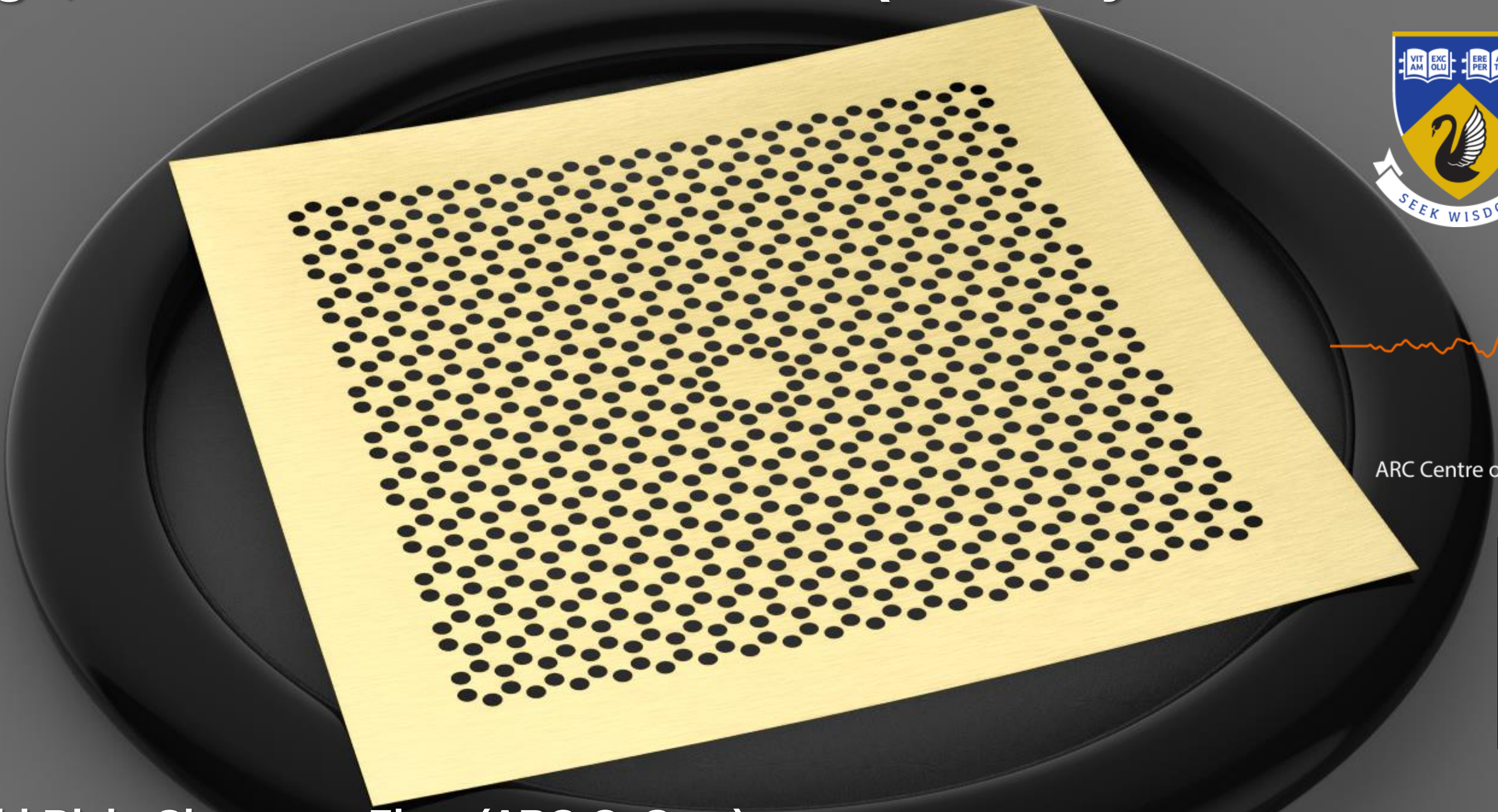
Broadband gravitational wave detectors using white light signal recycling

Michael A. Page, JSPS Fellow NAOJ Mitaka (formerly ARC OzGrav)



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OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

EQUS

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Massimiliano Rossi, Albert Schliesser (Neils Bohr Institute), David Mason (Yale Quantum Institute)
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Publication details

Gravitational wave detectors with broadband high frequency sensitivity

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ABSTRACT

Gravitational waves from the neutron star coalescence GW170817 were observed from the inspiral, but not the high frequency postmerger nuclear matter motion. Optomechanical white light signal recycling has been proposed for achieving broadband sensitivity in gravitational wave detectors, but has been reliant on development of suitable ultra-low loss mechanical components. Here we show demonstrated optomechanical resonators that meet loss requirements for a white light signal recycling interferometer with strain sensitivity below 10^{-24} $Hz^{-1/2}$ at a few kHz. Experimental data for two resonators are combined with analytic models of interferometers similar to LIGO to demonstrate enhancement across a broader band of frequencies versus dual-recycled Fabry-Perot Michelson detectors. Candidate resonators are a silicon nitride membrane acoustically isolated by a phononic crystal, and a single-crystal quartz acoustic cavity. Optical power requirements favour the membrane resonator, while thermal noise performance favours the quartz resonator. Both could be implemented as add-on components to existing detectors.

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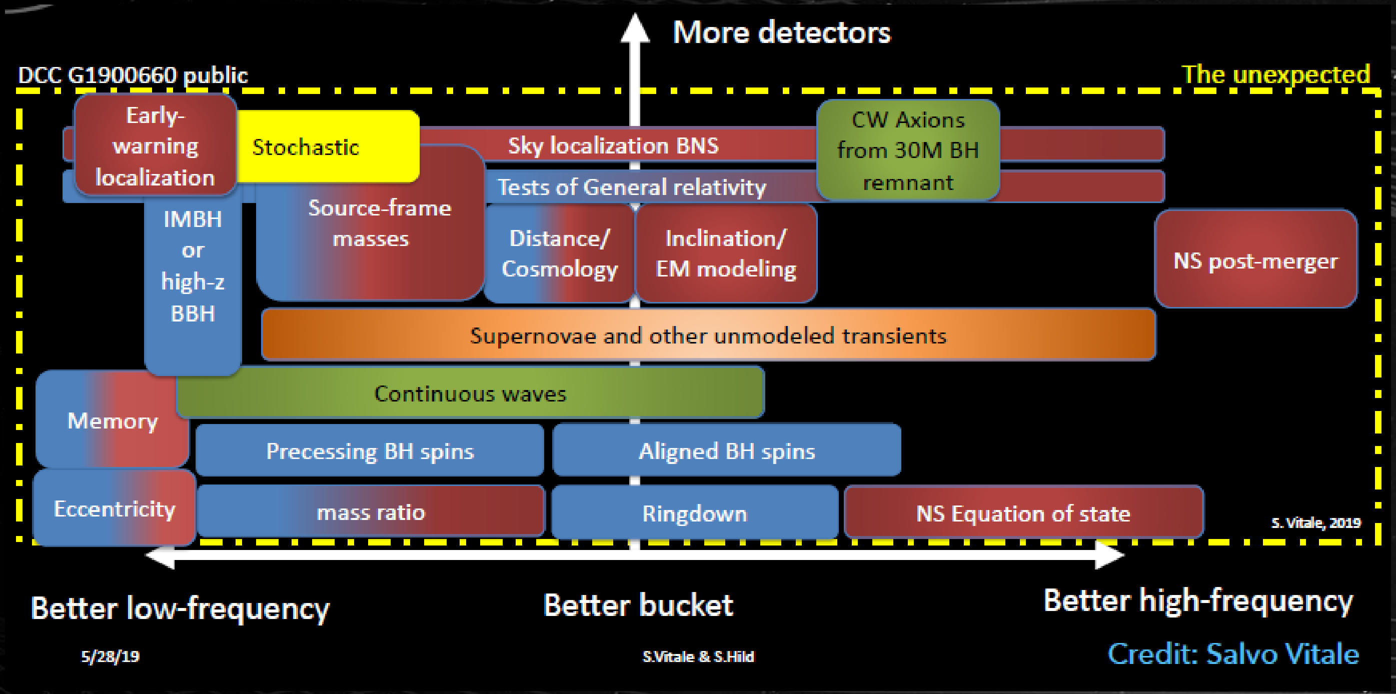
Major contributing institutions:

- ARC Center of Excellence for Gravitational Wave Discovery OzGrav (UWA node)
- ARC Center of Excellence for Engineered Quantum Systems EQuS
- Neils Bohr Institute, University of Copenhagen

Motivation - High frequency detection



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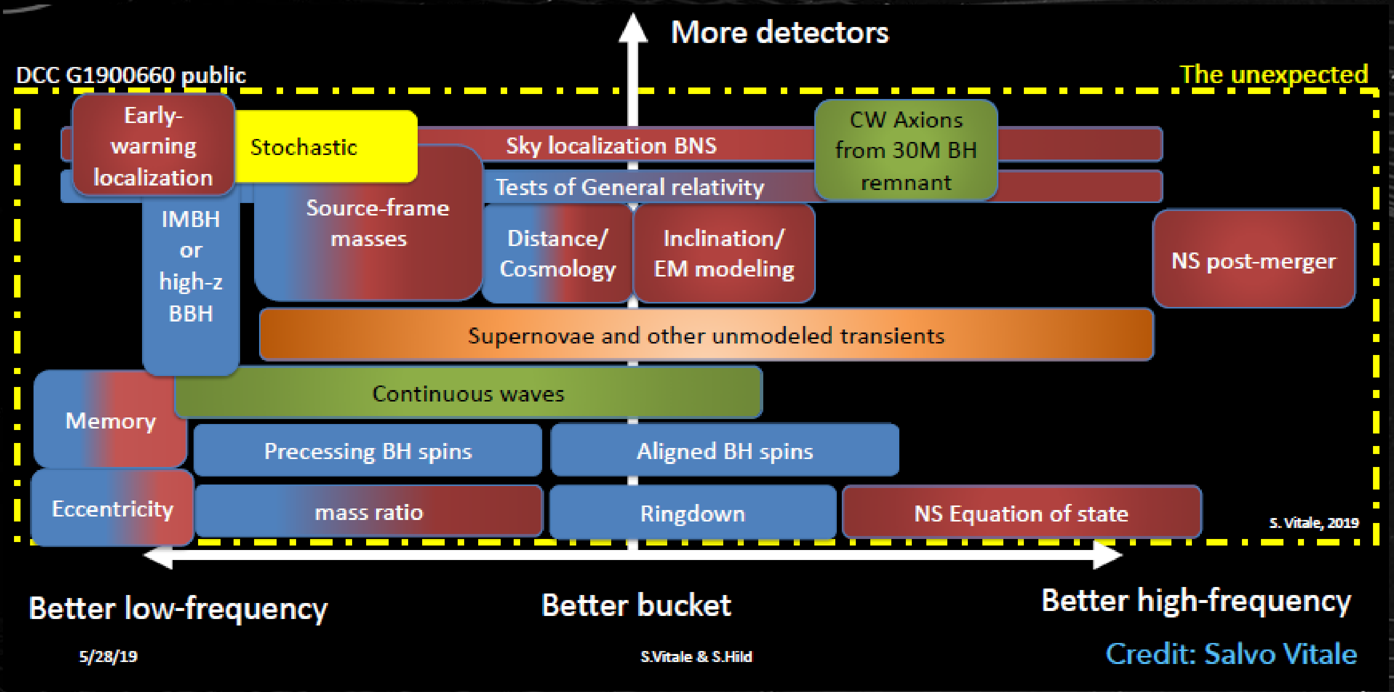
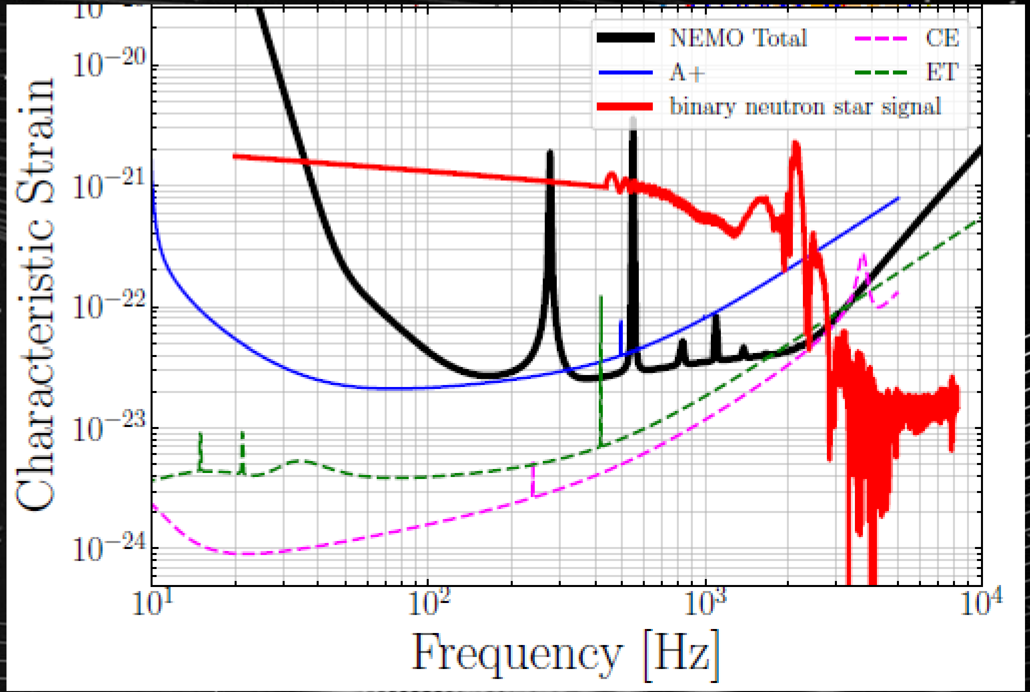
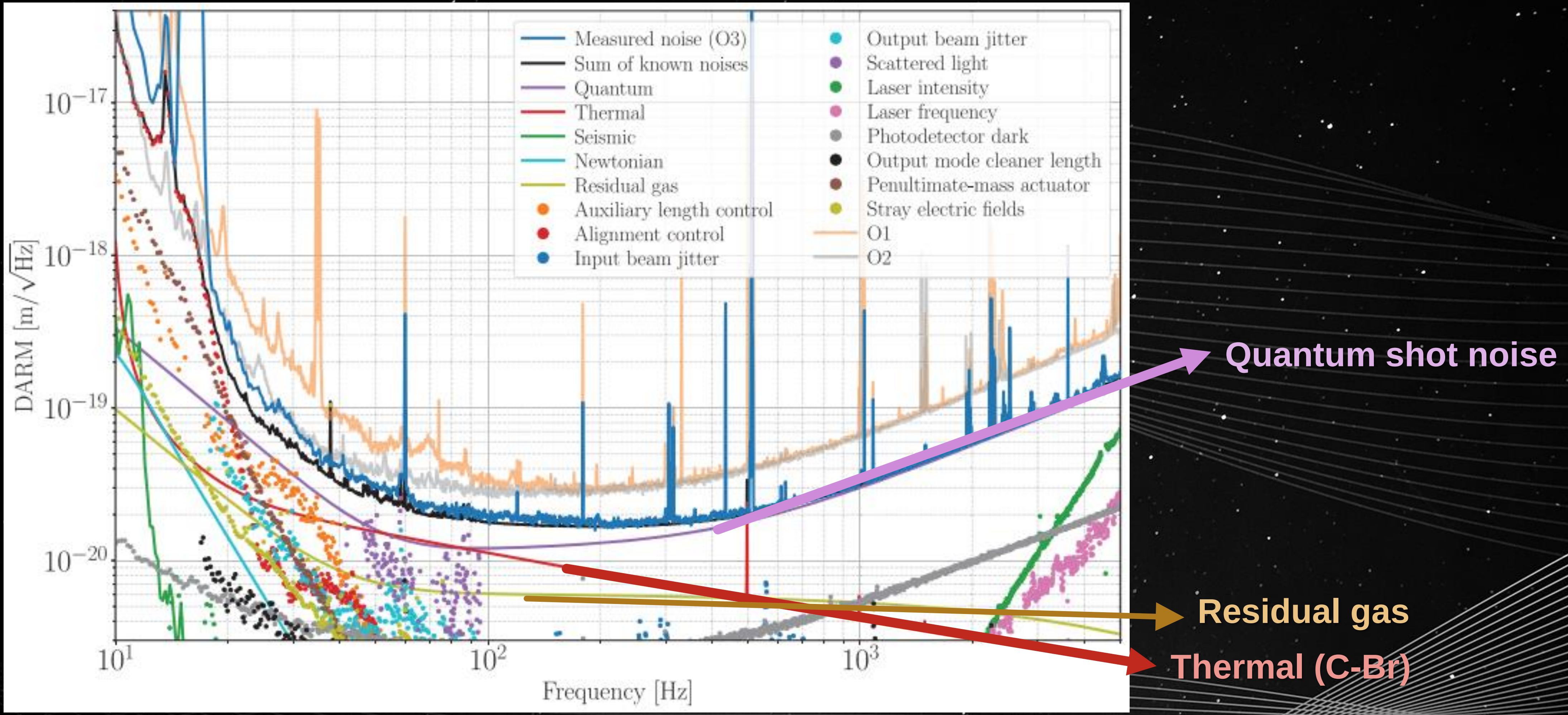




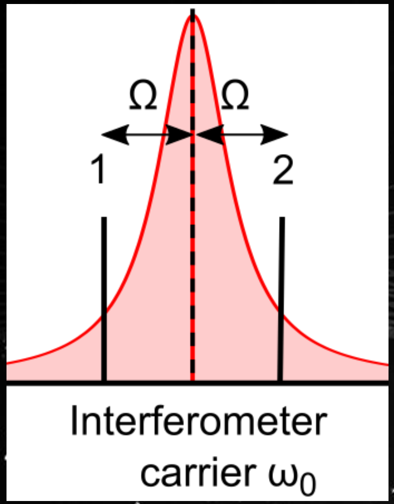
K. Ackley *et al.*, "Neutron Star Extreme Matter Observatory: A kilohertz-band gravitational-wave detector in the global network", Proceedings of the Astronomical Society of Australia, **37**, E047. doi:10.1017/pasa.2020.39

HF detection



A. Buikema *et al.* "Sensitivity and performance of the Advanced LIGO detectors in the third observing run", Phys Rev D **102** 062003 (2020)

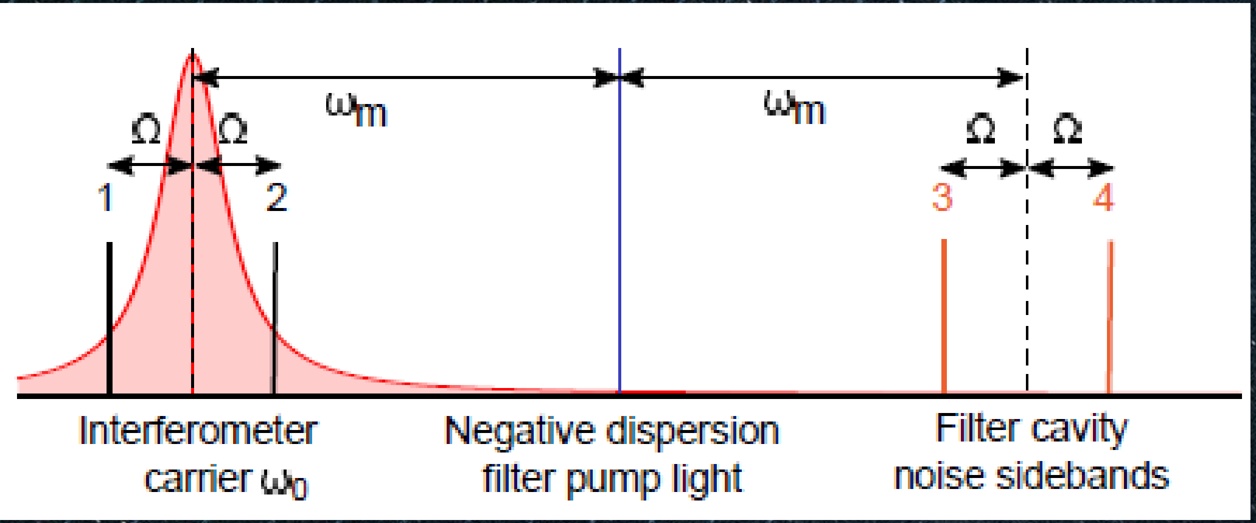
Loss of high frequency signal

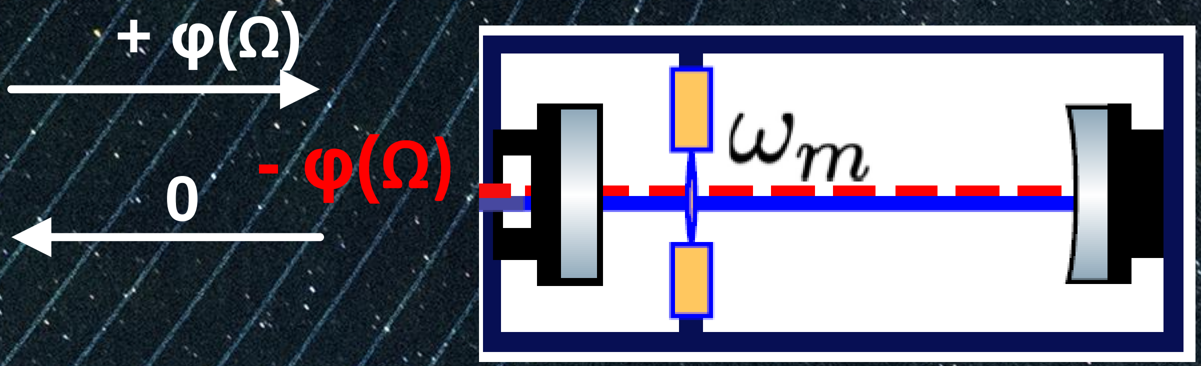


Gravitational wave sidebands acquire phase delay

Leads to loss of signal strength at high frequency

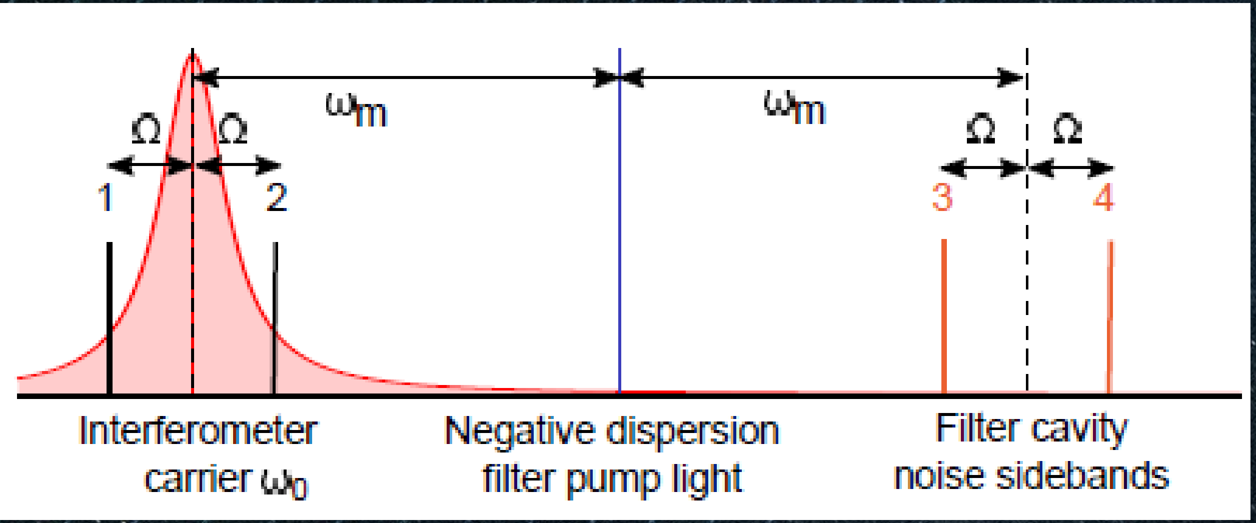
Quantum enhancement

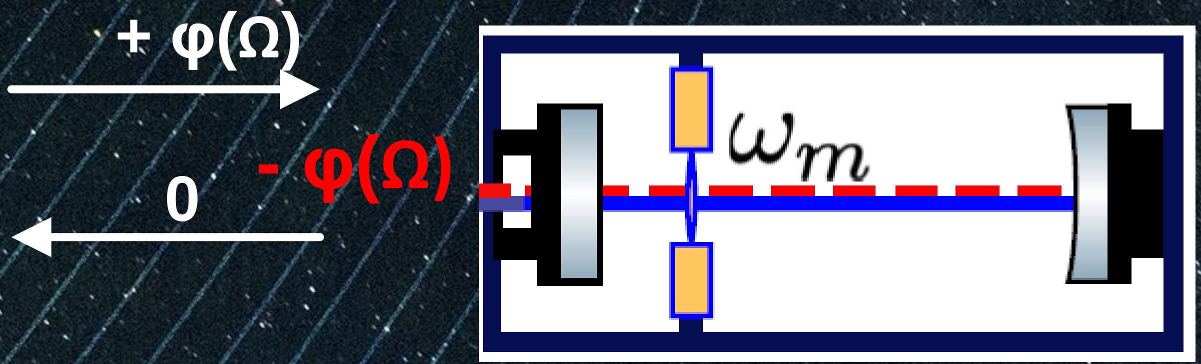




WLSR is generated by negative dispersion. Parametric interaction creates frequency dependent storage of light.

Quantum enhancement

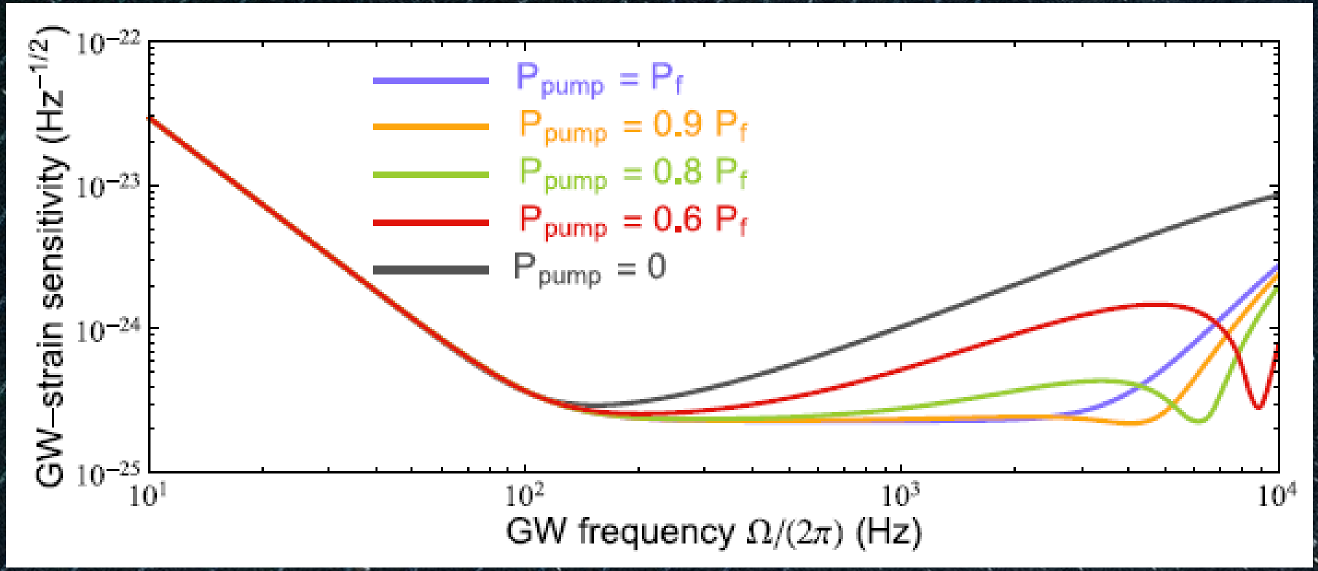


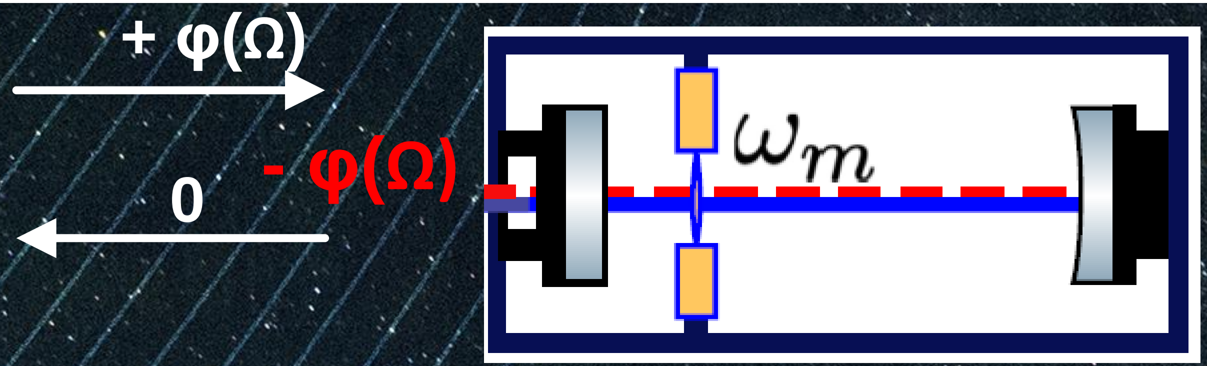


Parametric amplification of sidebands by blue detuned pump and ω_m gives negative dispersion input output: $\boldsymbol{a}_{out} \sim e^{-\mathbf{i}\,\Omega/\gamma_{opt}} \boldsymbol{a}_{in}$.

Negative dispersion is controlled by optomechanical coupling rate. By matching γ_{opt} to *c/L*, we can make $\boldsymbol{a}_{out} \sim e^{-\mathbf{i}} \boldsymbol{a}_{in}$

Quantum enhancement

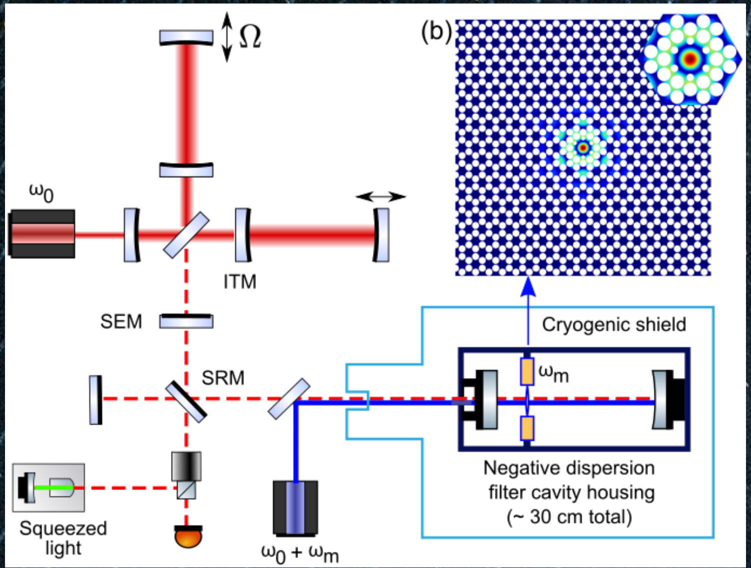


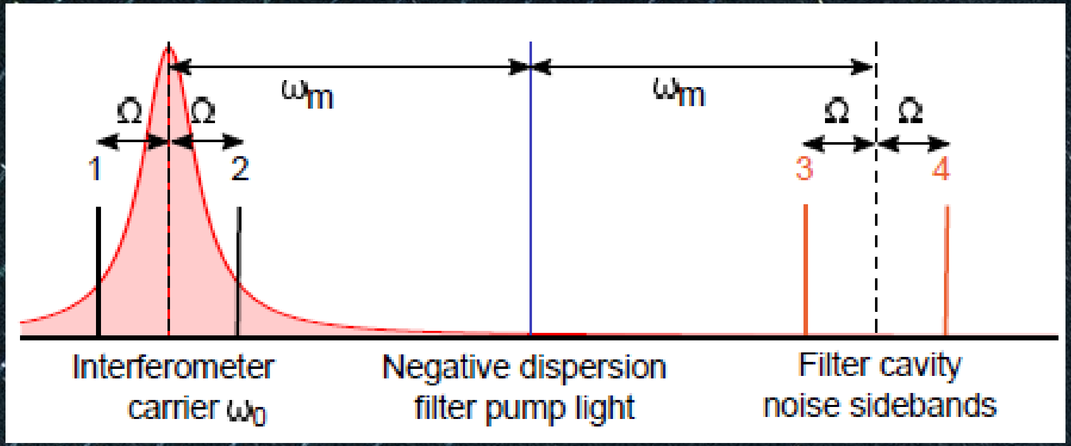


Quantum noise curve is broadened.

We can actually achieve better HF sensitivity by making γ_{opt} slightly < *c/L*

White light signal recycling



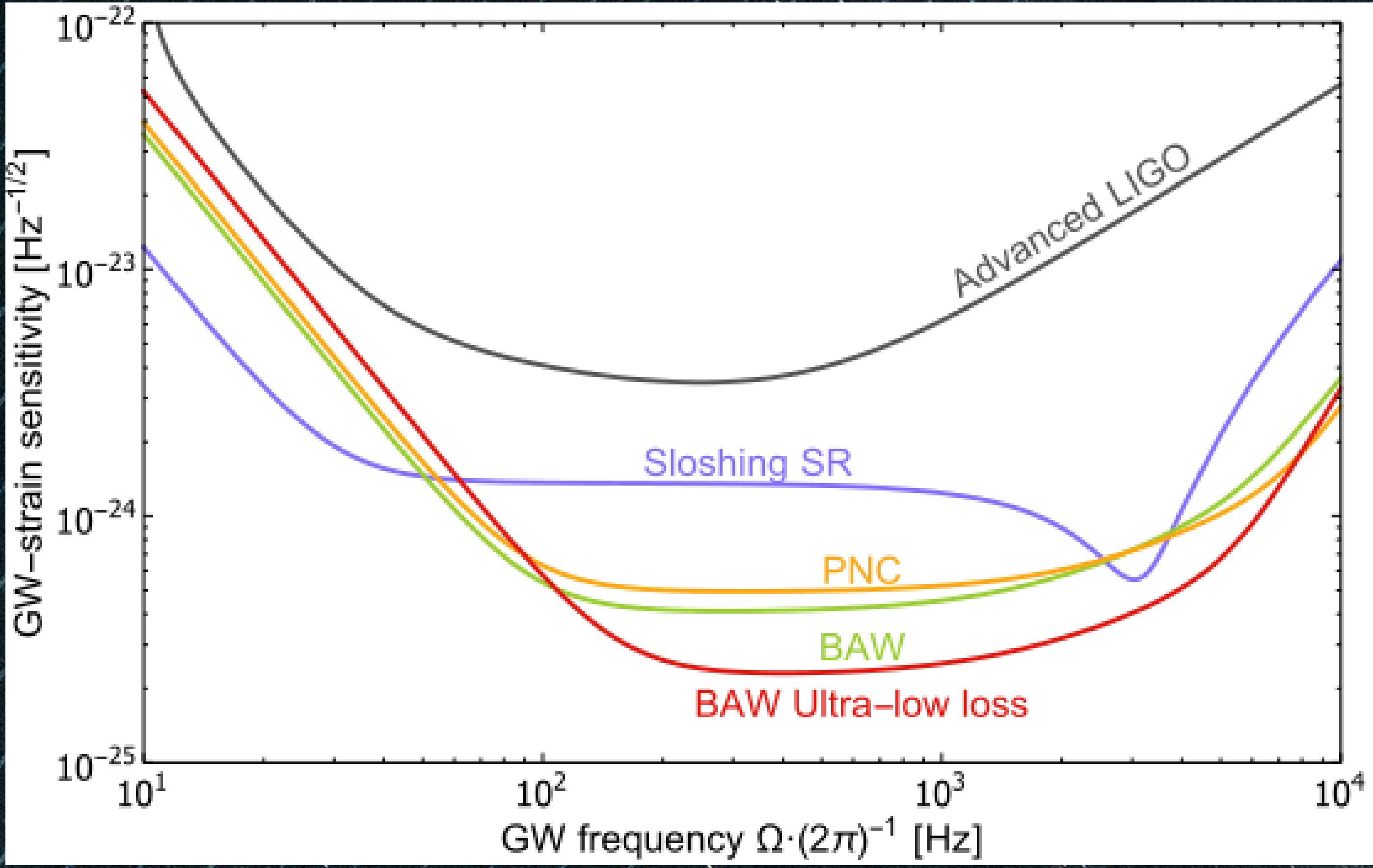


Low thermal noise mechanical resonator is essential!

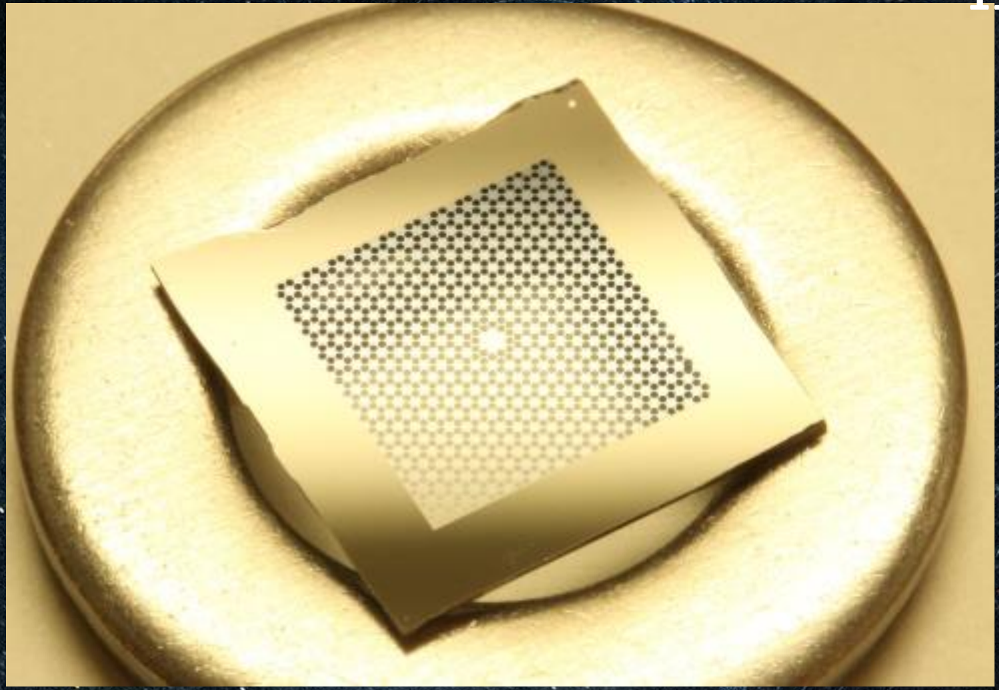
In addition to thermal noise, the mechanical resonator also introduces quantum noise sidebands, thus we need sufficient ωm to detune them.

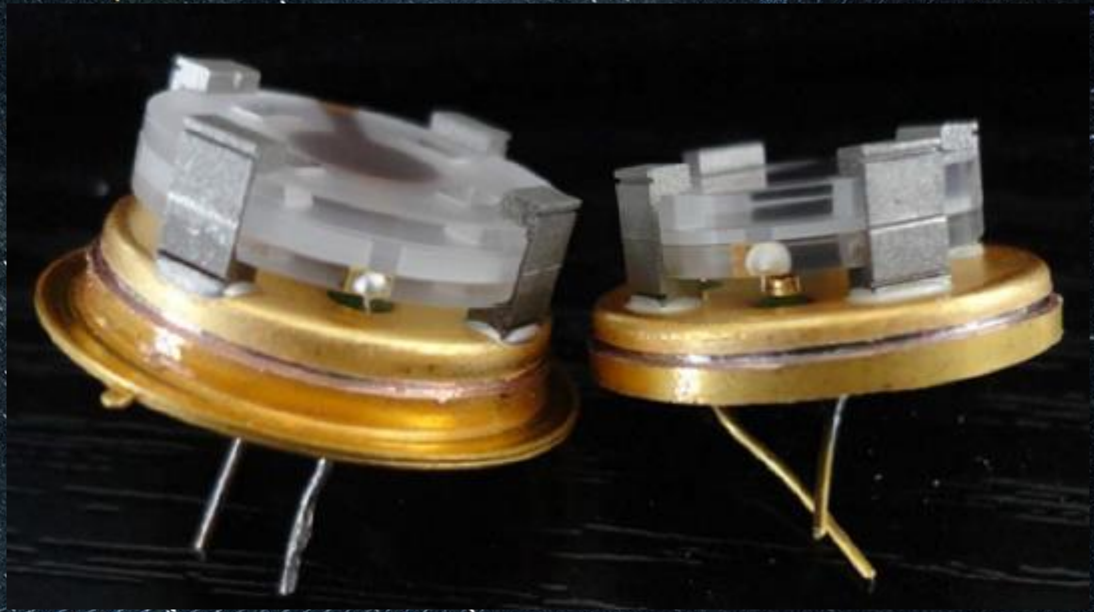
Tricky balance of Qm, ωm, resonator size and optical pumping power

White light vs dual recycling



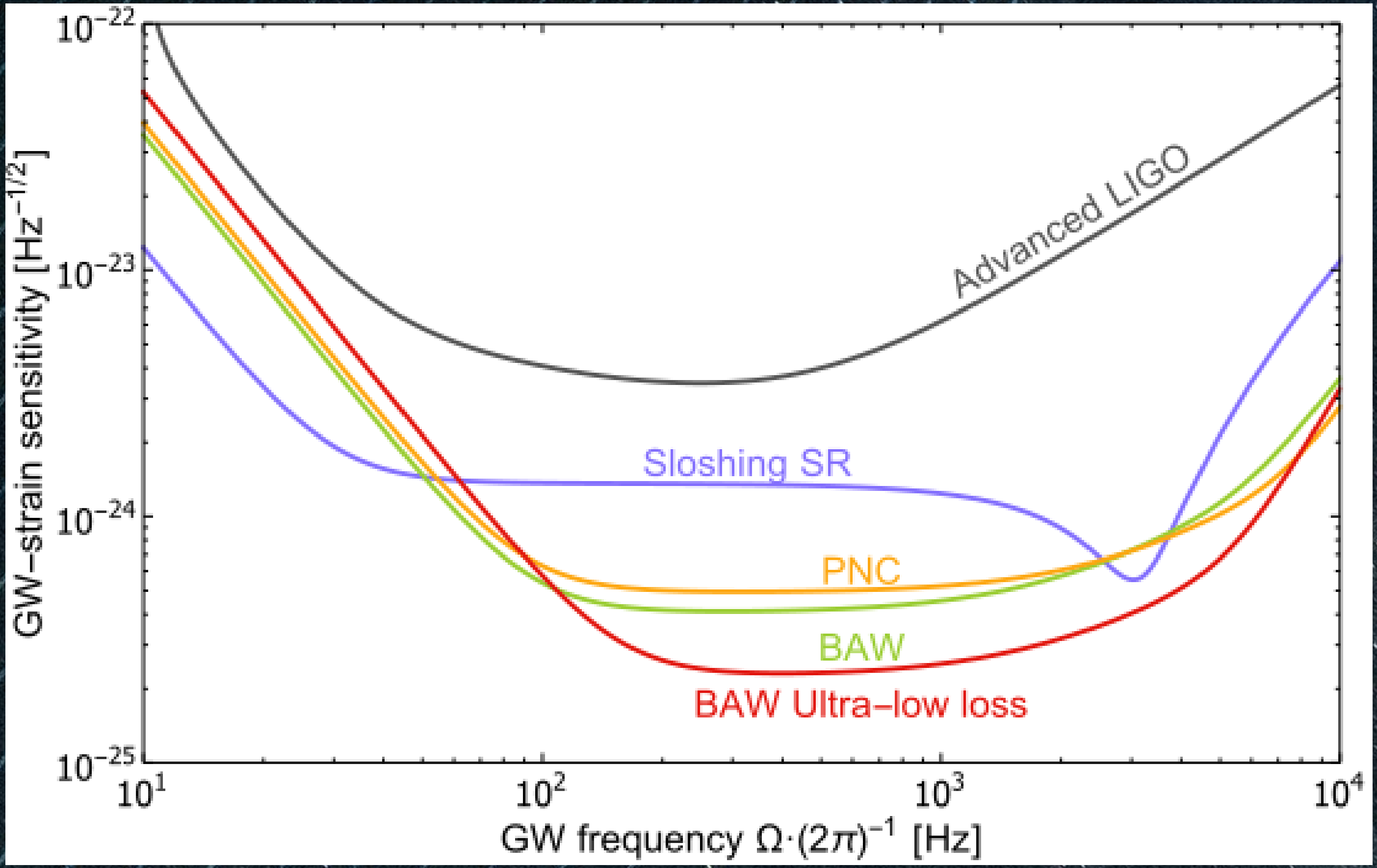
Phononic crystal resonator





Bulk acoustic wave resonator

White light vs dual recycling

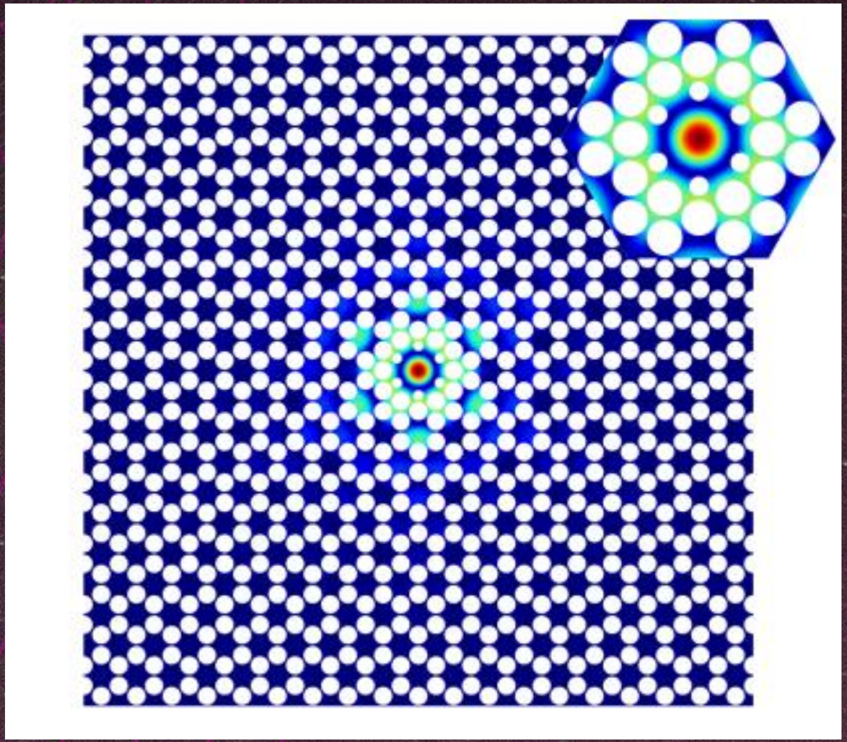


BAW resonator offers lowest possible thermal noise thus far, but is limited by other issues as follows

Given present mechanical properties, the PNC resonator is more convenient

Sloshing SR – uses optical resonance at 2.5 kHz to enhance a narrow band of NS frequencies (D. Martynov PRD **99** 102004)

Phononic crystal

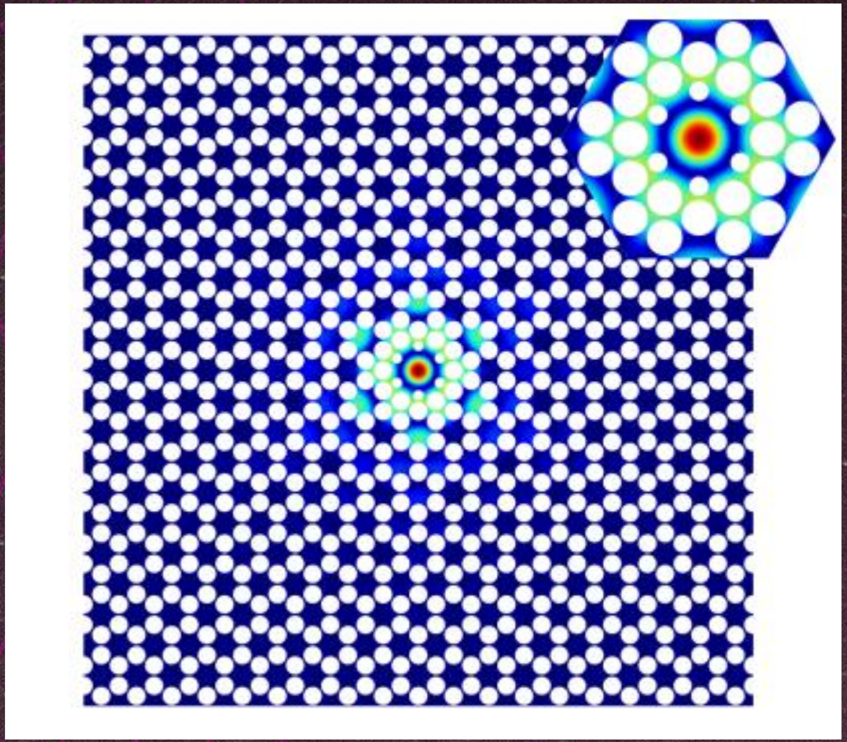


"Resonator" in the middle moves back and forth

2d lattice has an acoustic bandgap that prevents transmission of mechanical modes into and out of the resonator

(Our dielectric stack HR coatings are an example of a 1d photonic crystal)

Phononic crystal



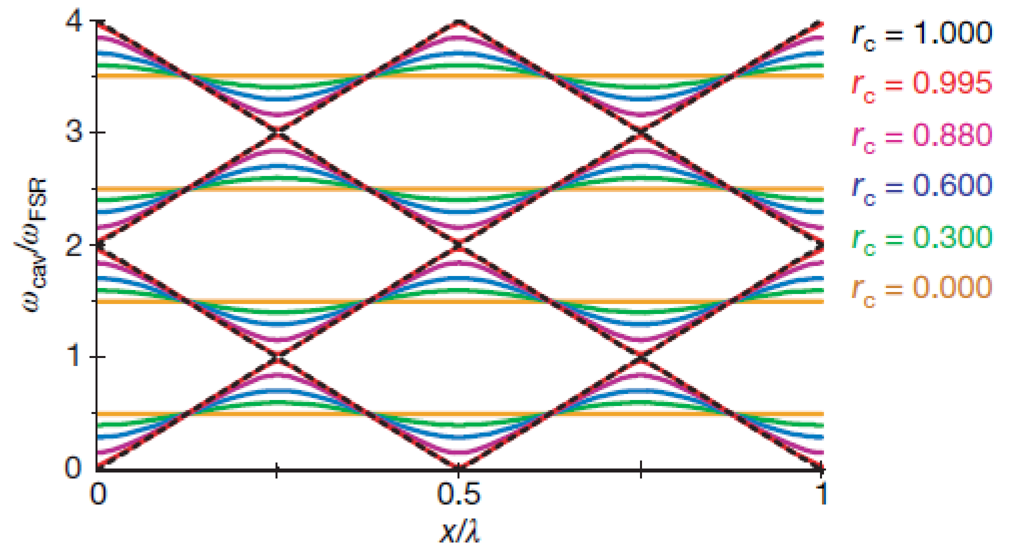
D. Mason, *et al.*, "Continuous force and displacement measurement below the standard quantum limit" Nature Physics, vol **15**, 745-749 (2019)

Demonstrated mode: $\Omega m = 2\pi*1.135$ MHz, effective mass 2.3 ng, Q = 1.03*10^9, at T = 10 K.

Need to cool to 1 K to meet thermal noise requirements, but has much lower filter cavity power requirements than the BAW resonator.

Optomechanical coupling

Thompson *et al.* Nature **452**
doi:10.1038/nature06715

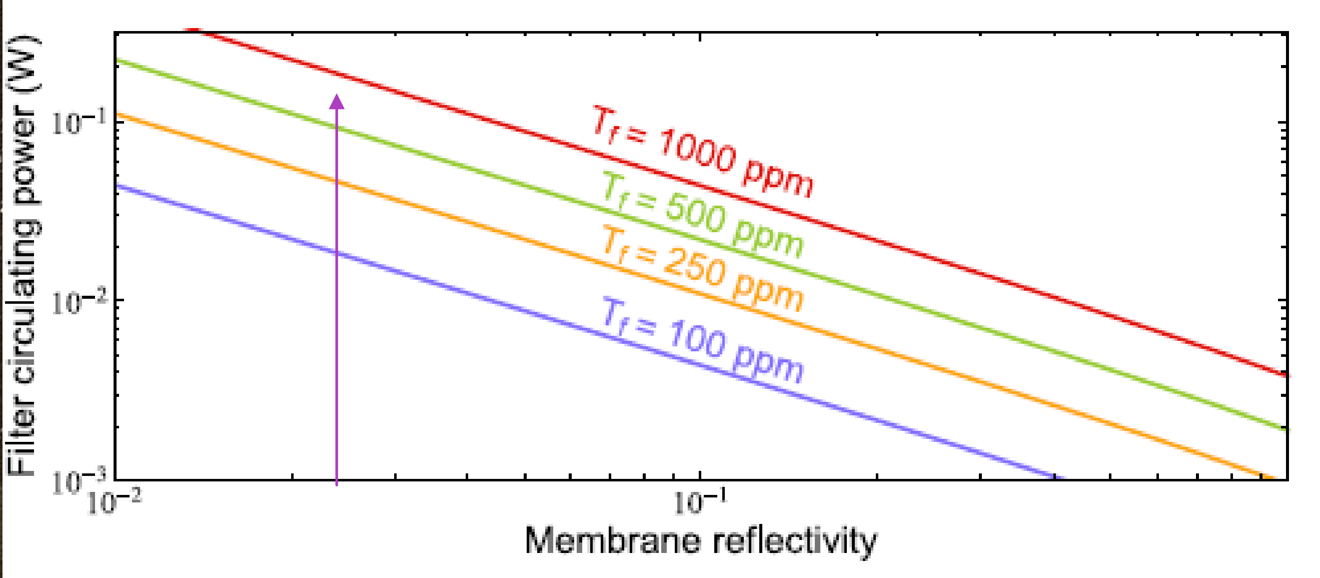


PNC resonator as membrane-in-the-middle

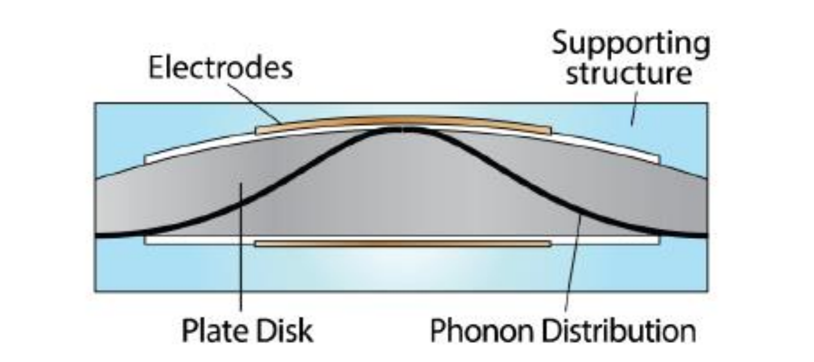
MIM cavities give well known OM coupling vs membrane position and reflectivity

20nm SiN membrane has power reflectivity ~ 3%. Small but sufficient.

Paper: Tf = 300 ppm, Pf = 42 mW



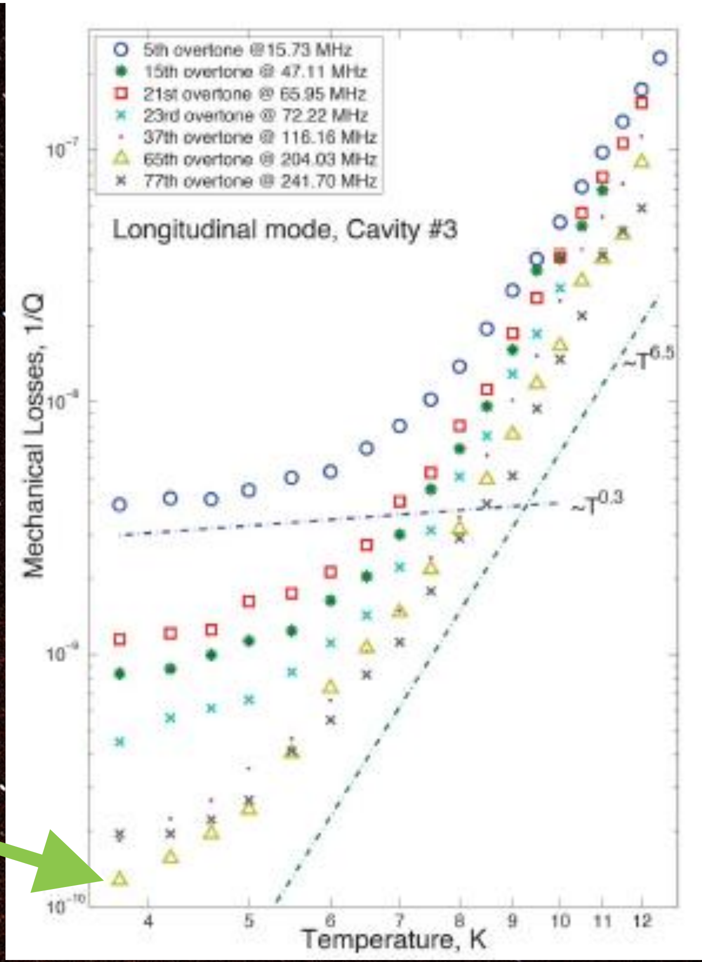
Bulk acoustic wave resonator optimal mechanical mode



Higher mode number confines the mode to the center, reducing **clamping** loss

However, smaller mode size causes more **scattering** from impurities

Selected mode: n = 65, Ωm= 2π·204 MHz, Q=8*10^9

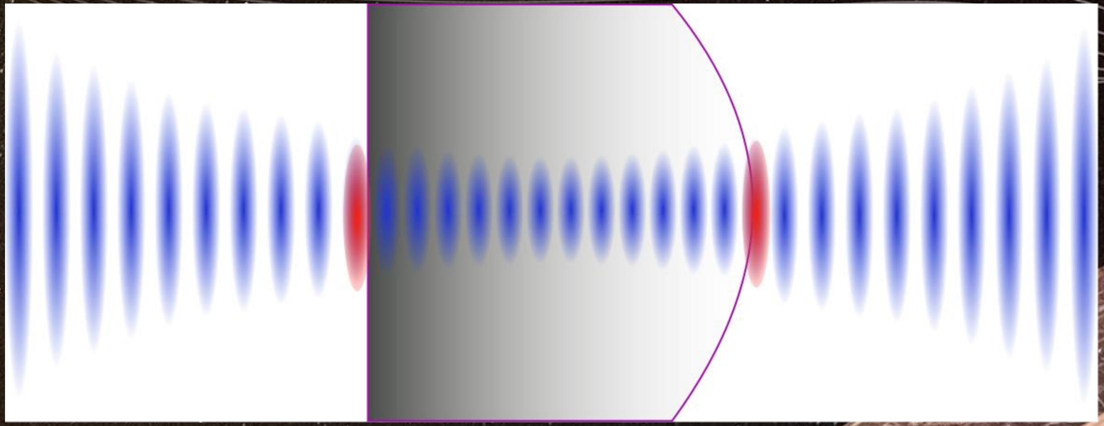


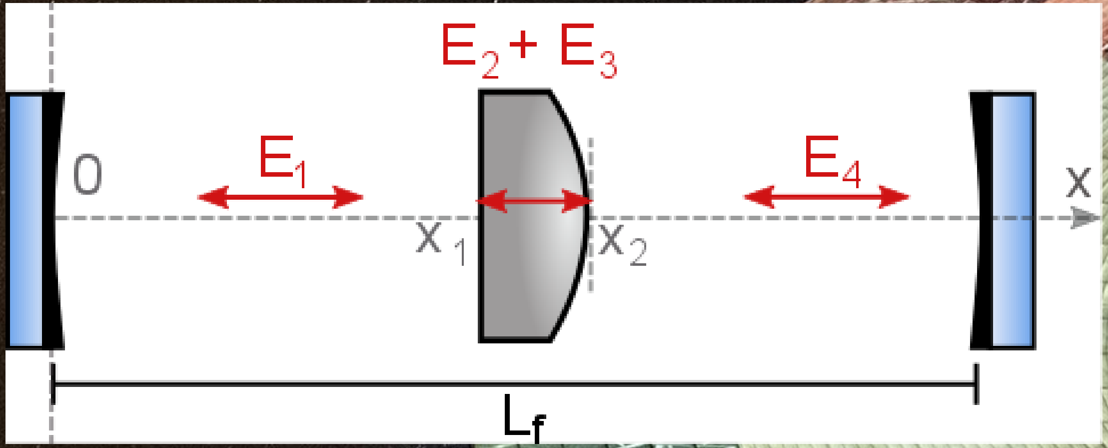
More information: S. Galliou *et al*. Scientific Reports **3** 10.1038/srep02132

BAW resonator

BAW optomechanics have been demonstrated with Brillouin scattering throughout the longitudinal axis, but this requires Ωm = 2π· 18 GHz (More information: Kharel *et al.* Science Advances **5** eaav0582 (2019))

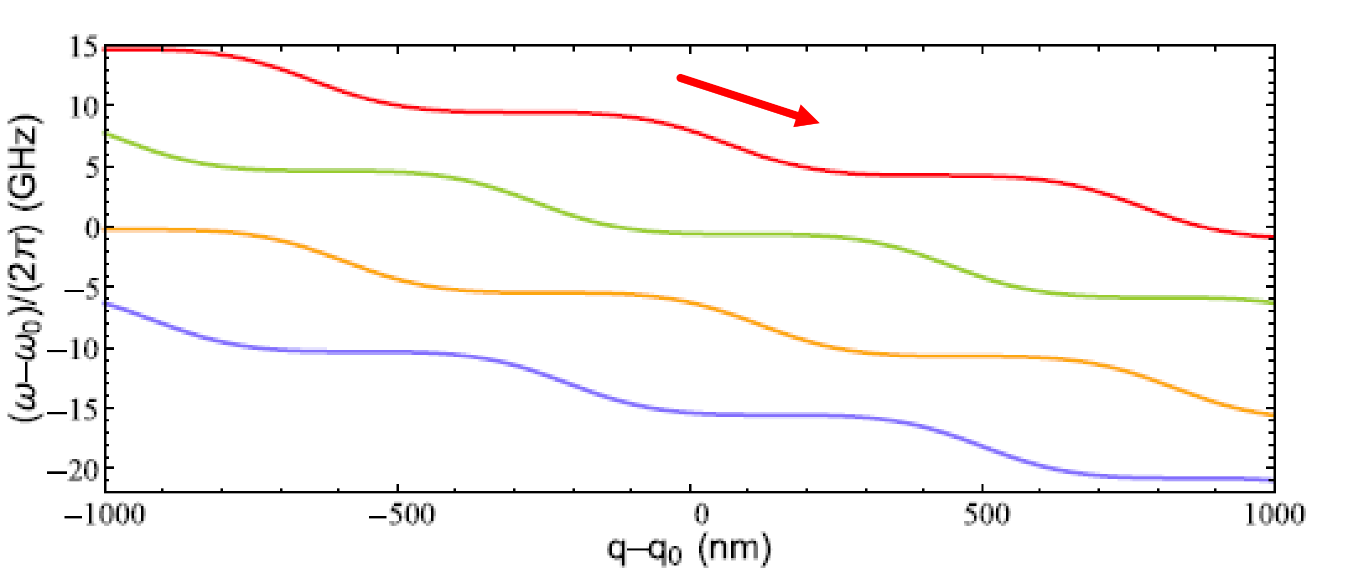
Must use coupling to antiphase surface motion





Optomechanical coupling

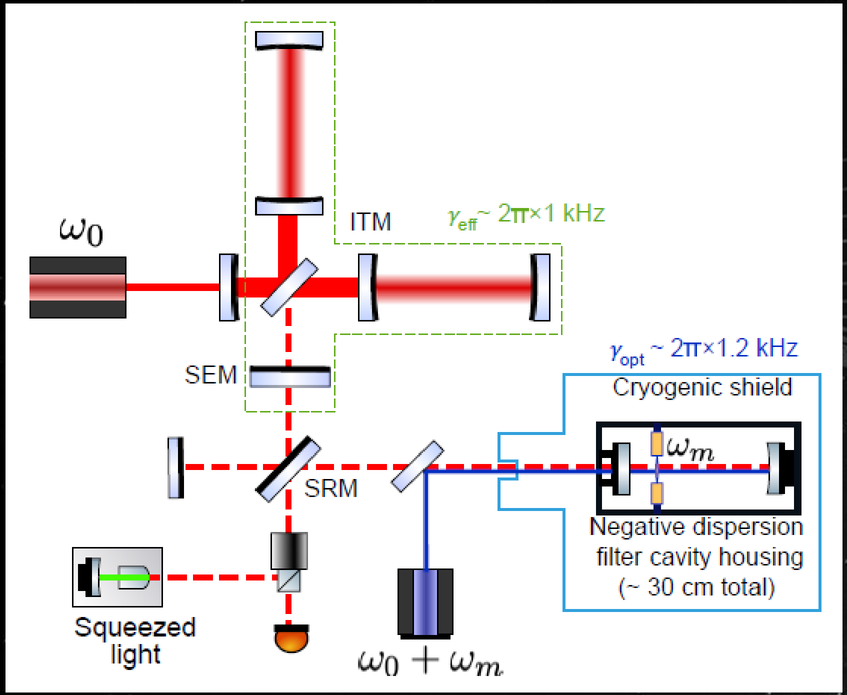
Small dω/dq * large effective mass

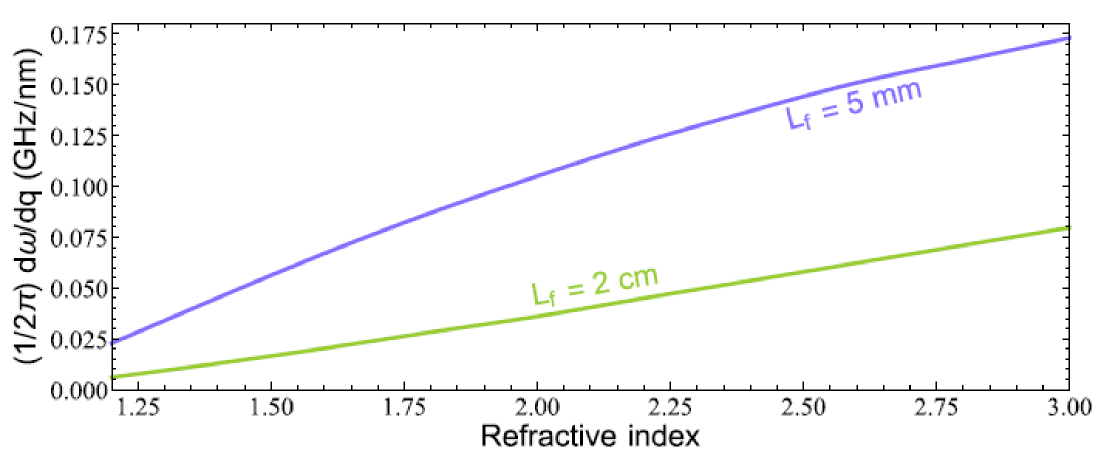


BAW antiphase surface coupling only has ~ 0.01 GHz/nm of optomechanical shift, with single photon rate ~ 0.1 Hz.

Filter cavity power requirement of 38 kW (!!)

Mitigating BAW power requirements



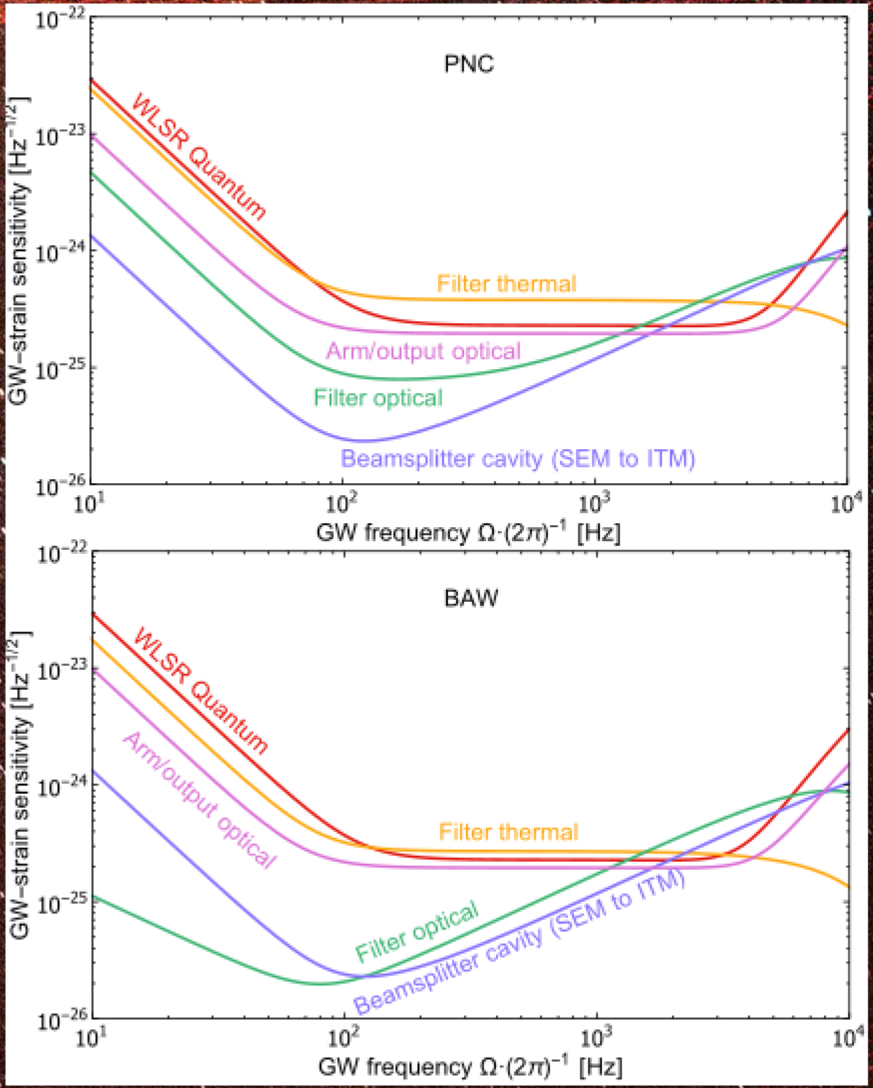


Match γopt and γarm (determined by the ITM and SRM). Can reduce γopt to 2π*1200 Hz, which takes power down by 10x, but also reduces bandwidth broadening.

Increase refractive index of BAW – possible with coatings, at cost of some Qm.

Find some way to get Brillouin scattering – would have to leave “known regimes” of Qm and optical absorption

Comparison of main result



BAW 4 K, PNC 1 K – arm 4 MW, 10 dB FDS

Thermal, filter optical and ITM/BS heating are dominant.

FC loss is 10 ppm in PNC case and 5 ppm in BAW case – very strict due to high finesse FC, causing high fractional contribution

Main quantum noise tweaks are FC bandwidth, FC power and SRM transmission

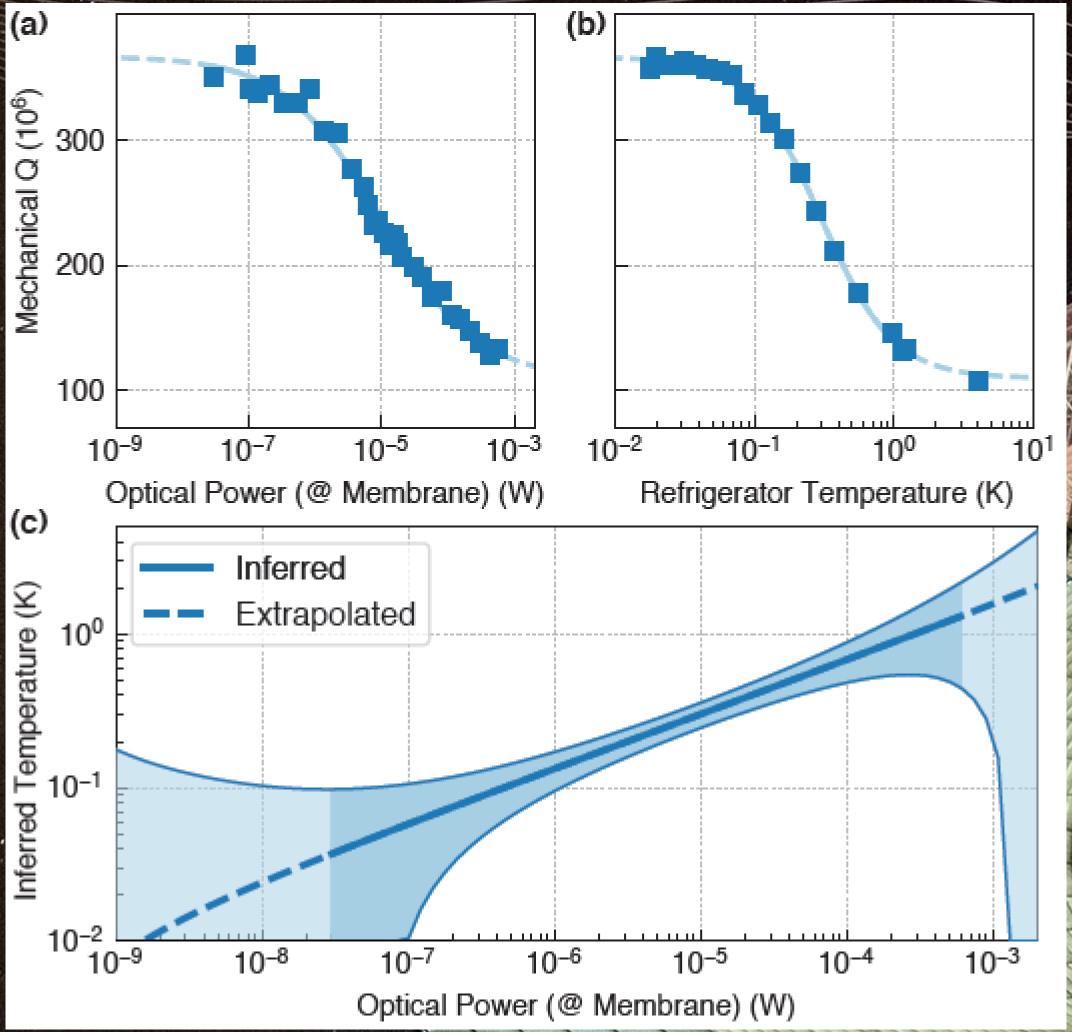
Arm, SRC loss ~ 0.1%. Output 2.5%. ITM/SEM round trip 957 ppm at T_ITM = T_SEM = 0.04

Absorption and temperature

PNC – inference for current samples indicates 10 K, 10 mW for 60 nm thick PNC

Recent experimental research has suggested that SiN membranes can be maintained at less than 1 K even for hundreds of mW of power, and that absorption heating isn't a limiting factor.

More information: R. Peterson *et al.* "Laser cooling of a micromechanical membrane to the quantum backaction limit" PRL **116** 063601

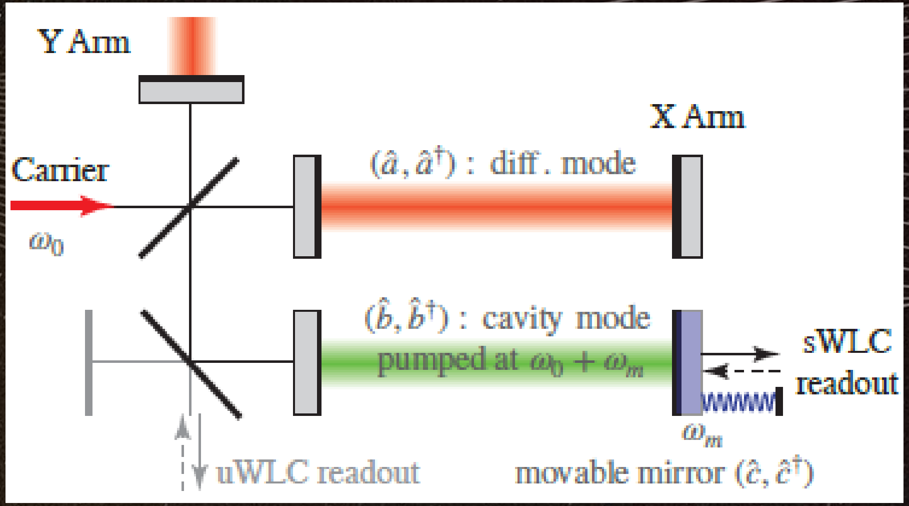


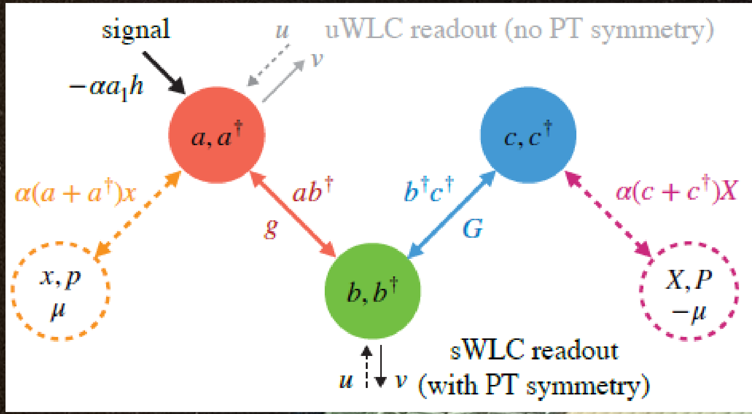
Quantum control

Blue detuned pumping scheme with 3 mode interaction creates instability.

Some indications from U. Birmingham that local control with matched filtering can mitigate this issue (mentioned in J. Bentley PRD **99** 102001)

Caltech have found a system which eliminates the stability issue at a fundamental level





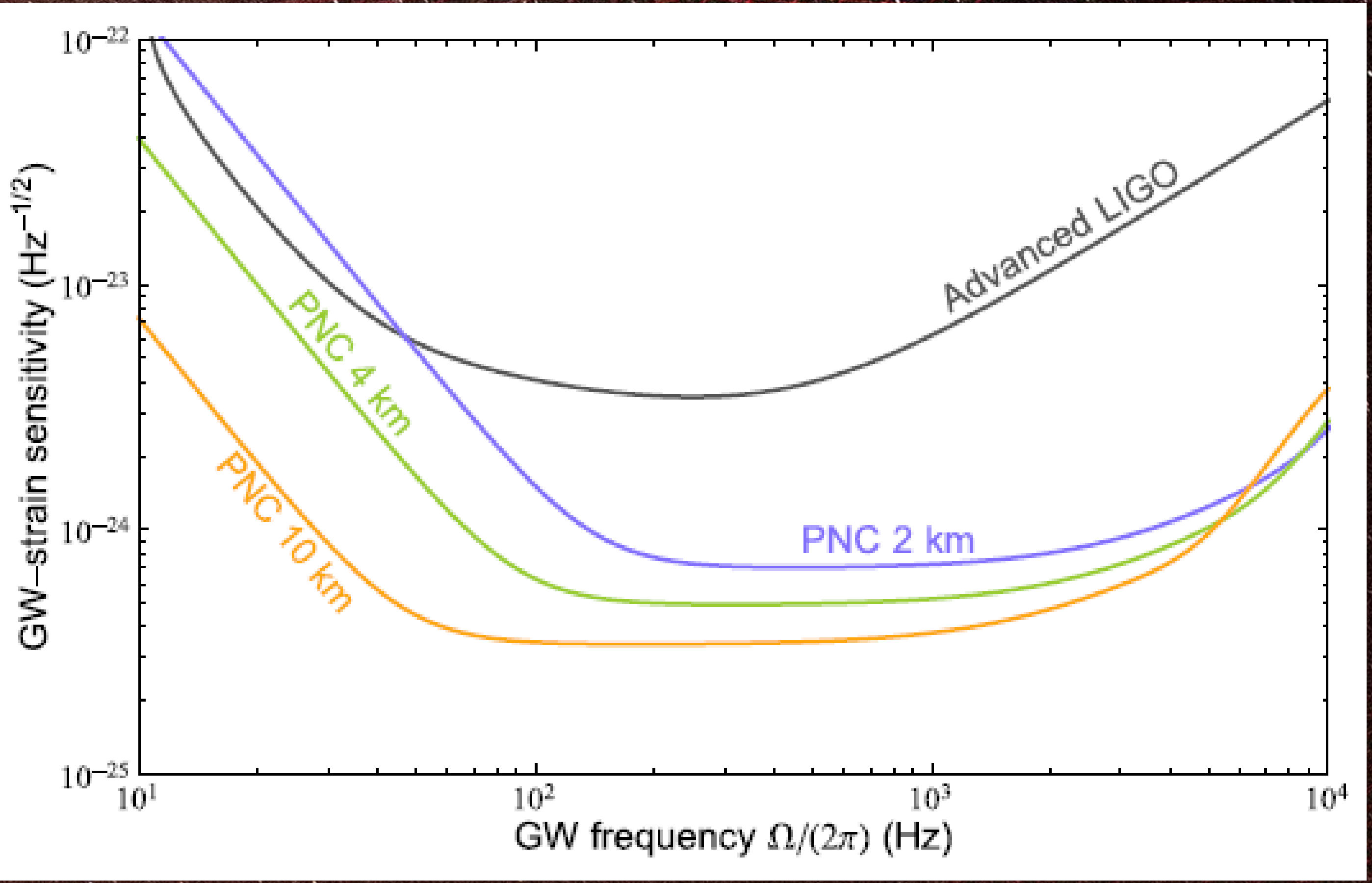
Further information: Xiang Li *et al.*, "Broadband sensitivity improvement by via coherent quantum feedback with PT symmetry" LIGO-P2000452

Conclusions

- Existing PNC resonators can give us broadband high frequency sensitivity using measured abilities of mechanical loss and optomechanical coupling
- BAW resonator – promising thermal noise performance. Daunting but not impossible. It seems like research will need to be done into custom purpose BAW resonators (OzGrav/EQuS UWA)
- In both cases, optical losses from the filter and ITM/BS distortion are particularly concerning at NS frequencies
- Longer interferometers allow somewhat relaxed optical loss for the purpose of WLSR
- Major groups involved in this research (Caltech, Birmingham, Northwestern) are investigating quantum controllability of the filter

Extra info

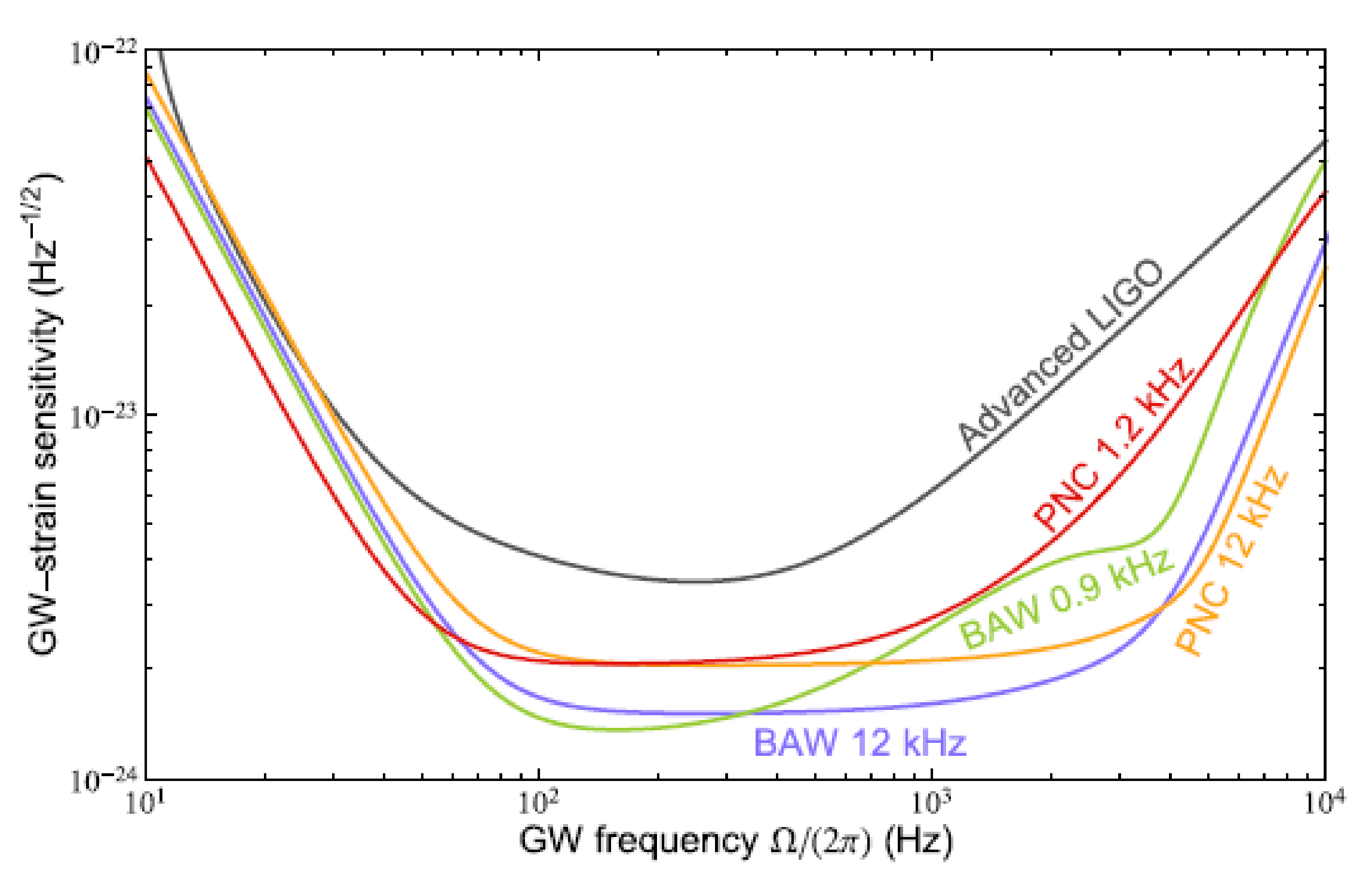
Implications for future detectors – longer interferometers



Even though long interferometer starts with lower bandwidth, end result of WLSR still better for NS detection.

Filter and interferometer optical loss in the 10 km case is 2.5x larger than the 4 km case, but still has better results

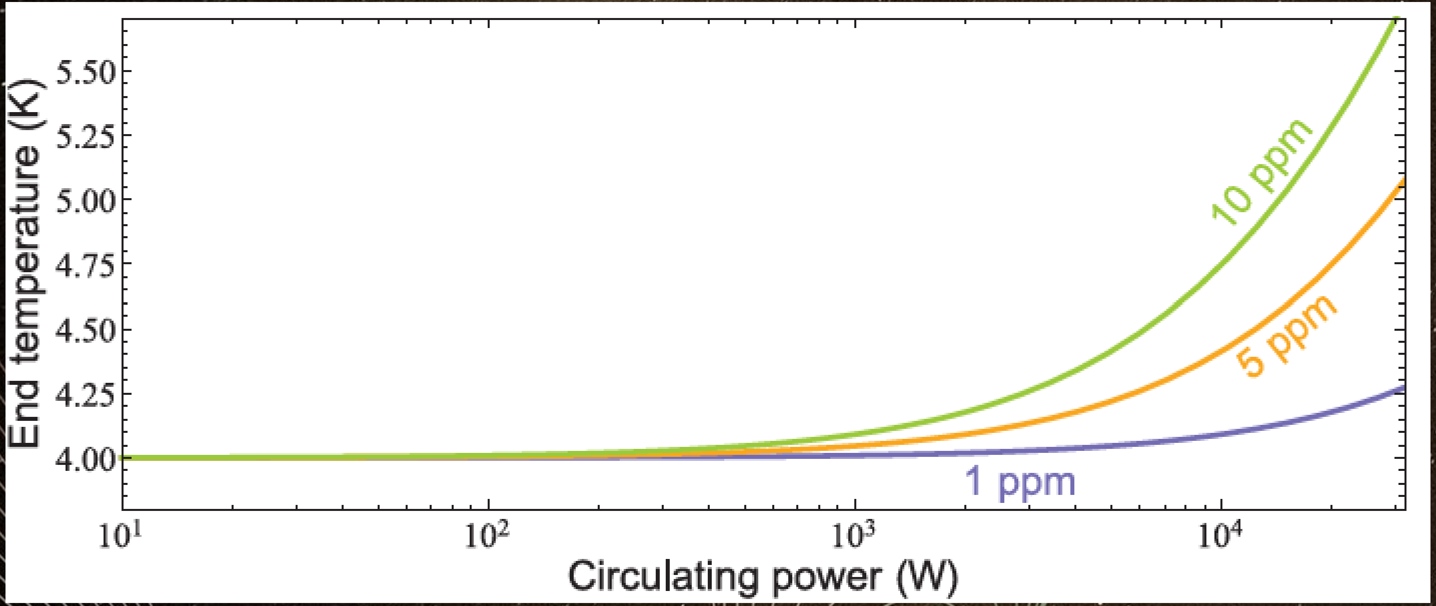
Mitigating BAW power requirements – alternate interferomter configuration



Full WLSR is better, obviously, especially in HF band.

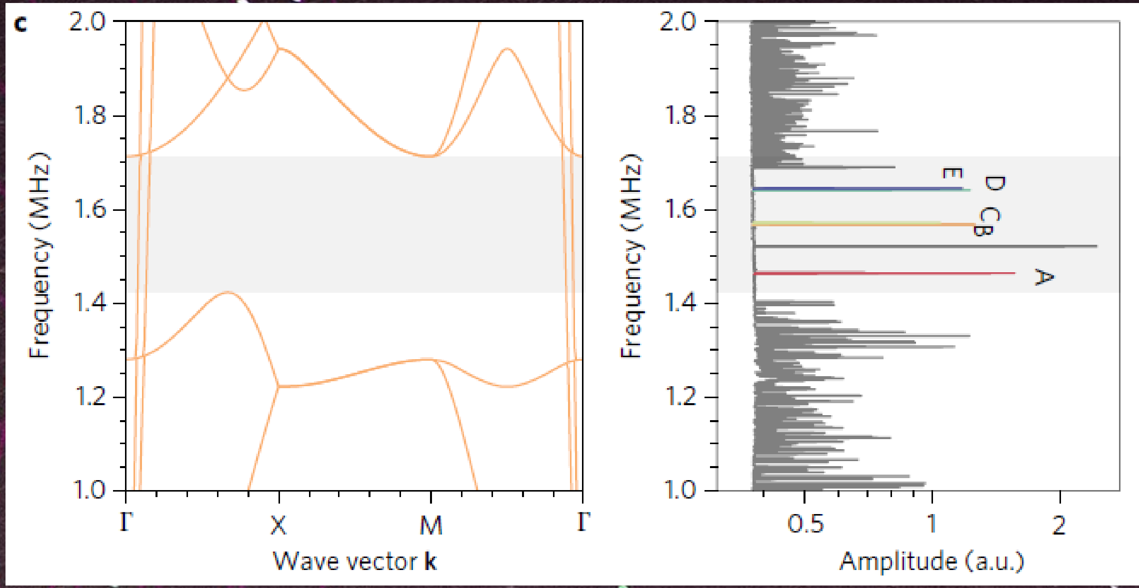
Strange shape of BAW curve is due to filter cavity fractional optical loss contribution (higher finesse required in BAW case).

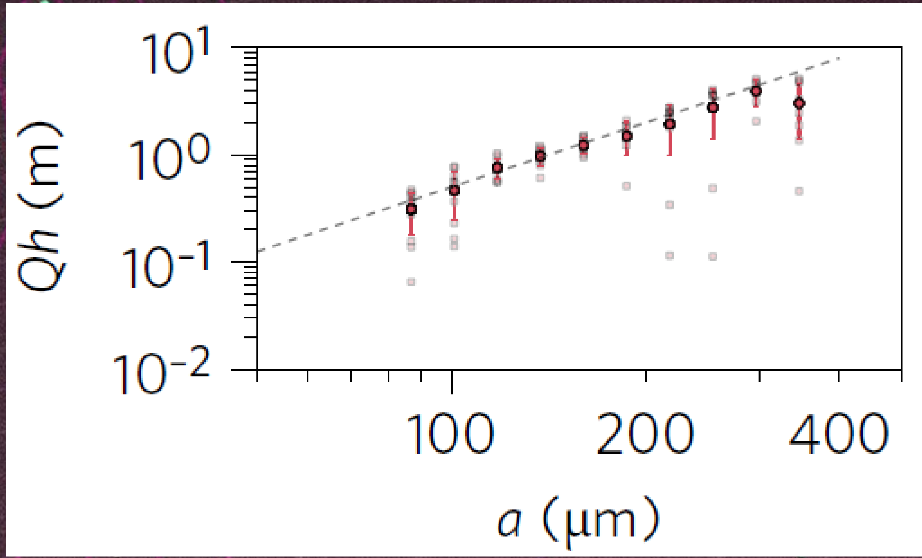
Absorption and temperature



BAW – limiting conduction dimension assumed 15mm long, 5mm wide, 1mm thick. 10 kW circulating, absorb 1 ppm at 4 K gives equilibrium temp 4.05 K.

Phononic crystal





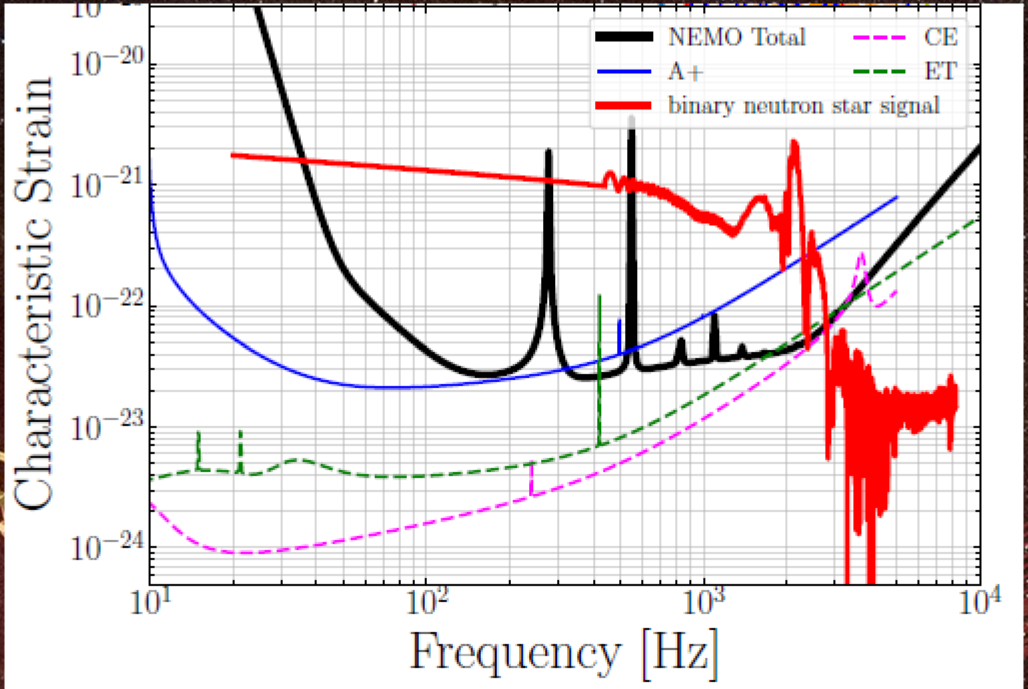
Y. Tsaturyan *et al*, *"Ultracoherent nanomechanical resonators via soft clamping and dissipation dilution"*, **Nature Nanotechnology** (2017)

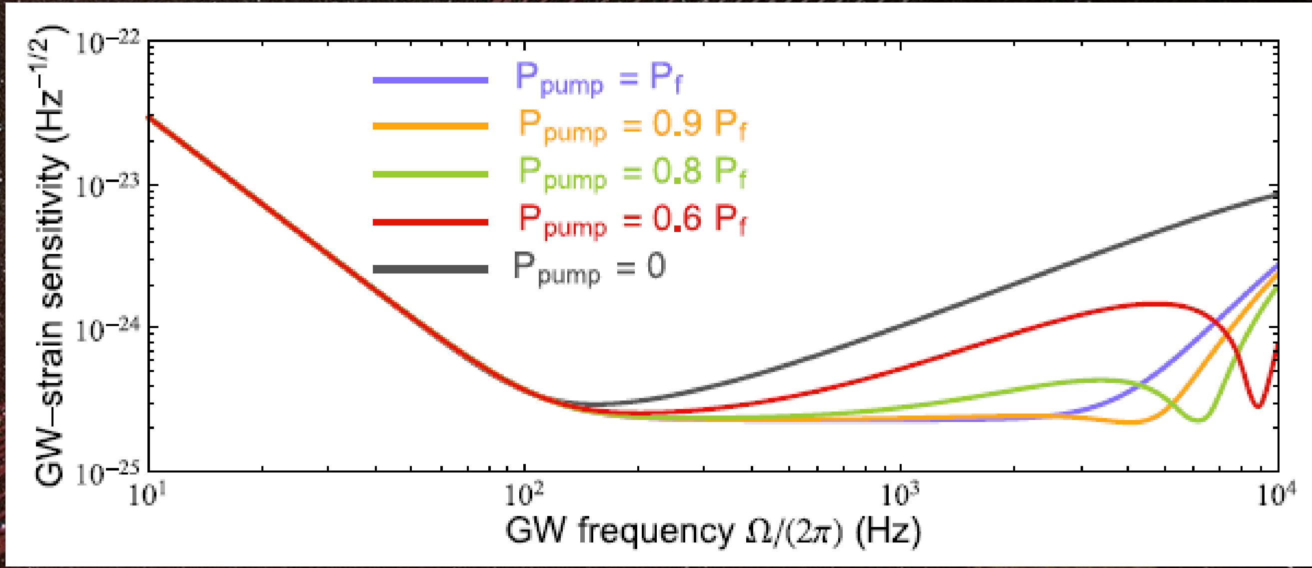
Can tweak these things somewhat to shift the acoustic bandgap

Q-factors of up to 10^9 have been demonstrated at 10 K.

Larger unit cell, lower thickness implies higher Q-factor - measured for unit cell size 87 to 346 µm

Implications for future detectors- Shifting the quantum noise curve

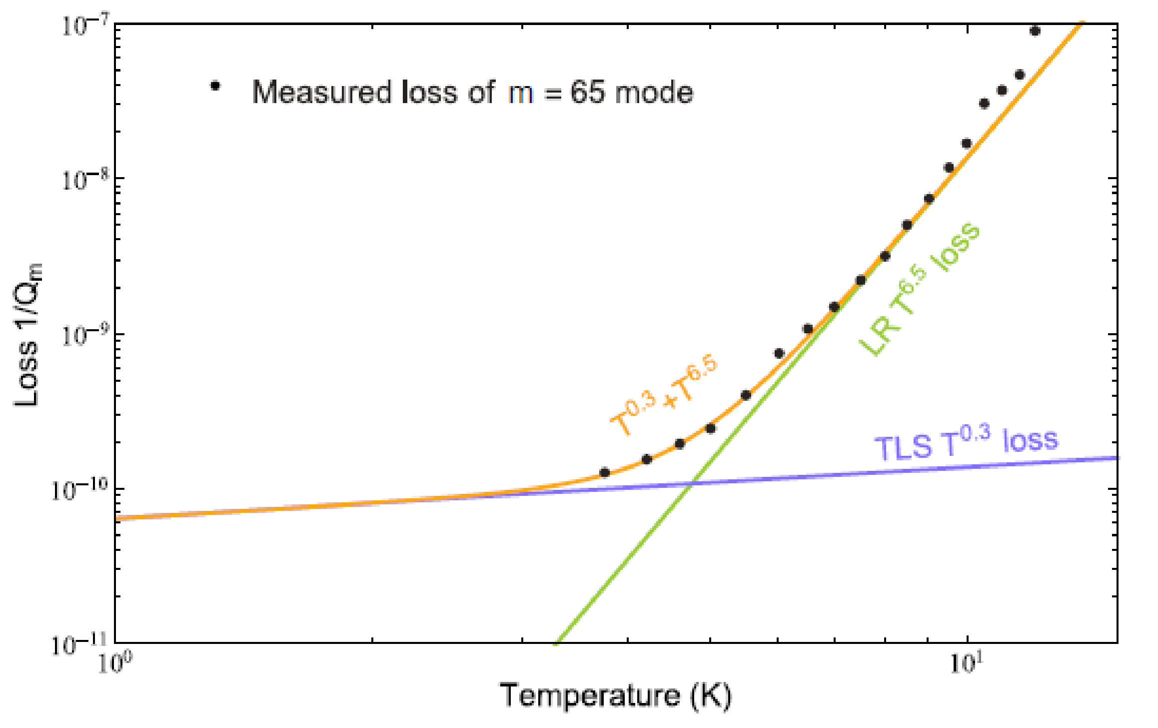




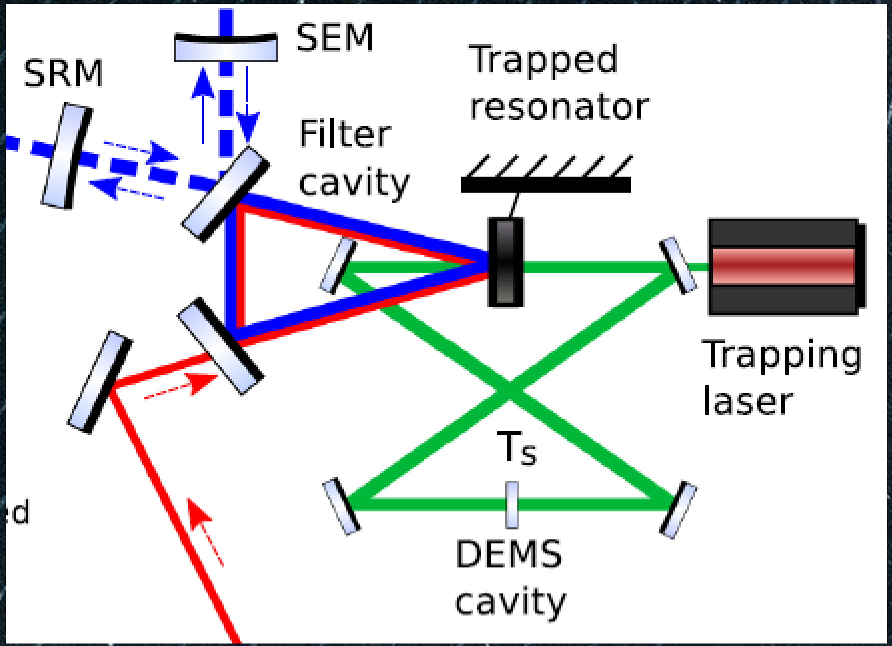
Bulk acoustic wave resonator Q vs T

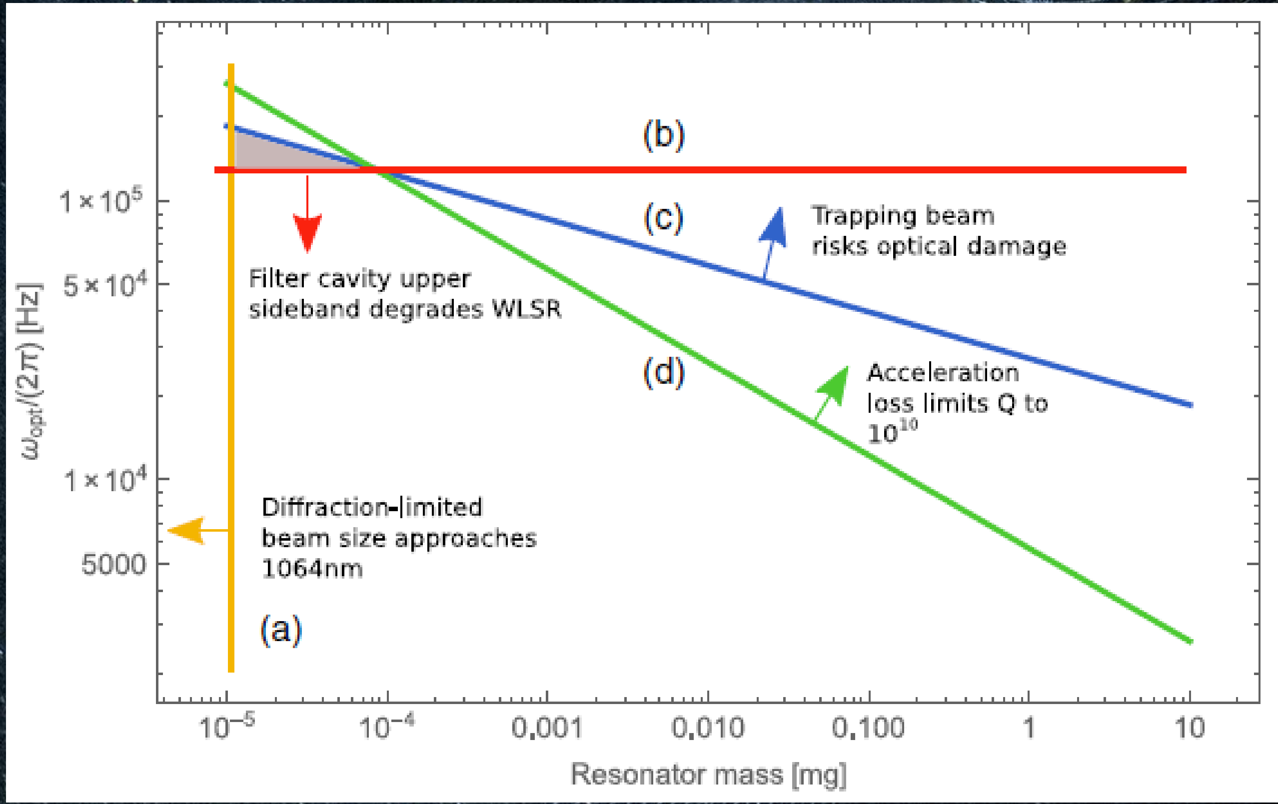
Capable of getting even lower loss at 1K temperature.

Promising thermal noise performance even vs PNC

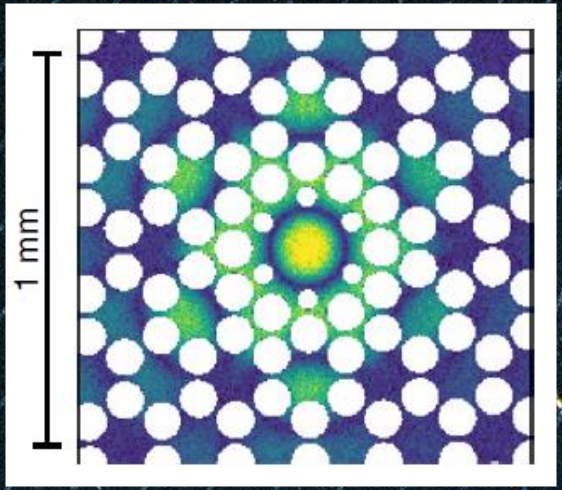


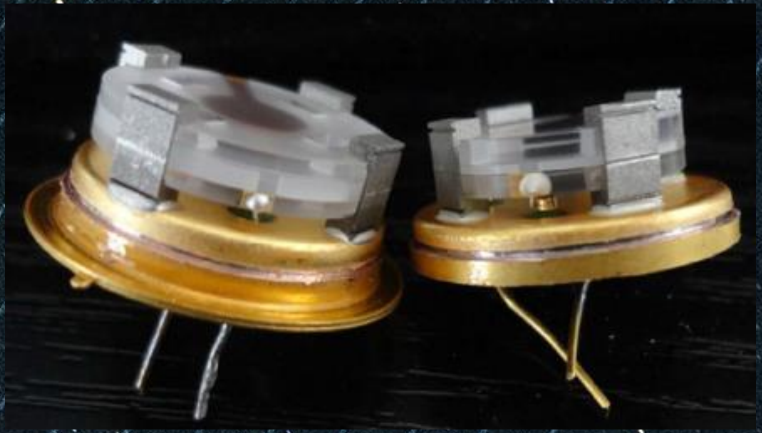
“Cat-flap” micro pendulum WLSR parameter space





Quantum noise and WLSR parameter space

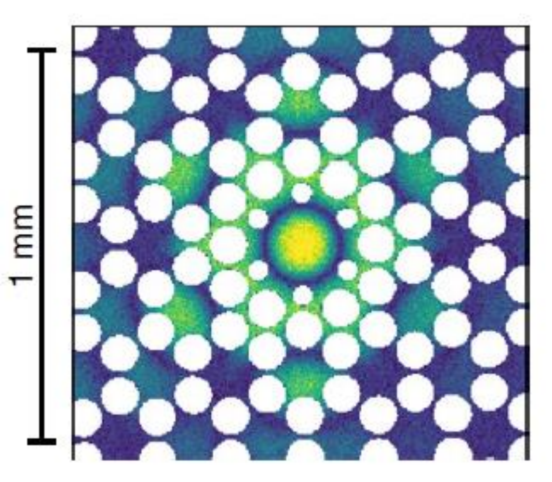




Our candidate resonators have recently been demonstrated in high Q optomechanics.

Can reach thermal noise and mechanical frequency requirements with resonators larger than optically diluted micro pendulums.

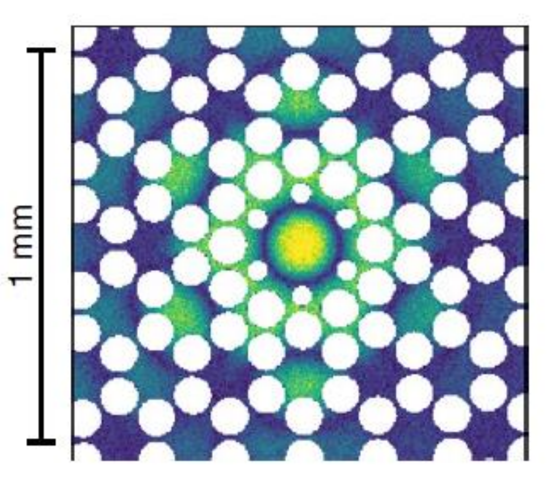
Quantum noise and WLSR parameter space

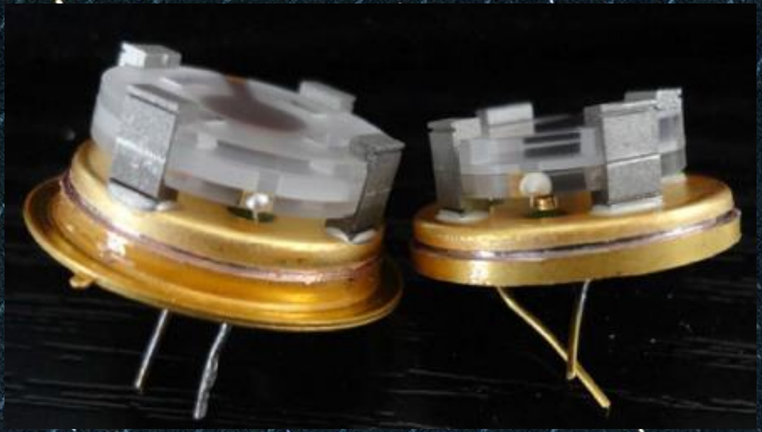


Main tweaks:

Filter cavity bandwidth:
Increases interferometer bandwidth enhancement and reduces fractional contribution of optical loss, but also increases the filter cavity pumping power

Quantum noise and WLSR parameter space

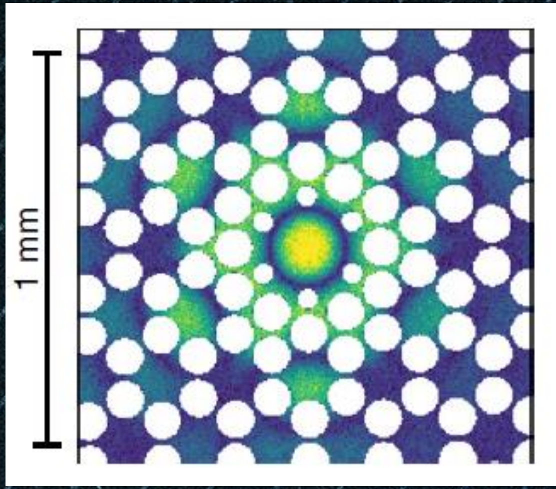


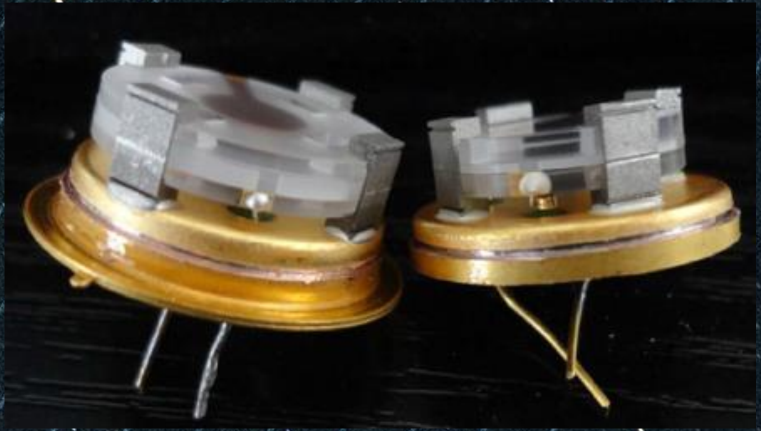


Main tweaks:

SRM transmission:
Adjusted depending on the level of quantum noise relative to other noises in the overall budget.

Quantum noise and WLSR parameter space



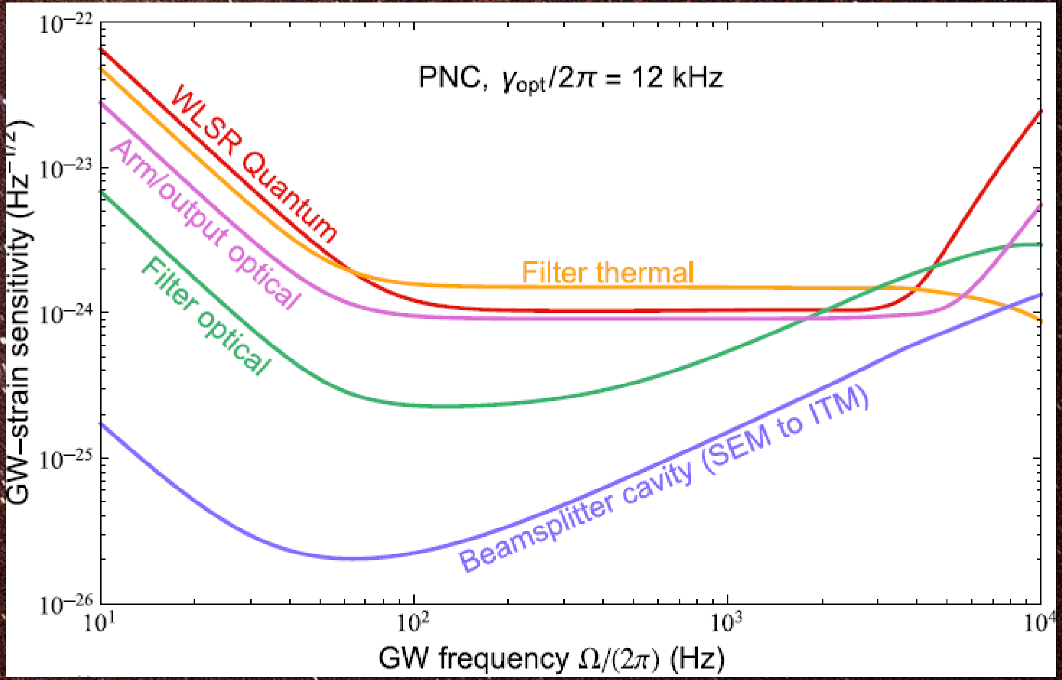


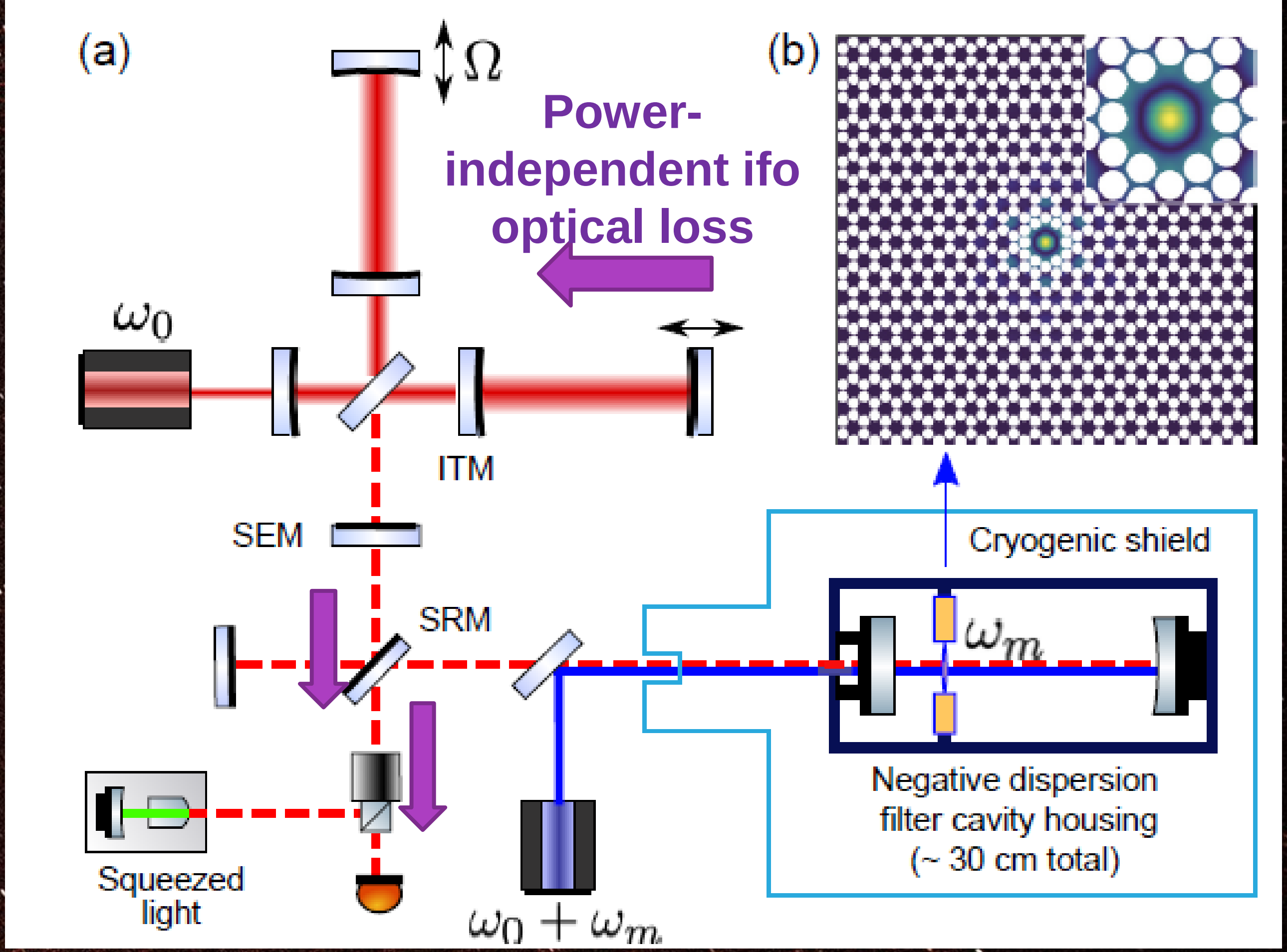
Main tweaks:

Filter cavity pumping power:
Must maintain a certain pumping power to keep the negative dispersion effect. However, it also may cause absorption heating.

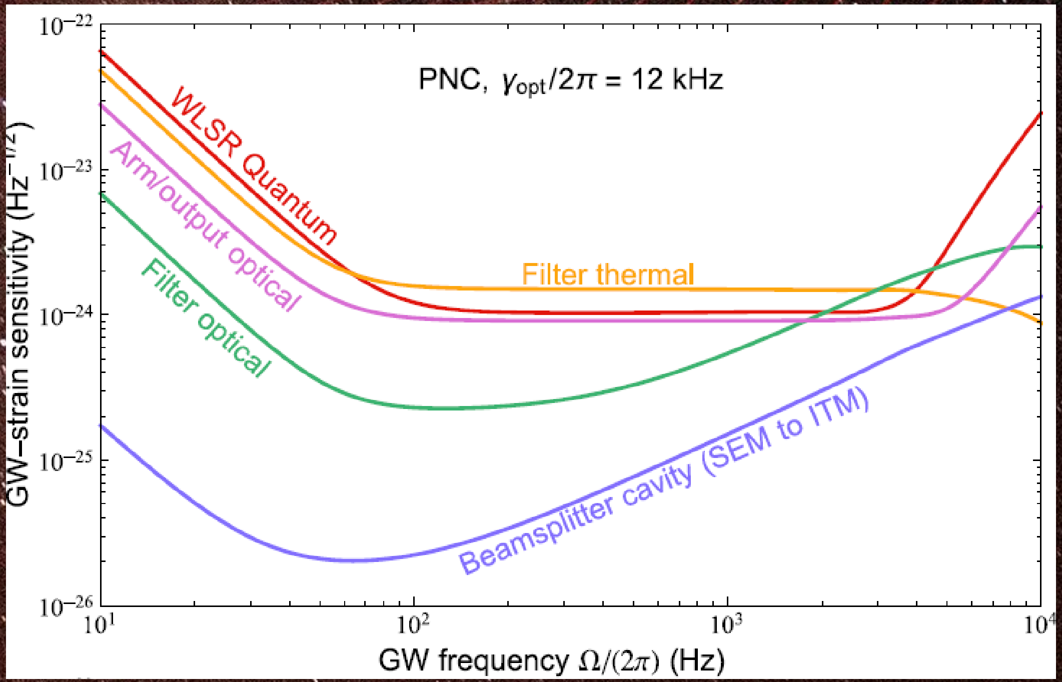
Proportional to: Filter bandwidth, mechanical and optical frequency, resonator effective mass, c/L_{arm}
Inversely proportional to optomechanical coupling rate

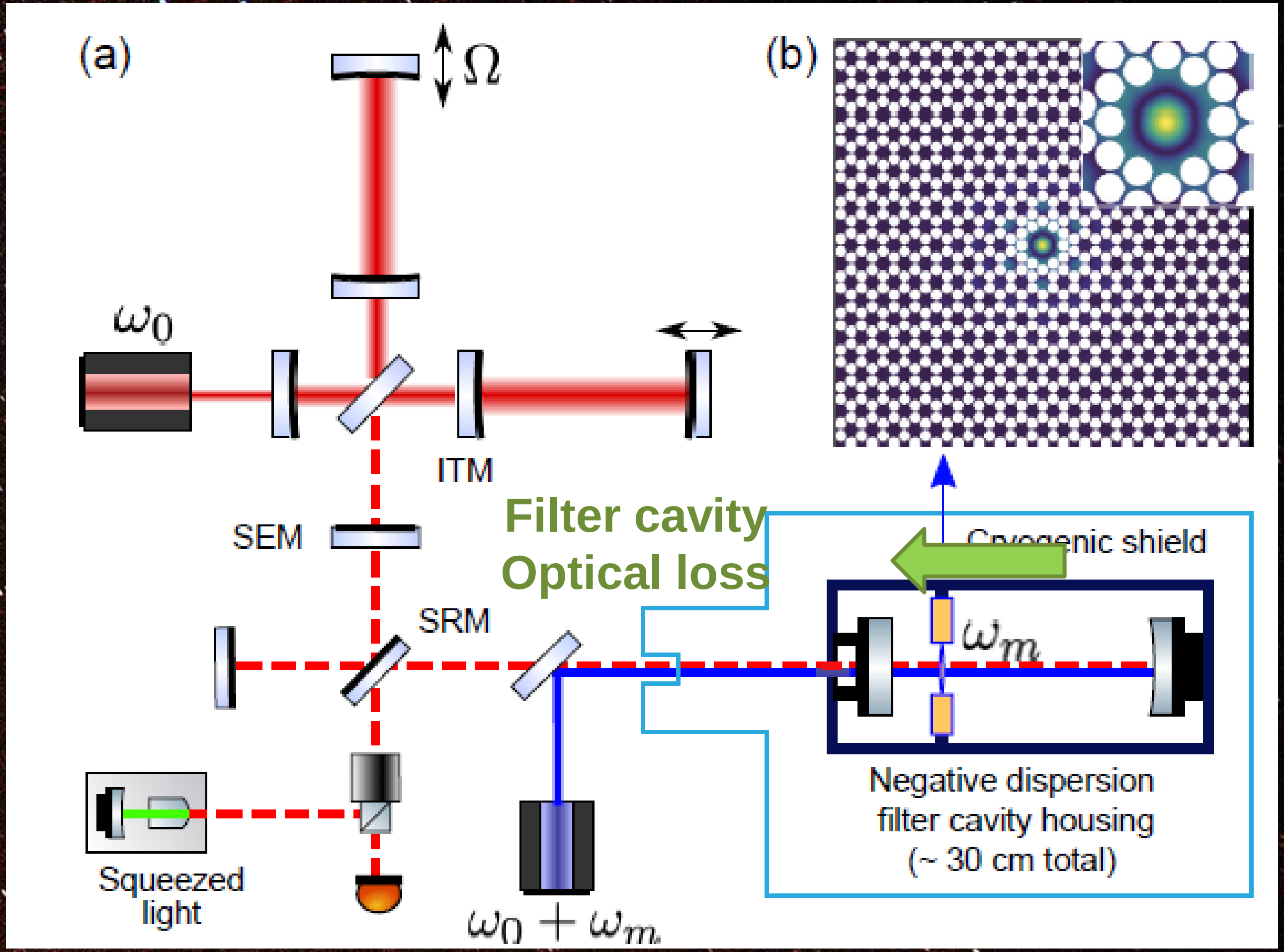
Example noise inputs



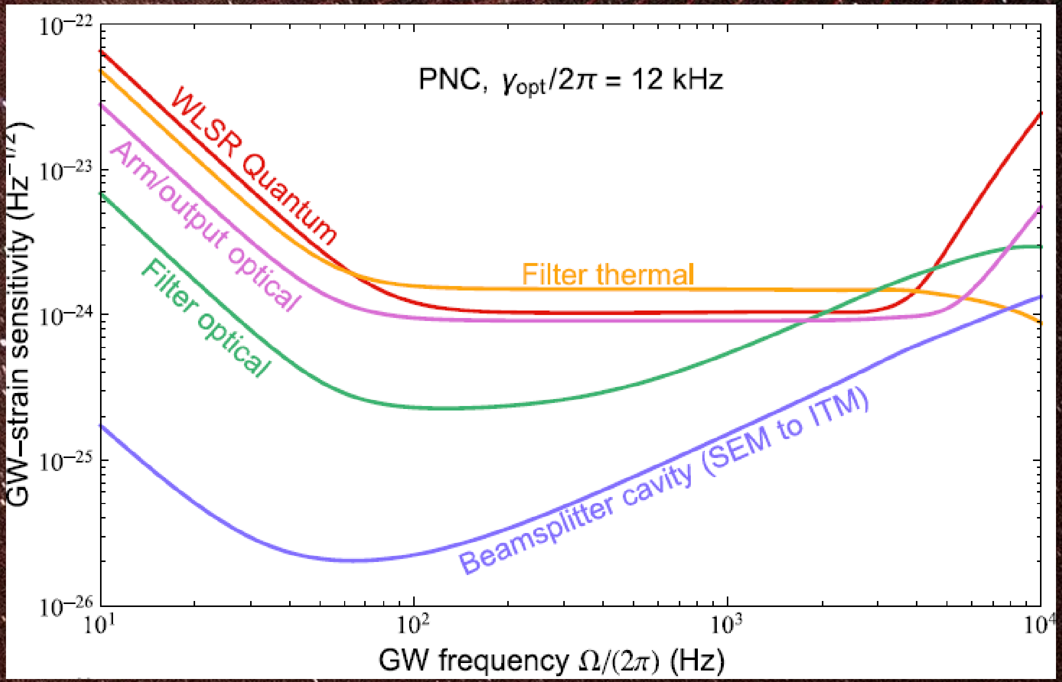


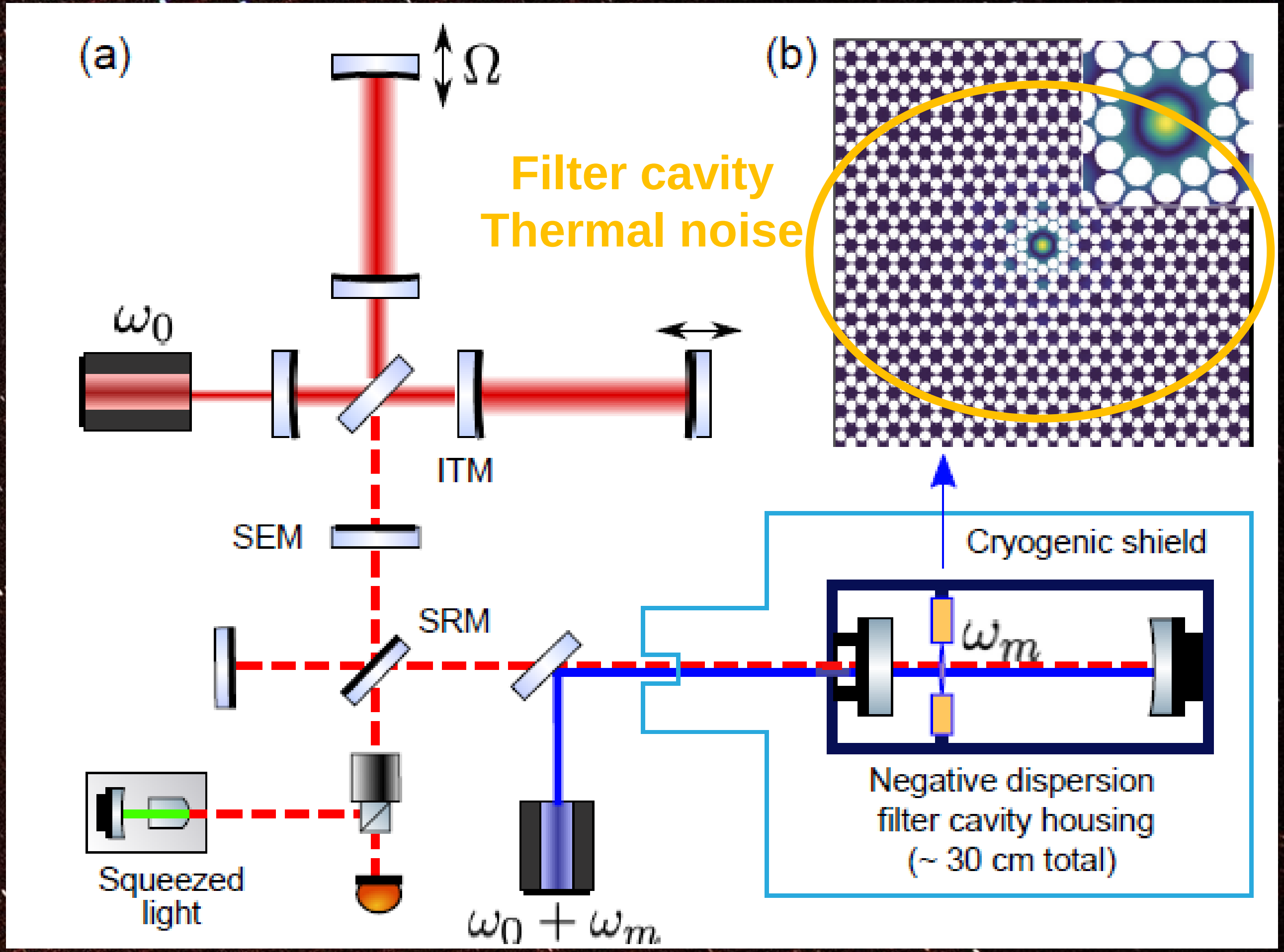
Example noise inputs



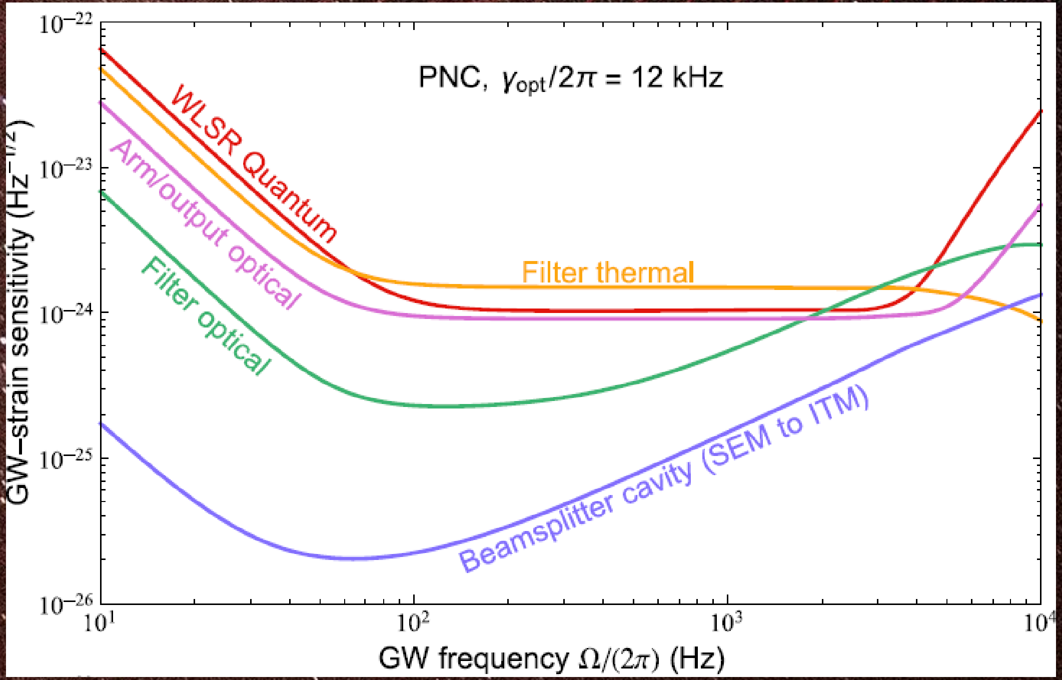


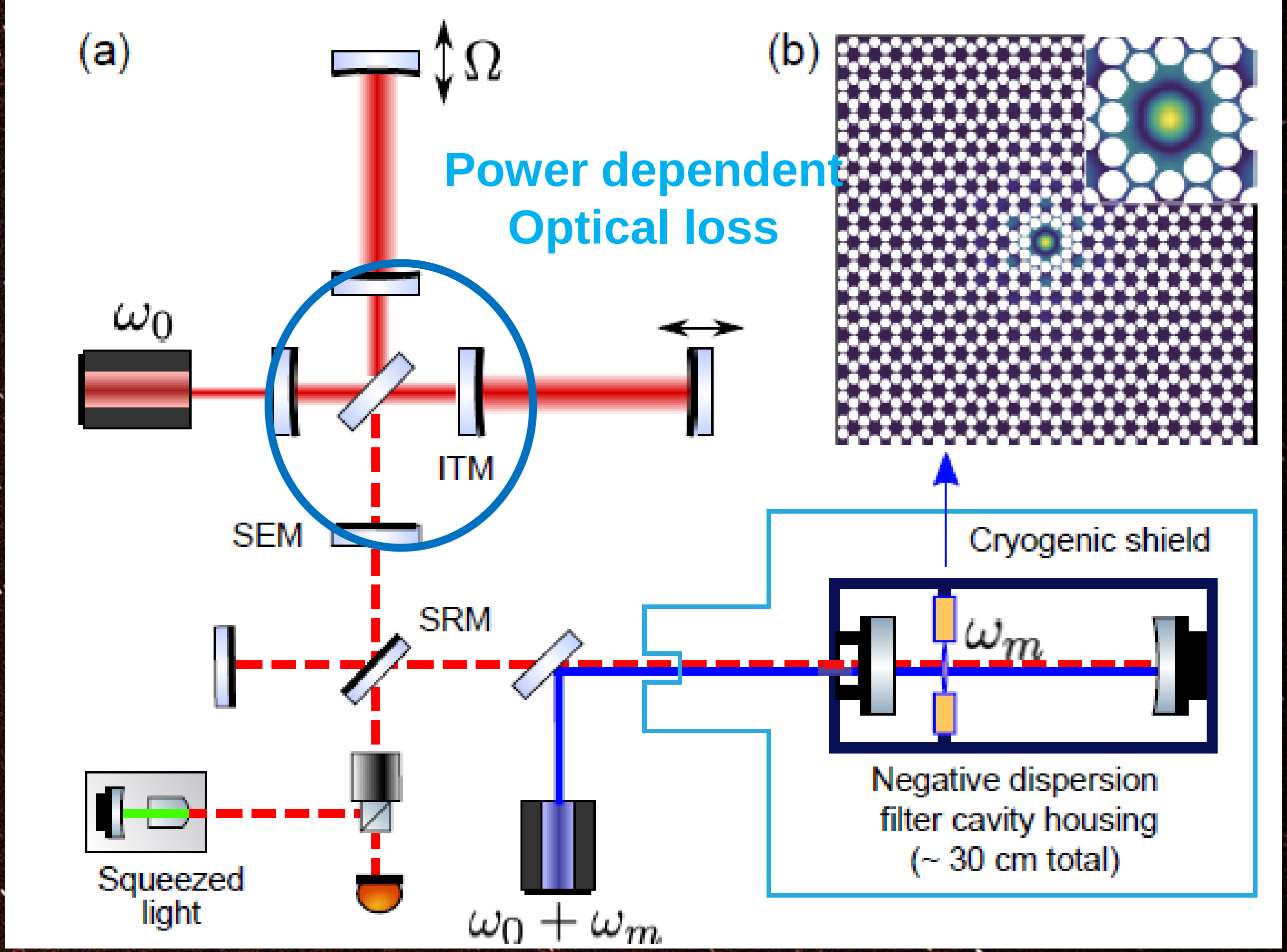
Example noise inputs





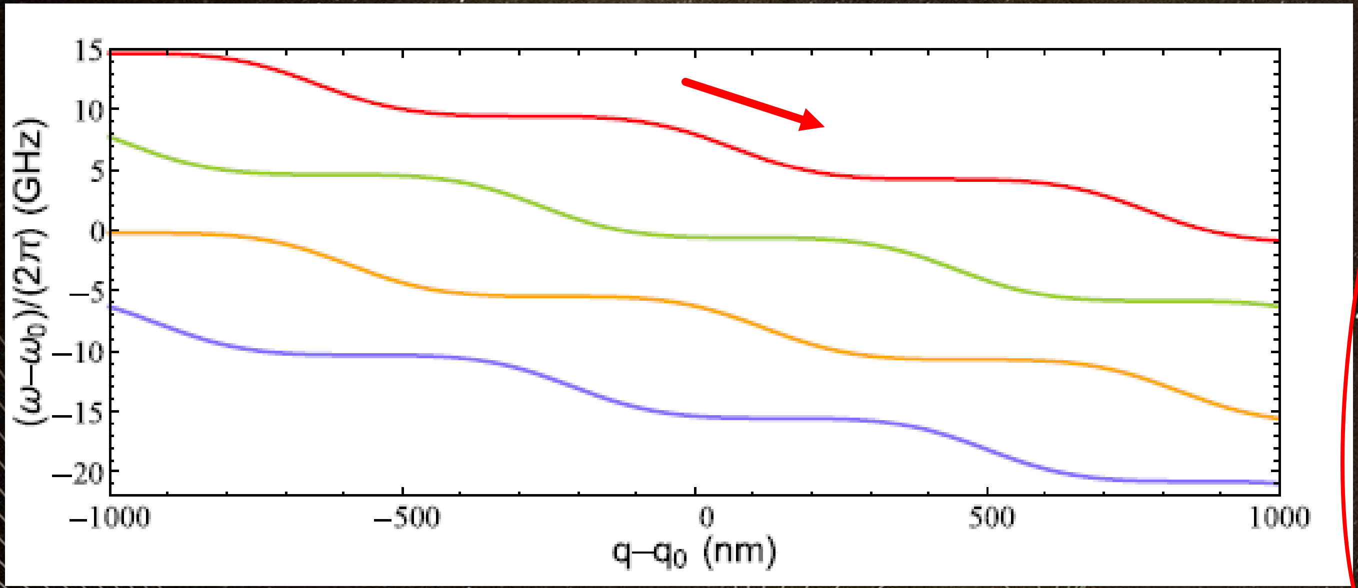
Example noise inputs

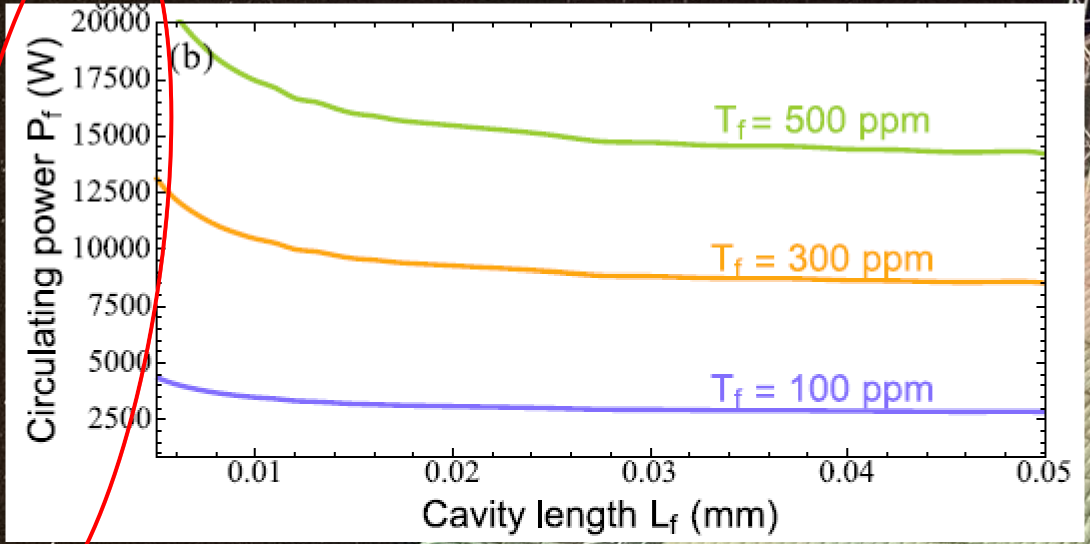




Optomechanical coupling

Small dω/dq * large effective mass





Absorption and temperature

$$P_{cond} = P_{abs} = -\sigma\, \kappa(T)\, \frac{dT}{dz}$$

Absorption creates heating

Use 1D approximation of conduction heating to estimate equilibrium temperature

Absorption and temperature

$$P_{abs} = \kappa_0 \frac{2\sigma}{(n+1)l_{lim}}\left(T_{eq}^{n+1} - T_{bth}^{n+1}\right)$$

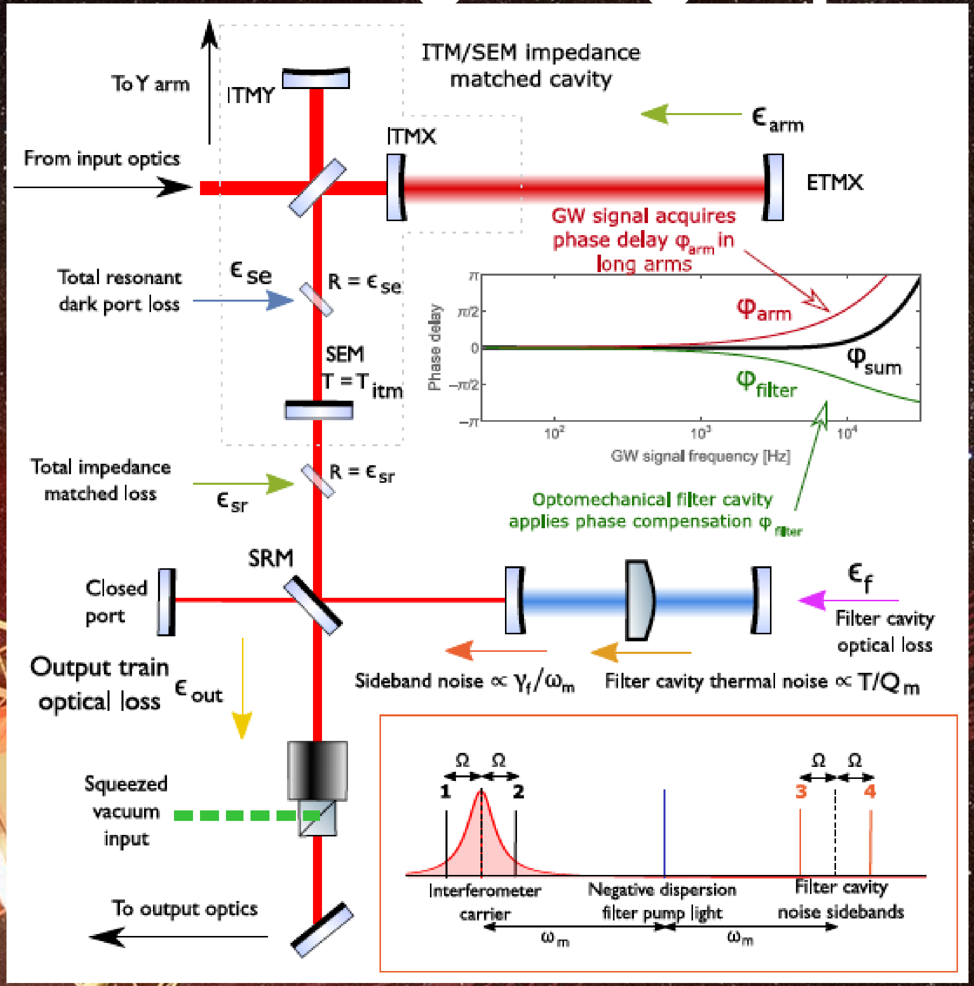
Integrating across conduction direction and assuming that at cryogenic temperature, thermal conductivity is roughly $\kappa = \kappa_0 T^n$ (valid below 10K)

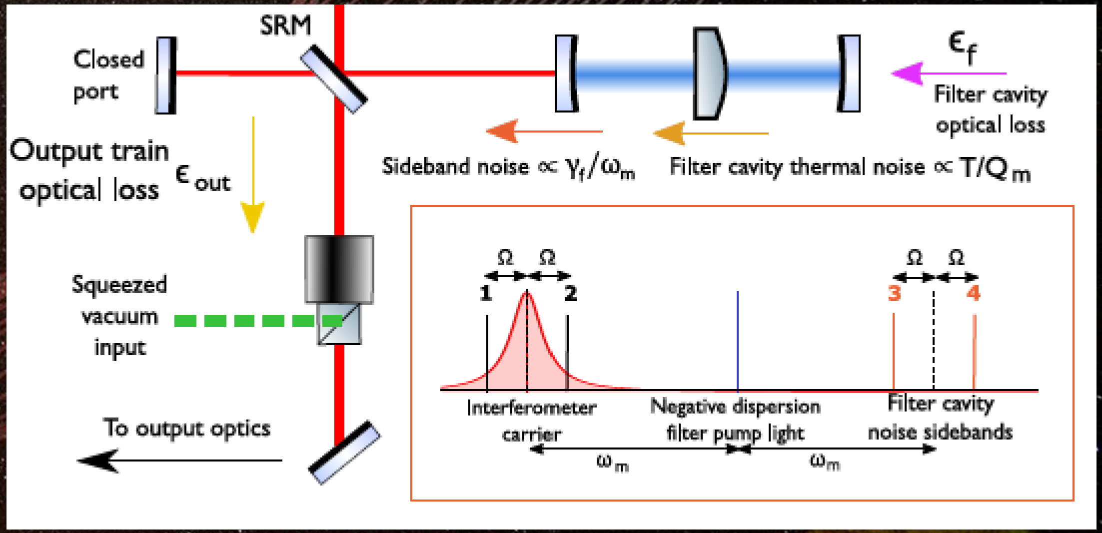
Absorption and temperature

$$T_{eq} = \left(\frac{P_{abs}(n+1)l_{lim}}{2\,\kappa_0 \sigma} + T_{bth}^{n+1} \right)^{1/(n+1)}$$

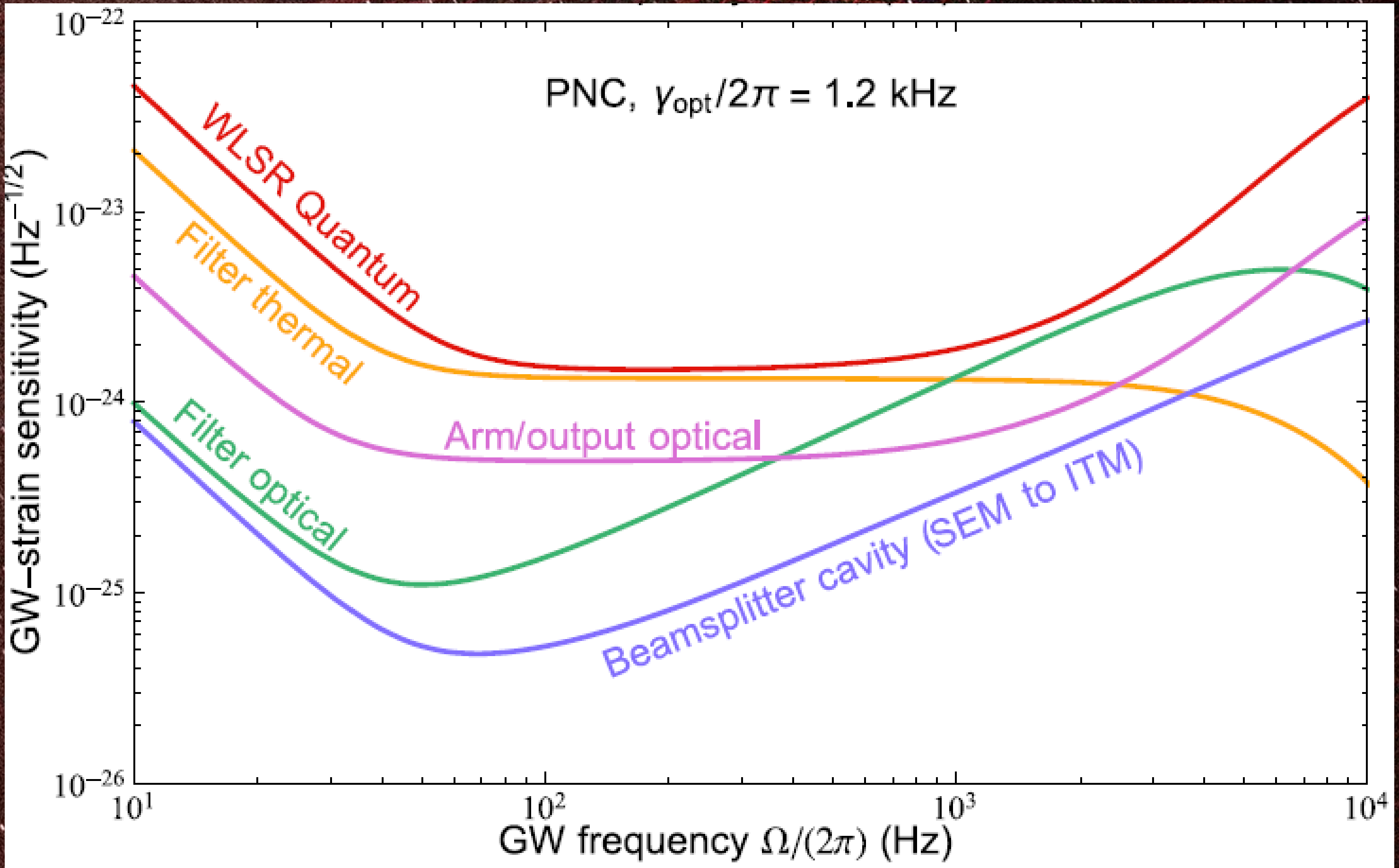
Integrating across conduction direction and assuming that at cryogenic temperature, thermal conductivity is roughly $\kappa = \kappa_0 T^n$ (valid below 10K)

Noise budgeting – primary noise sources



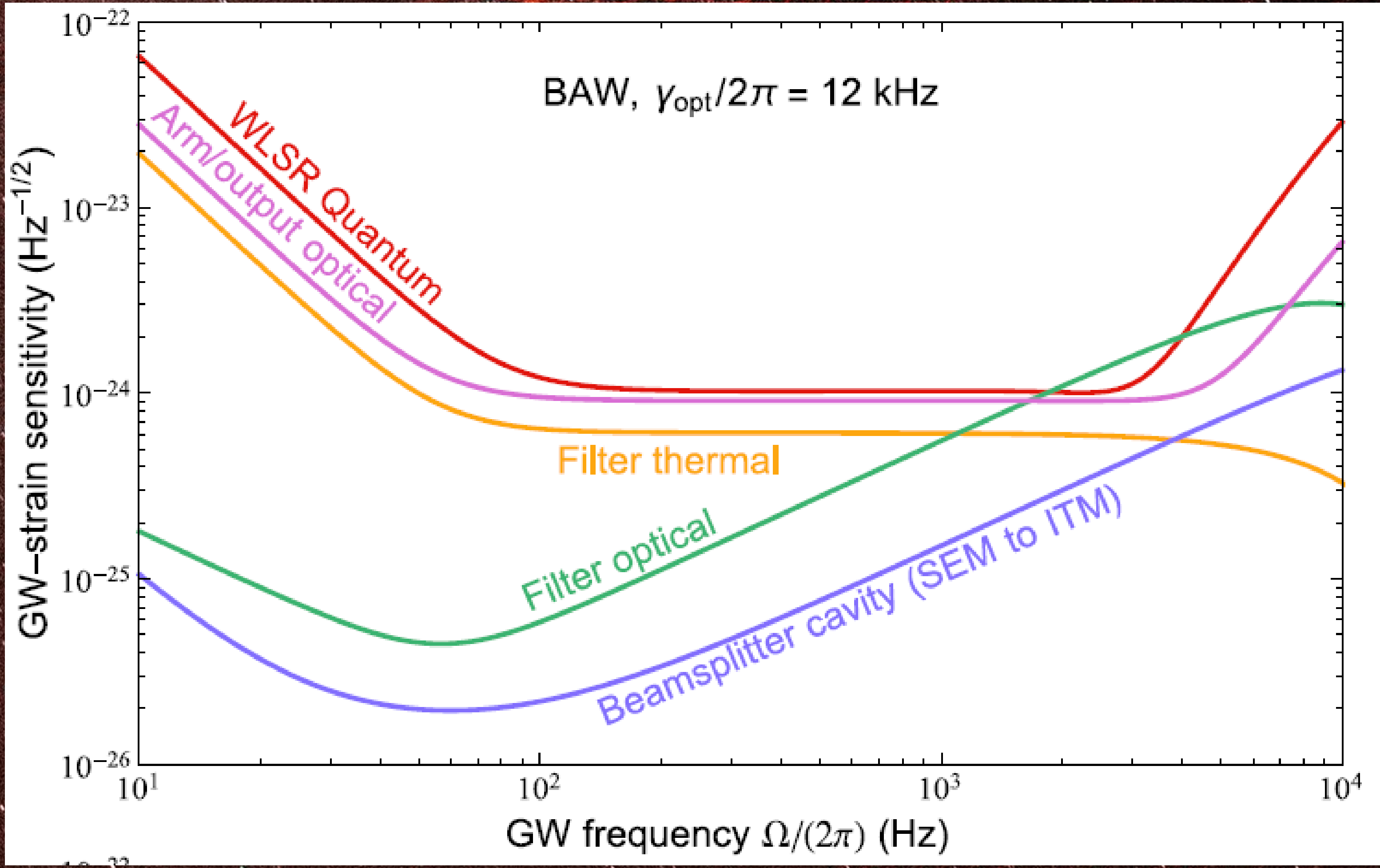


PNC 1.2 kHz



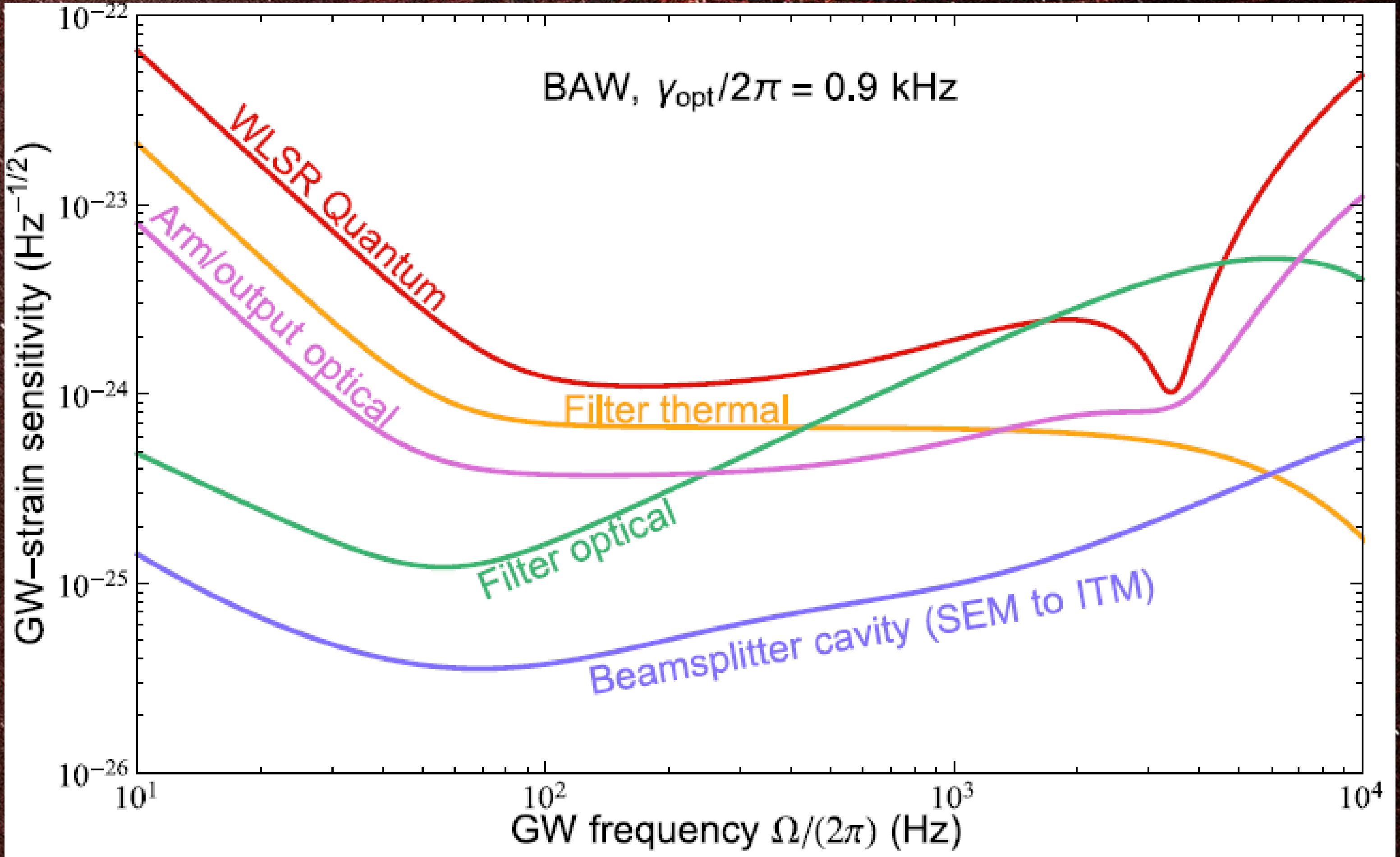
PNC, $\gamma_{opt}/2\pi$ = 1.2 kHz
WLSR Quantum
Filter thermal
Arm/output optical
Filter optical
Beamsplitter cavity (SEM to ITM)
GW–strain sensitivity ($Hz^{-1/2}$)
GW frequency $\Omega/(2\pi)$ (Hz)
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{1}
10^{2}
10^{3}
10^{4}

BAW 12 kHz



BAW, $\gamma_{opt}/2\pi$ = 12 kHz
WLSR Quantum
Arm/output optical
Filter thermal
Filter optical
Beamsplitter cavity (SEM to ITM)
GW–strain sensitivity (Hz$^{-1/2}$)
GW frequency $\Omega/(2\pi)$ (Hz)
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^1
10^2
10^3
10^4

BAW 0.9 kHz



BAW, $\gamma_{opt}/2\pi$ = 0.9 kHz
WLSR Quantum
Arm/output optical
Filter thermal
Filter optical
Beamsplitter cavity (SEM to ITM)
GW–strain sensitivity (Hz$^{-1/2}$)
GW frequency $\Omega/(2\pi)$ (Hz)
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{1}
10^{2}
10^{3}
10^{4}

Quantum control

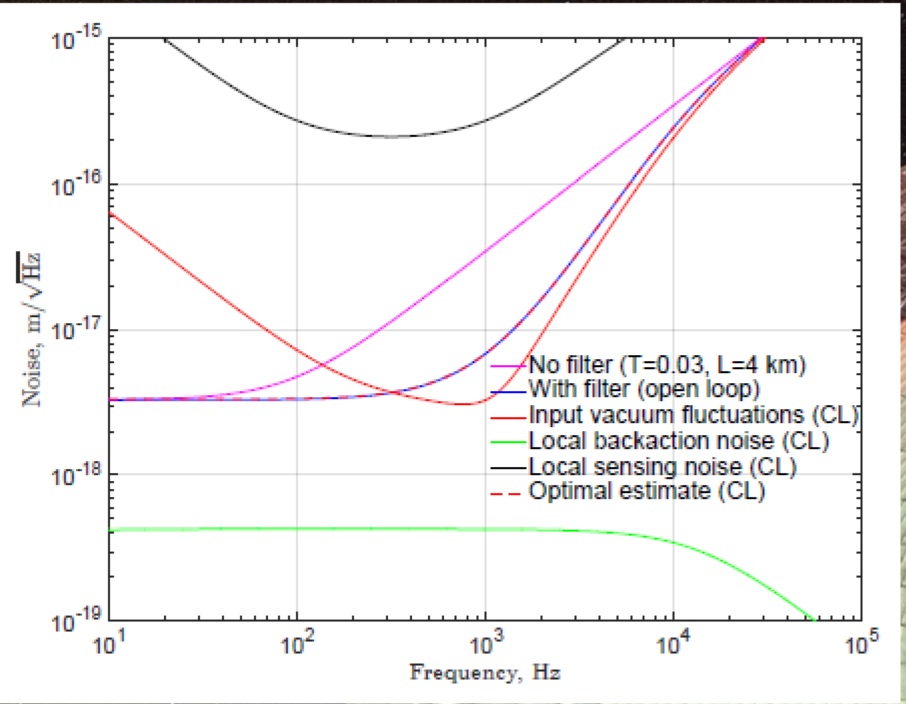
Blue detuned pumping scheme with 3 mode interaction creates instability.

Some indications from U. Birmingham that local control with postprocessed matched filtering can mitigate this issue (mentioned in J. Bentley PRD **99** 102001)

Caltech have found a system which eliminates the stability issue at a fundamental level

Further information: Xiang Li *et al*., “Broadband sensitivity improvement by via coherent quantum feedback with PT symmetry” LIGO-P2000452

Denis Martynov, Joe Bentley, *unpublished*



Other thoughts and issues

Heating – analysis probably needs to go deeper with regards to 3d heat distribution and heat gradient effects

Mode matching specific contribution? A+ targets 1% loss overall. OMC beam size 500 μm.

Scattered light from the filter cavity enclosure – prelim 1D calc suggests that we want no more than 0.5 ppm scattered light from the enclosure rejoining the beam.