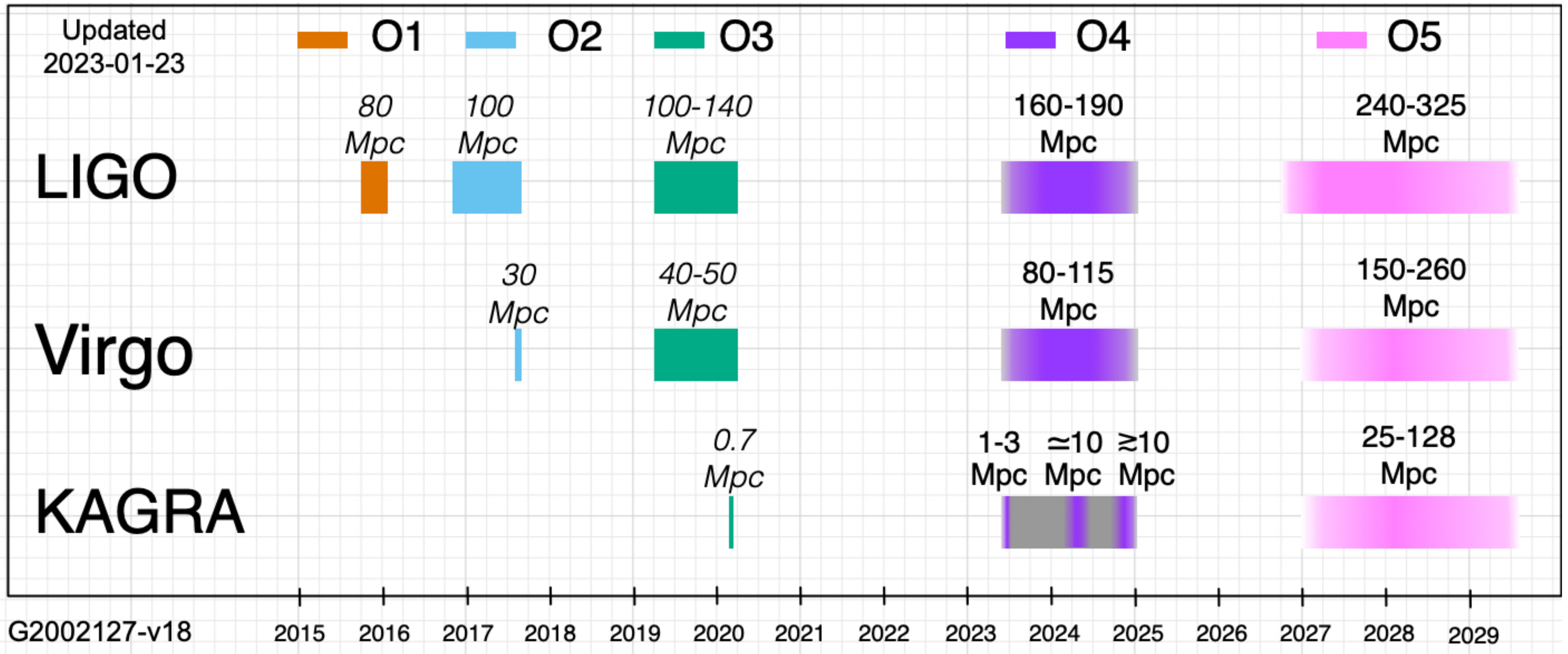
Ground based GW detectors: a (possible) roadmap

Current infrastructures | New infrastructures



- Virgo_nEXT
- A#

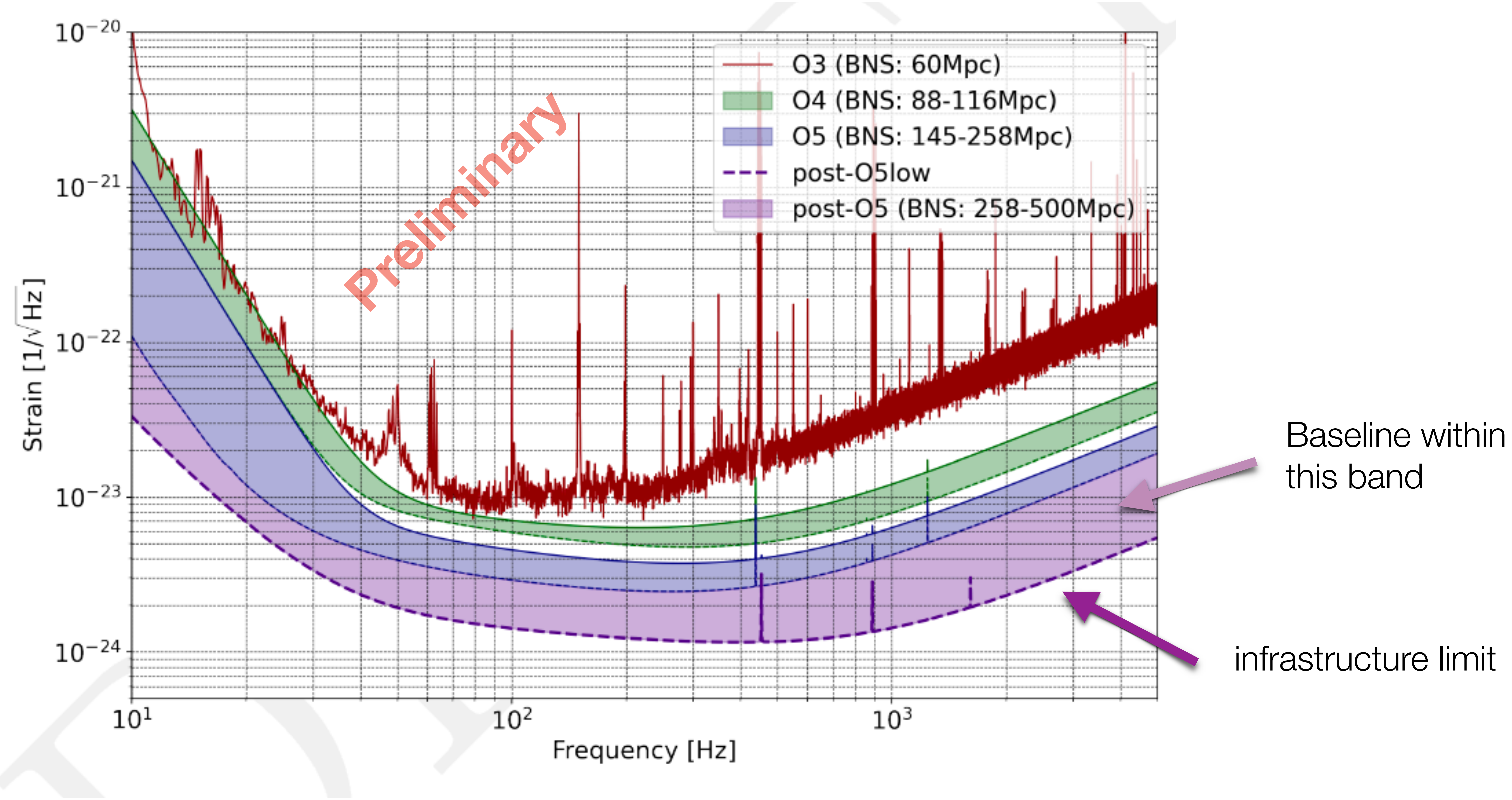
Decades 2030

- EinsteinTelescope
- Cosmic Explorer

Decades 2040
and following

- Reduce the “dark ages” between 2G and 3G
- Pave the way to the 3rd generation (test technologies and risk reduction)
- Maintain a community of high-level experimentalists to run 3G detectors
- Concept study submitted to funding agencies (non yet a baseline design)

Virgo_nEXT sensitivity



- Official sensitivity and baseline under discussion

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

*Note that Virgo_nEXT will use stable cavities

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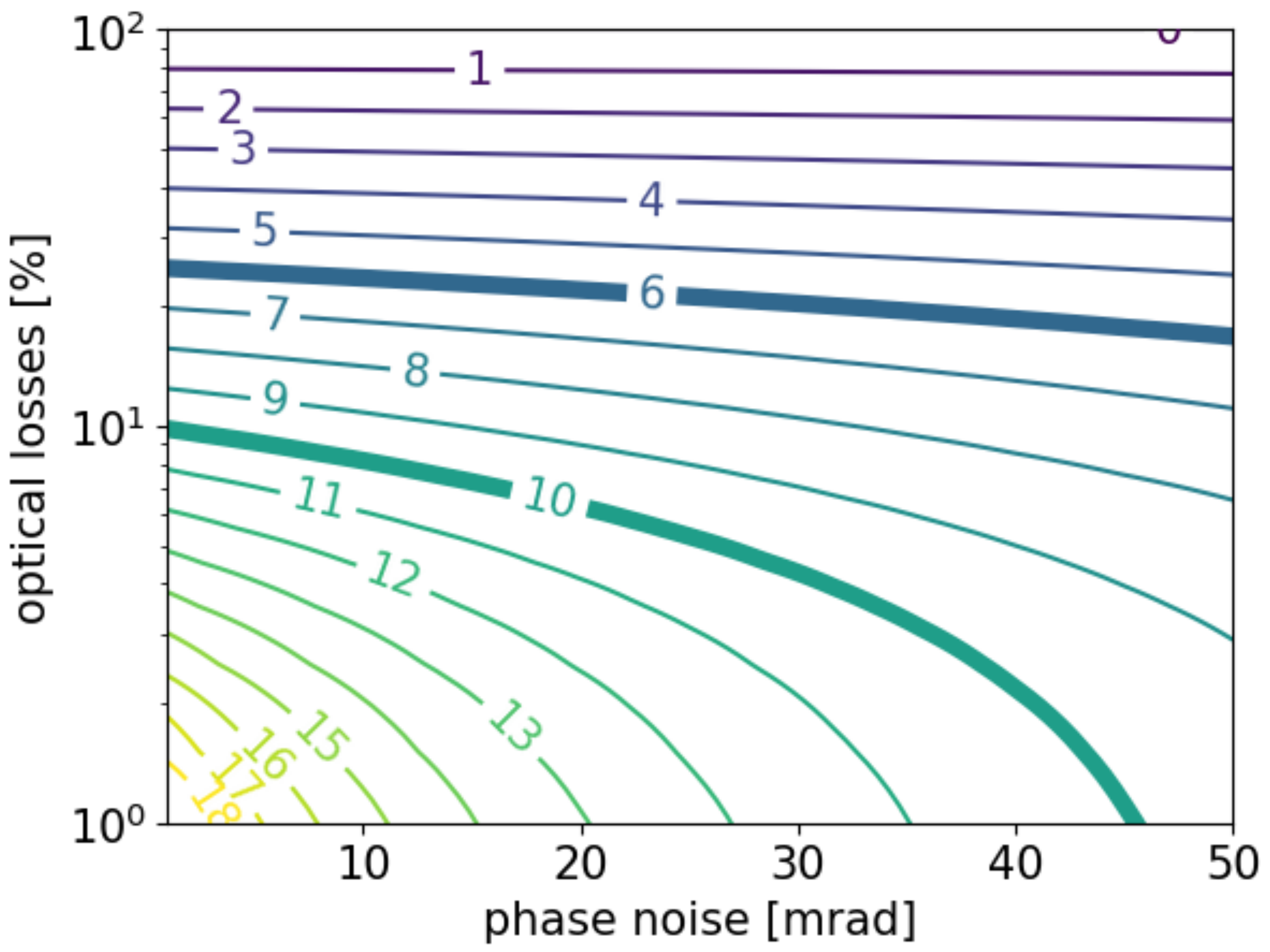
- Technology : frequency dependent squeezing with filter cavities for post O5 and 3G
  - Successfully demonstrated in A+
- Incremental approach to reduce optical losses and phase noise to target value

*Note that Virgo_nEXT will use stable cavities

Squeezing target: 10 dB

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

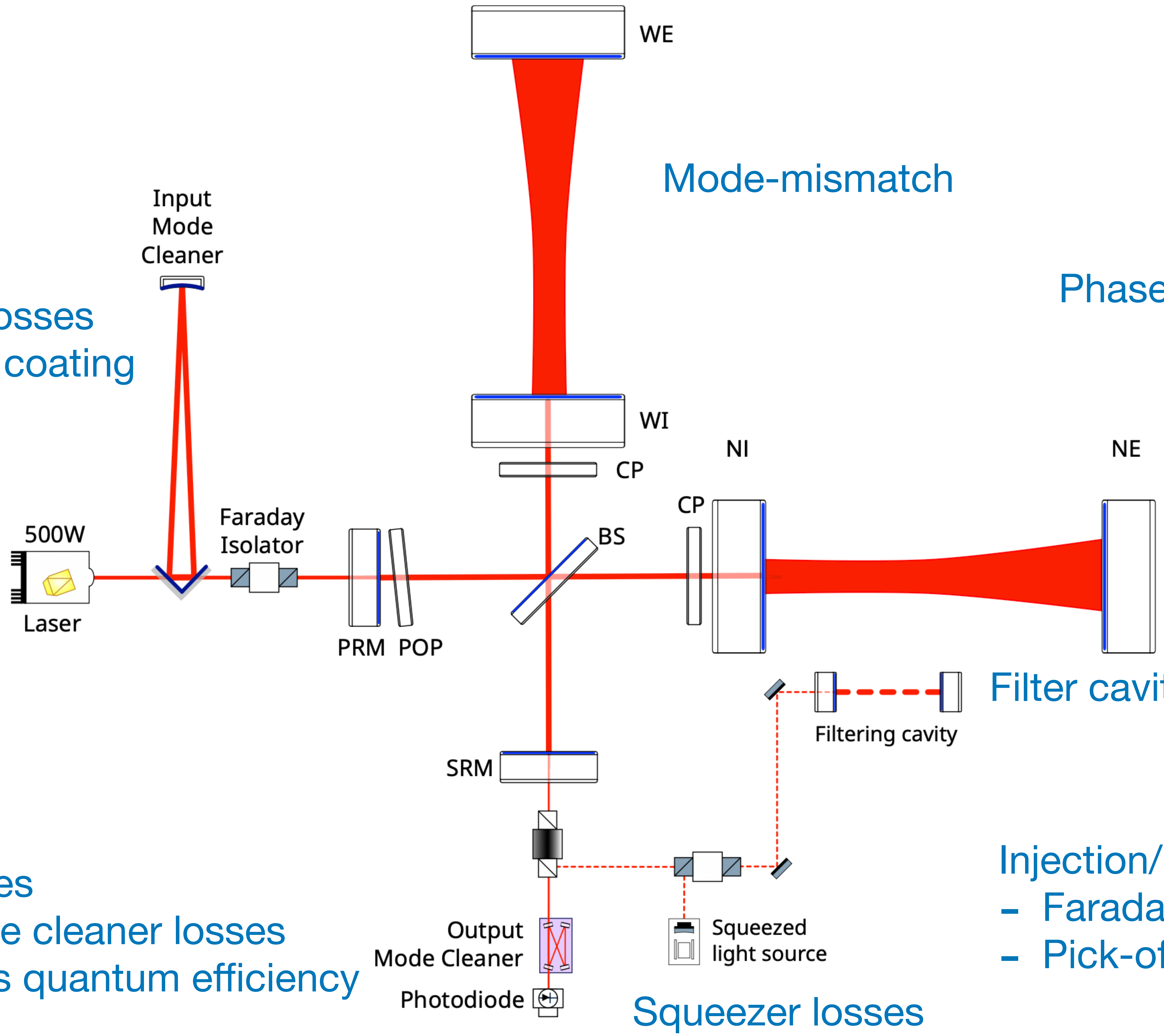


- Current results

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

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

Virgo_nEXT squeezing degradation sources



Mode-mismatch

Phase noise

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

Filter cavity losses

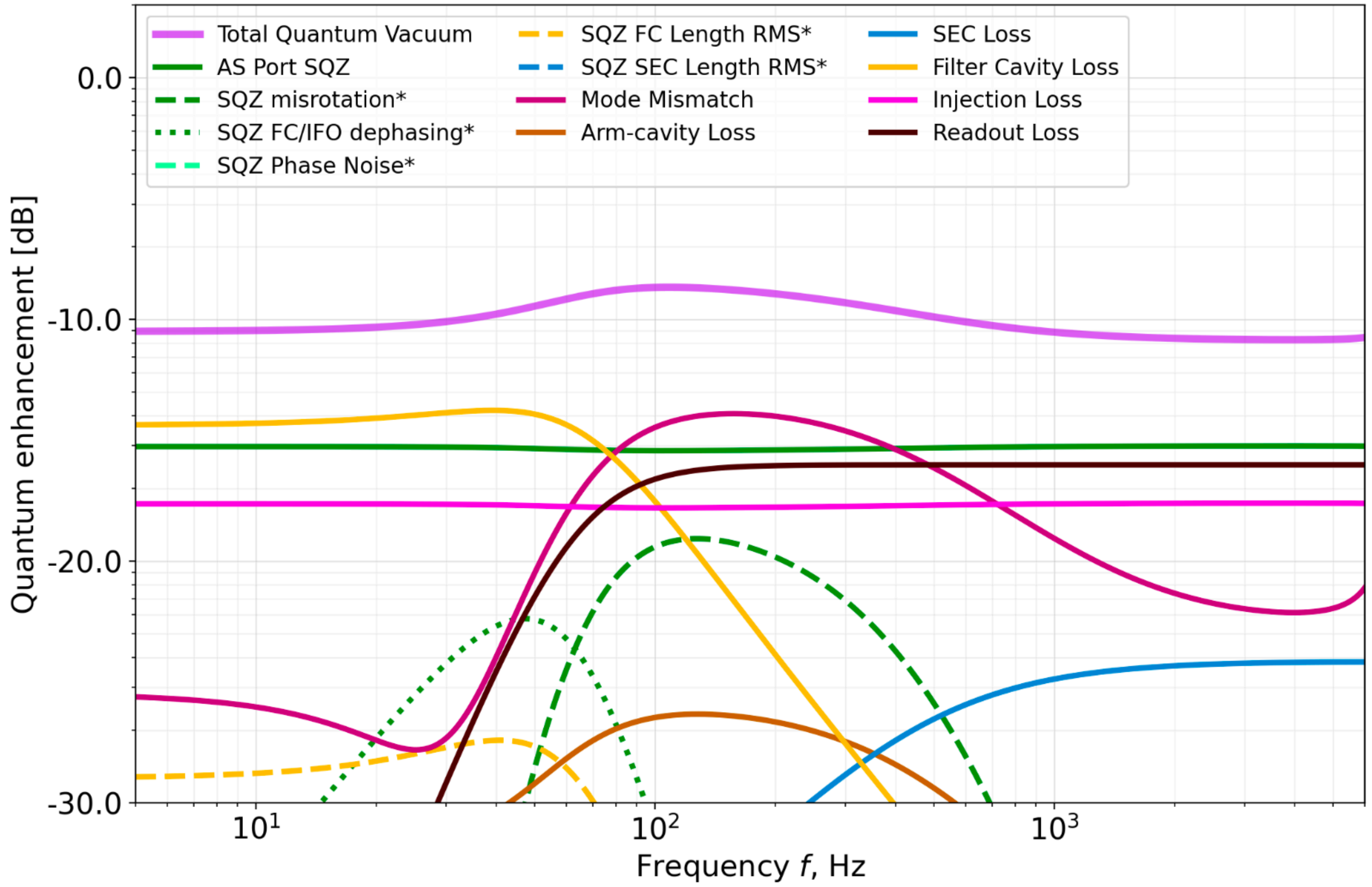
Readout losses
- Output mode cleaner losses
- Photodiodes quantum efficiency

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

Squeezer losses

*Note that Virgo_nEXT will use stable cavities

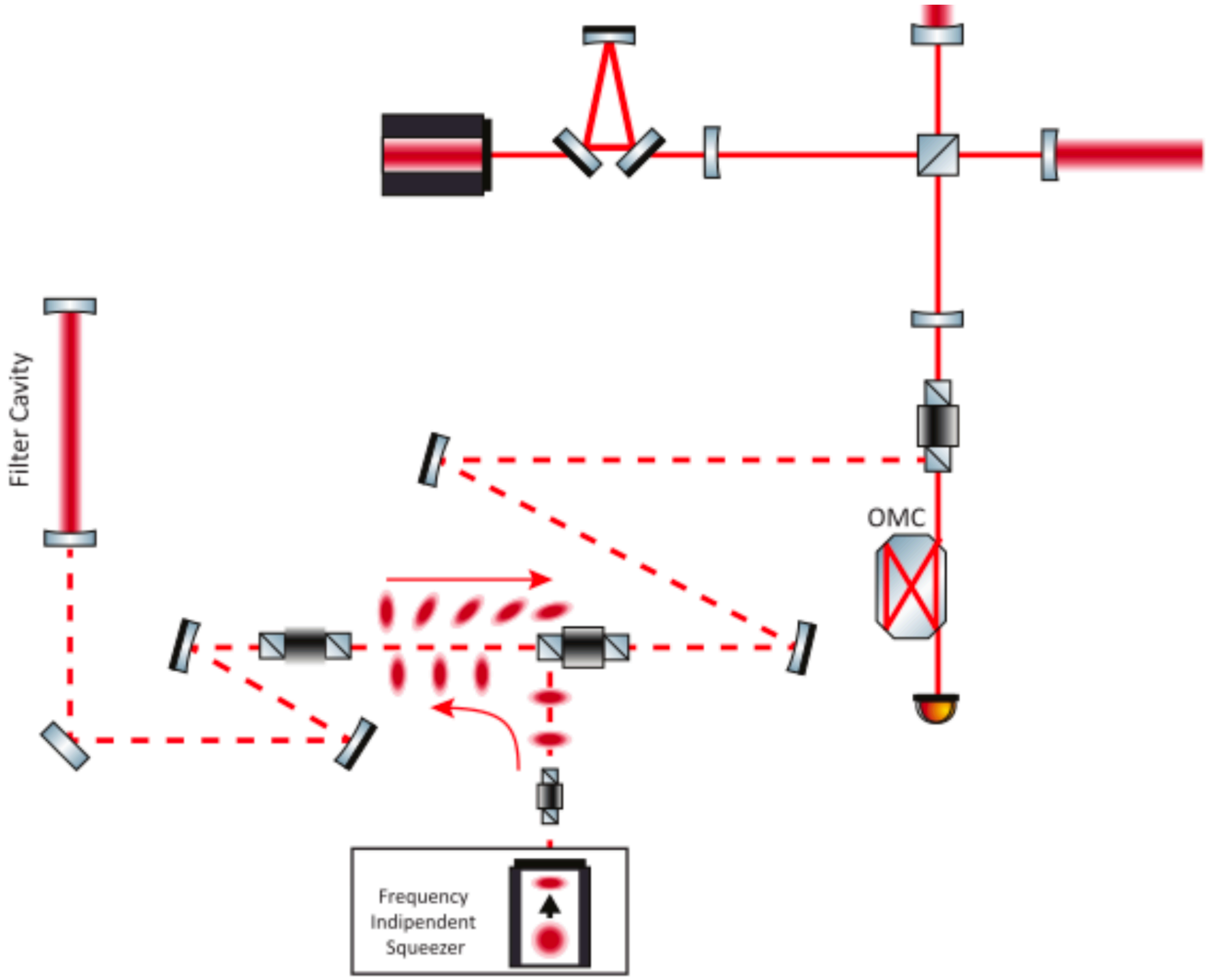
Virgo_nEXT goal quantum noise reduction



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**

Squeezer and injection losses

- Possible use of in-vacuum squeezing source (unlike LIGO, current one is in-air)
- Injection losses mainly due to several passes trough Faraday isolator (currently around 1% each pass)



R&D on-going

- In-vacuum squeezer demonstration
- Faraday isolation loss reduction: goal 0.35%

Component	Loss (ppm)	best scenario (ppm)
Input polarizer (surface 1)	1700	1000
Input polarizer (surface 2)	310	100
TGG crystal surfaces reflectivity	500	200
TGG crystal bulk absorption	3060	1500
half waveplate surfaces reflectivity	400	100
Output polarizer (surface 1)	1100	300
Output polarizer (surface 2)	200	100
Total Losses	7270	3300

Filter cavity losses

- No plans to increase the current length (285 m): heavier test masses -> cavity finesse can be slightly reduced (now is 10.000)
- Currently 50-90 ppm of round trip losses -> target 20 ppm
- Other degradation mechanisms are less critical. Control strategy to be tested when FDS is injected into the interferometer

R&D on-going

- 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)
  - Implement an in-situ monitoring system to study the contaminant in the Grand Coater machine.

Interferometer core optics losses

- Arm cavity round trip losses (75 ppm) already compliant with requirement
- SEC losses are more critical
  - Current estimated budget 1000 ppm (not measured yet)

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

- Target reduction of SEC losses by a factor 2

R&D on-going

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

Readout chain losses

- Photodiode efficiency (>99%) should be compliant with requirements
- Replace the current monolithic OMC cavity by an open cavity or a hollow cavity to remove absorption losses and Rayleigh scattering losses inside the cavity medium.
- Possible reduction of pick off control beam before OMC

R&D

- Design and test of a reduced loss output mode cleaner

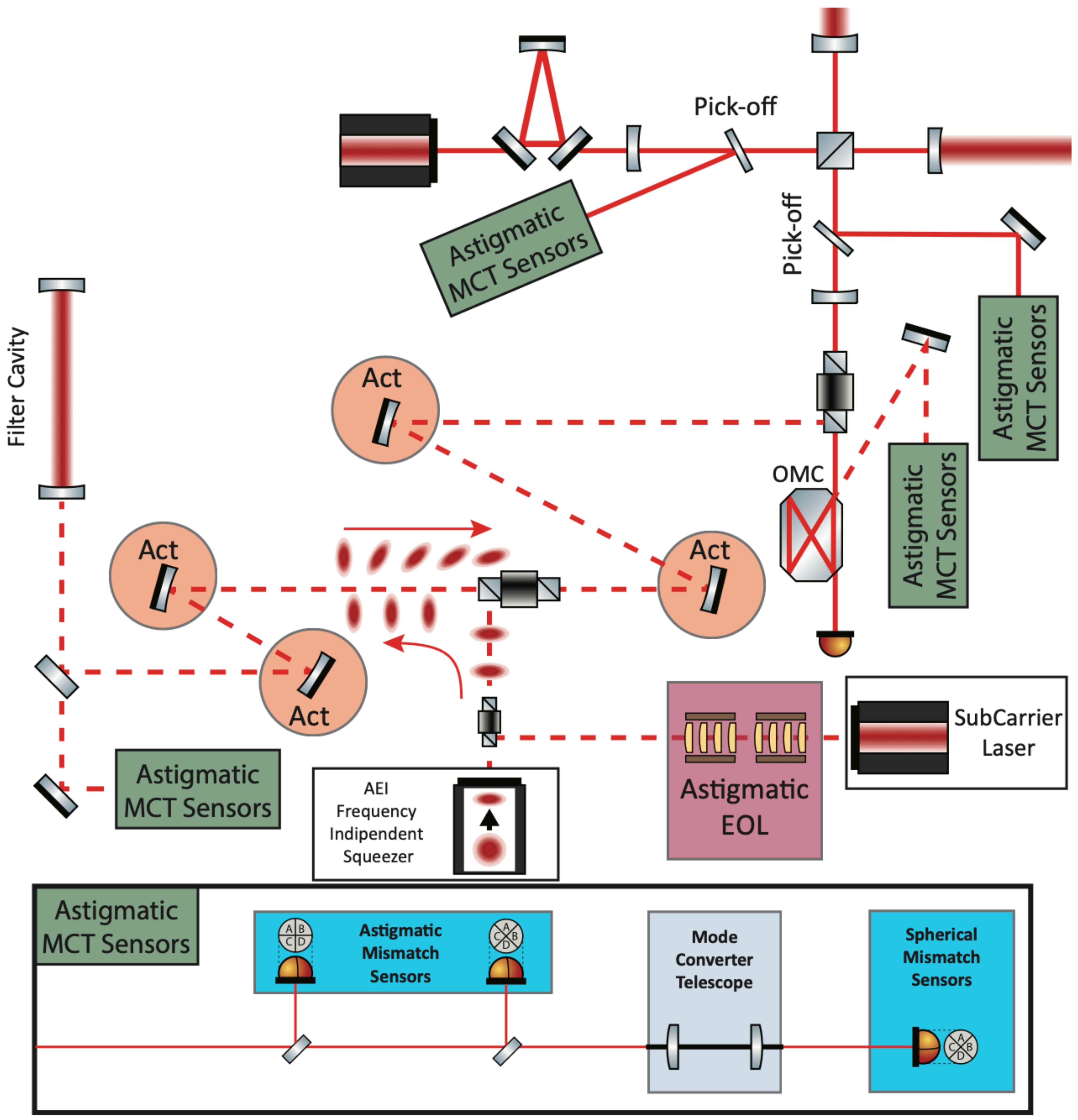
Mode-mismatching

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

R&D

- Upgrade of Mode converter telescope (MCT) and/or electro-optic lens (EOL) to sense astigmatism
- Implement of astigmatism actuator

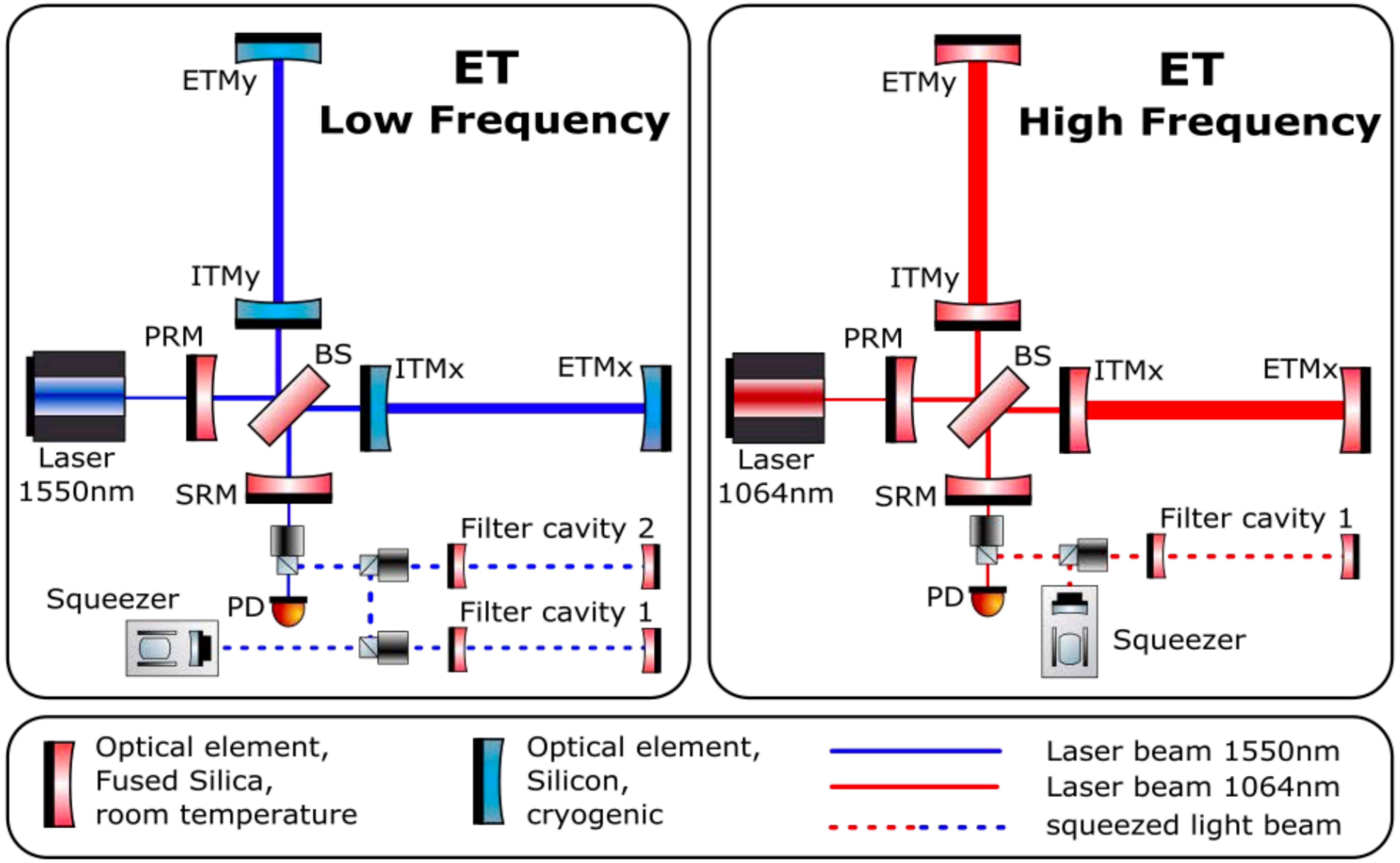
- Higher order mismatches between the arms and the SEC due to optical path length distortions in the ITMs with high power: can TCS compensate ?



Scheme of possible mode matching sensors and actuators implementation for VnEXT. Adaptive optics are also planned for the OMC mode matching telescope which is not shown in this scheme.

Synergies with Einstein telescope

- Same technology (FDS) and same squeezing target: needed R&D are basically the same for ET-HF
- 10 dB target is more challenging for ET-LF:
  - Different wavelength
  - Detuned configuration requires 2 filter cavities with very low bandwidth



Summary

- Post-O5 virgo upgrade (Virgo_nEXT) is targeting 10 dB of quantum noise reduction
    - Well established technology: frequency dependent squeezing with filter cavities.
    - No change to current infrastructure
- Main challenge: total loss reduction below 8%
    - Loss sources mainly identified, mitigation strategy to be developed: some R&D required and some more modelling to be done.
- Strong synergy with ET, A#, CE (same 10dB target and same technologies)