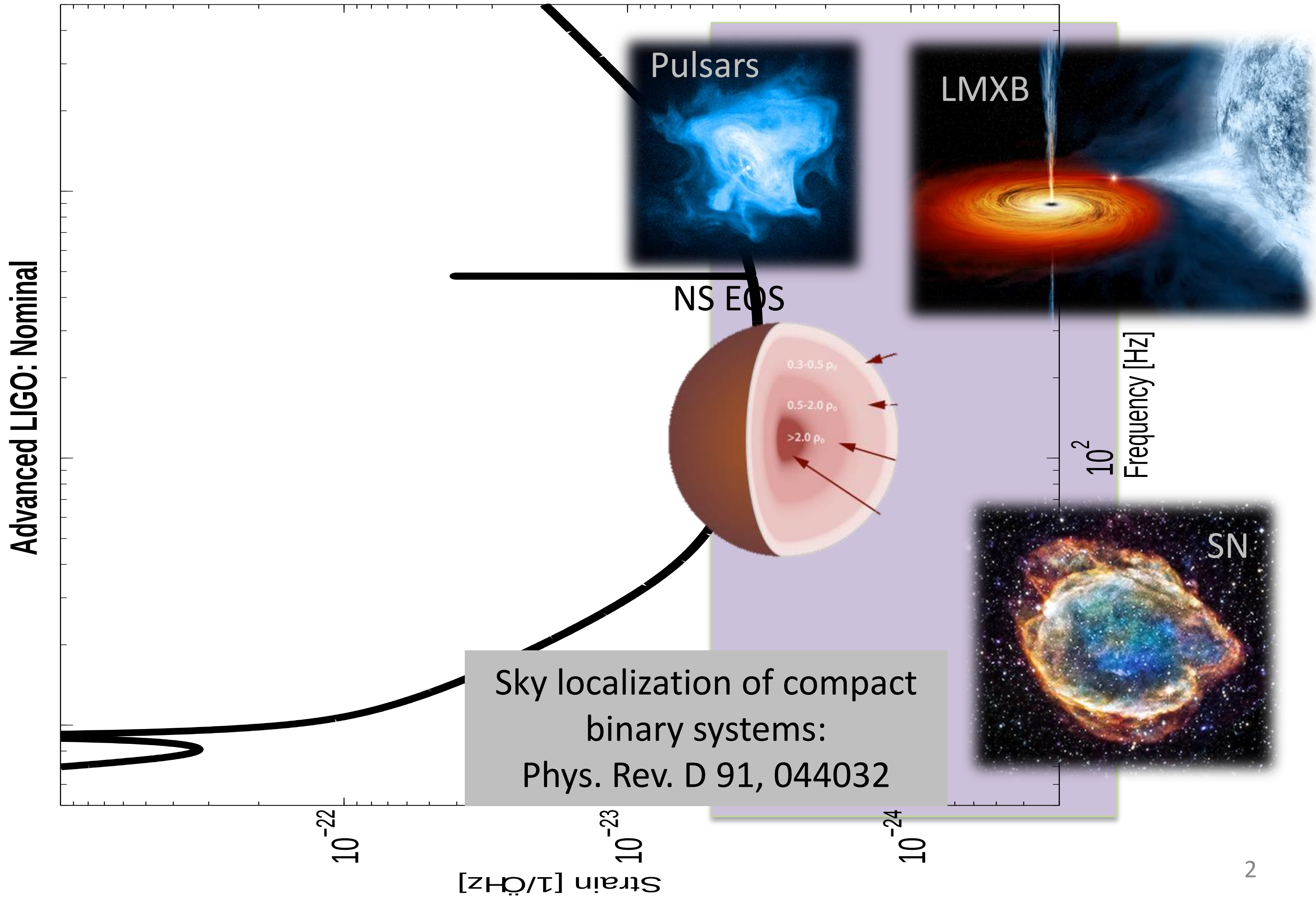
Focus on High Frequency Sources

Lisa Barsotti (LIGO-MIT)

"What comes next for LIGO?"

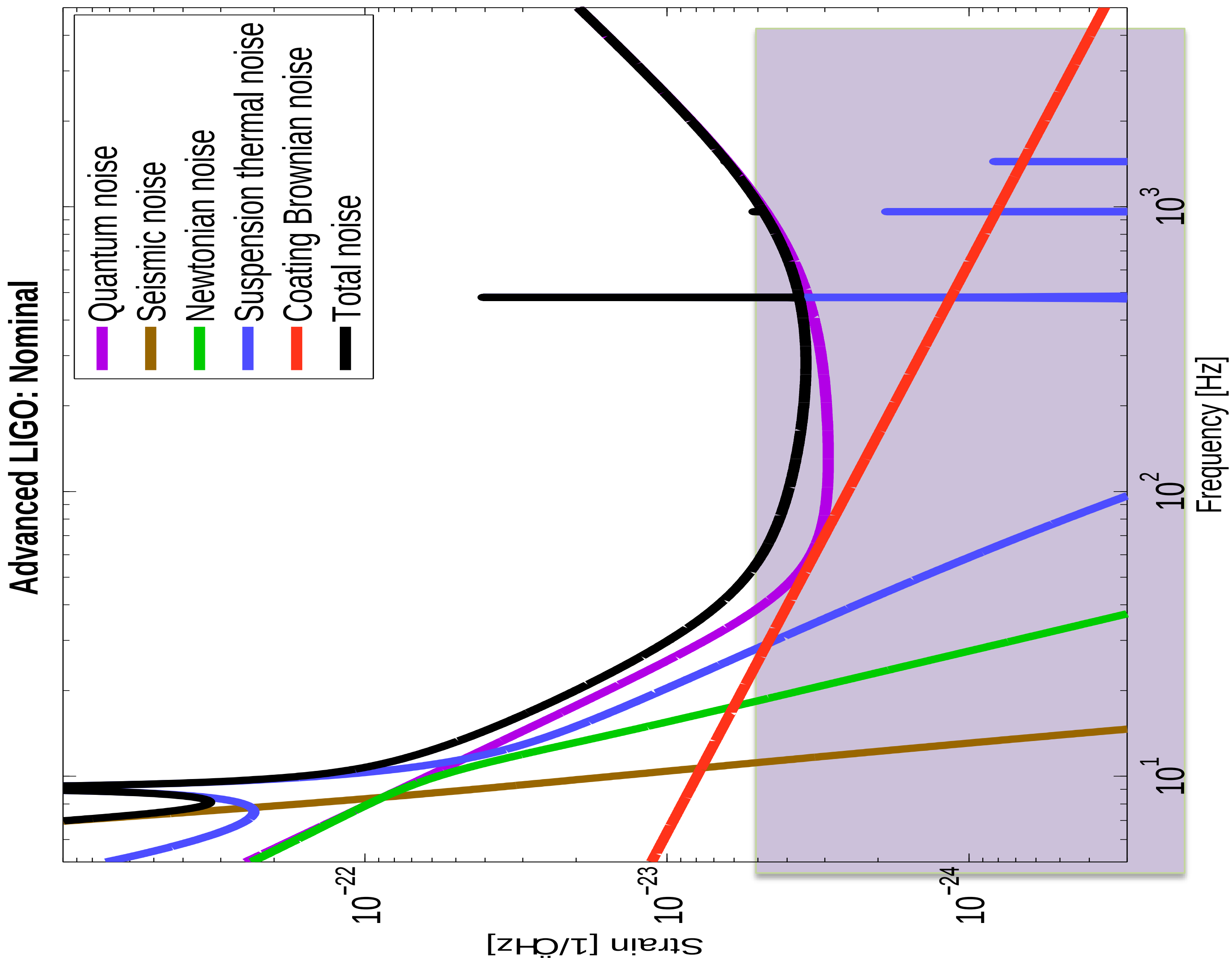
Silver Spring, Maryland --- May 7, 2015

Focus on High Frequency Sources

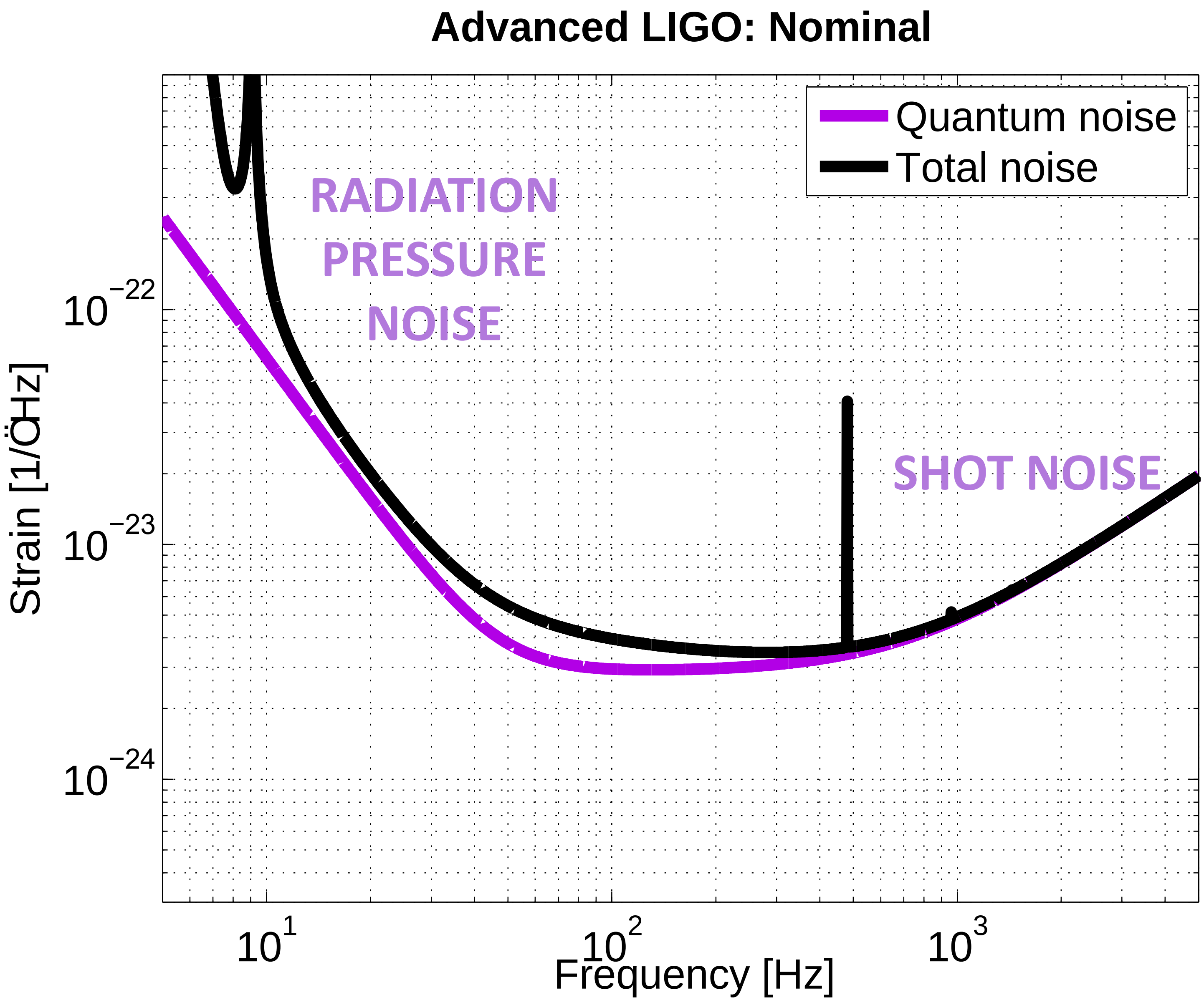


Sky localization of compact binary systems:
Phys. Rev. D 91, 044032

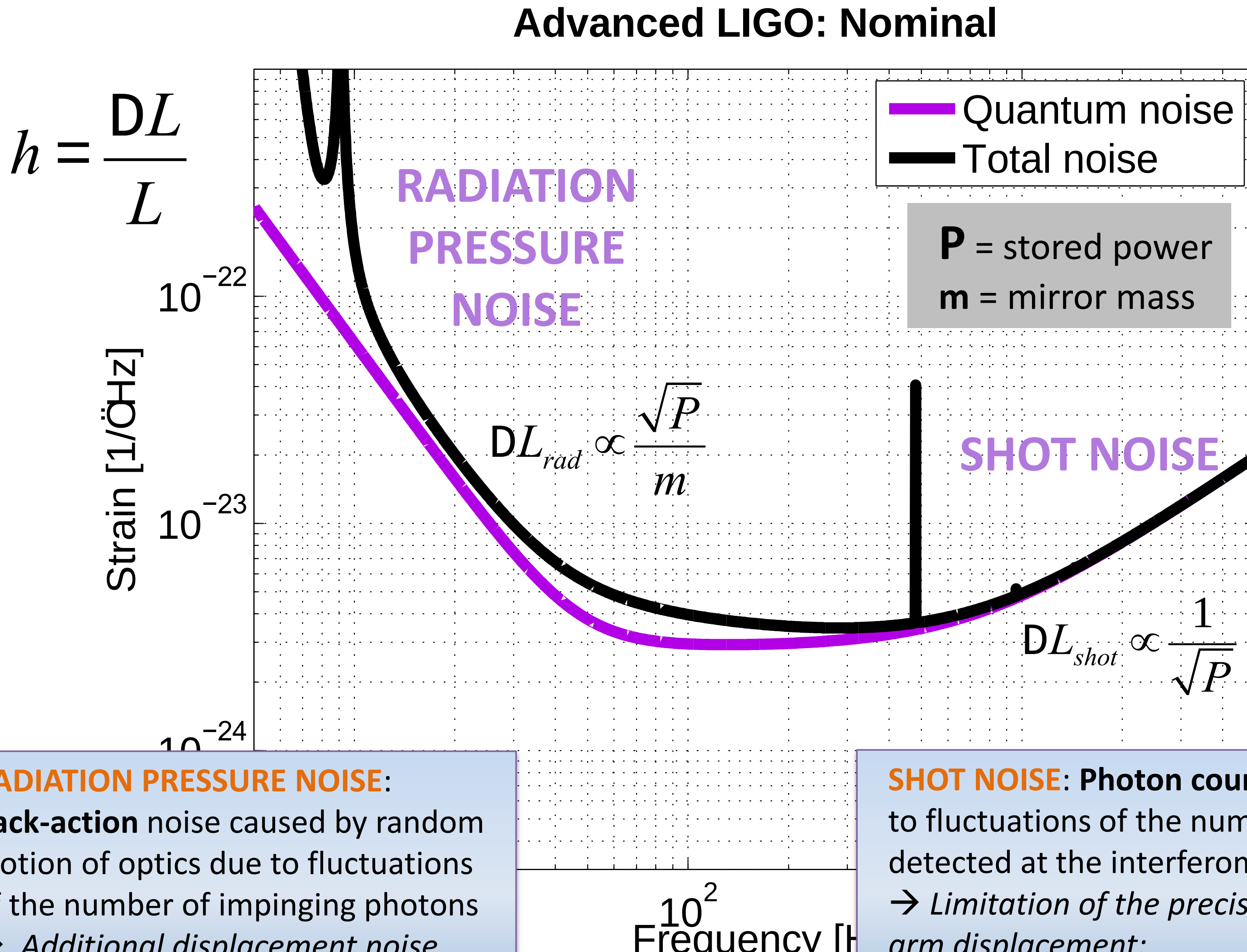
Limiting noise: quantum shot noise



Quantum shot noise limits the high frequency sensitivity



Quantum shot noise limits the high frequency sensitivity



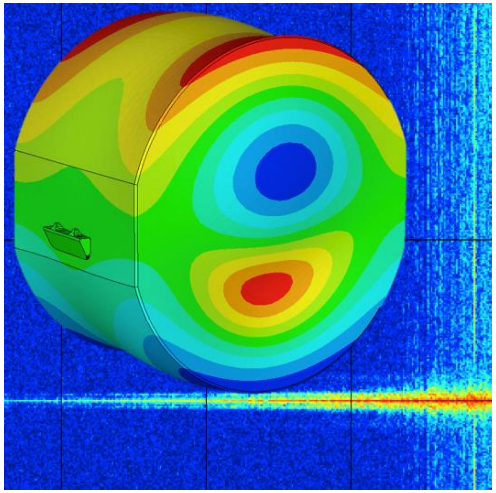
RADIATION PRESSURE NOISE: **Back-action** noise caused by random motion of optics due to fluctuations of the number of impinging photons
→ *Additional displacement noise*

SHOT NOISE: **Photon counting noise** due to fluctuations of the number of photon detected at the interferometer output
→ *Limitation of the precision to measure arm displacement:*

Options for reducing shot noise beyond Advanced LIGO design

- ✧More laser power in the arms, in principle, BUT:
  - ✧Already ~1 MW in the arm cavities at full power
  - ✧Difficult to go beyond that, due to:
    - thermal effects
    - alignment stability
    - parametric instability

➔ Very unlikely to be able to increase the power beyond aLIGO design in the near term



Phys. Rev. Lett. 114, 161102

Options for reducing shot noise beyond Advanced LIGO design

✧Injection of squeezed light

✧ Re-shape the interferometer optical response

➔ signal recycling detuning

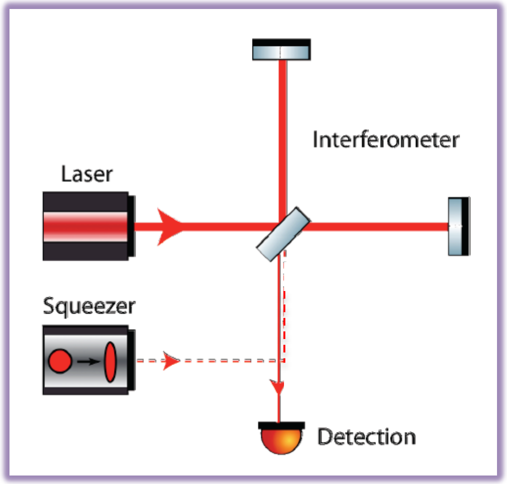
➔ change interferometer bandwidth

Injection of Squeezed Light

Two "flavors" of squeezing:

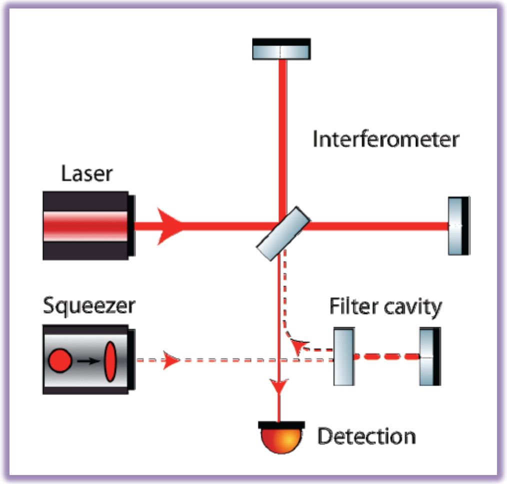
✧ **Frequency independent**

- ✓ Reduce shot noise, but radiation pressure noise gets worse

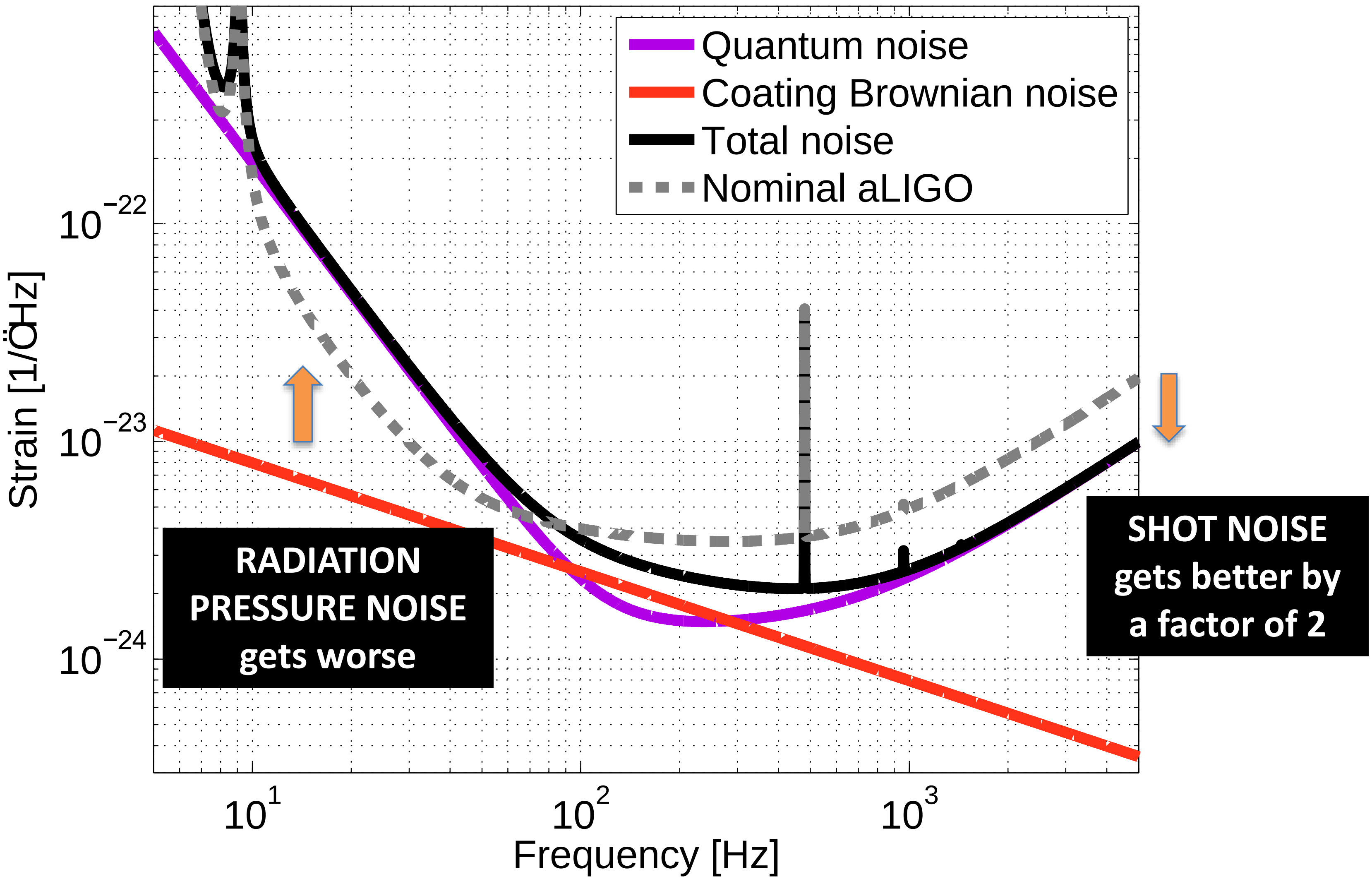


✧ **Frequency dependent**

- ✓ Uses a "filter cavity"
- ✓ Preserve low frequency performance

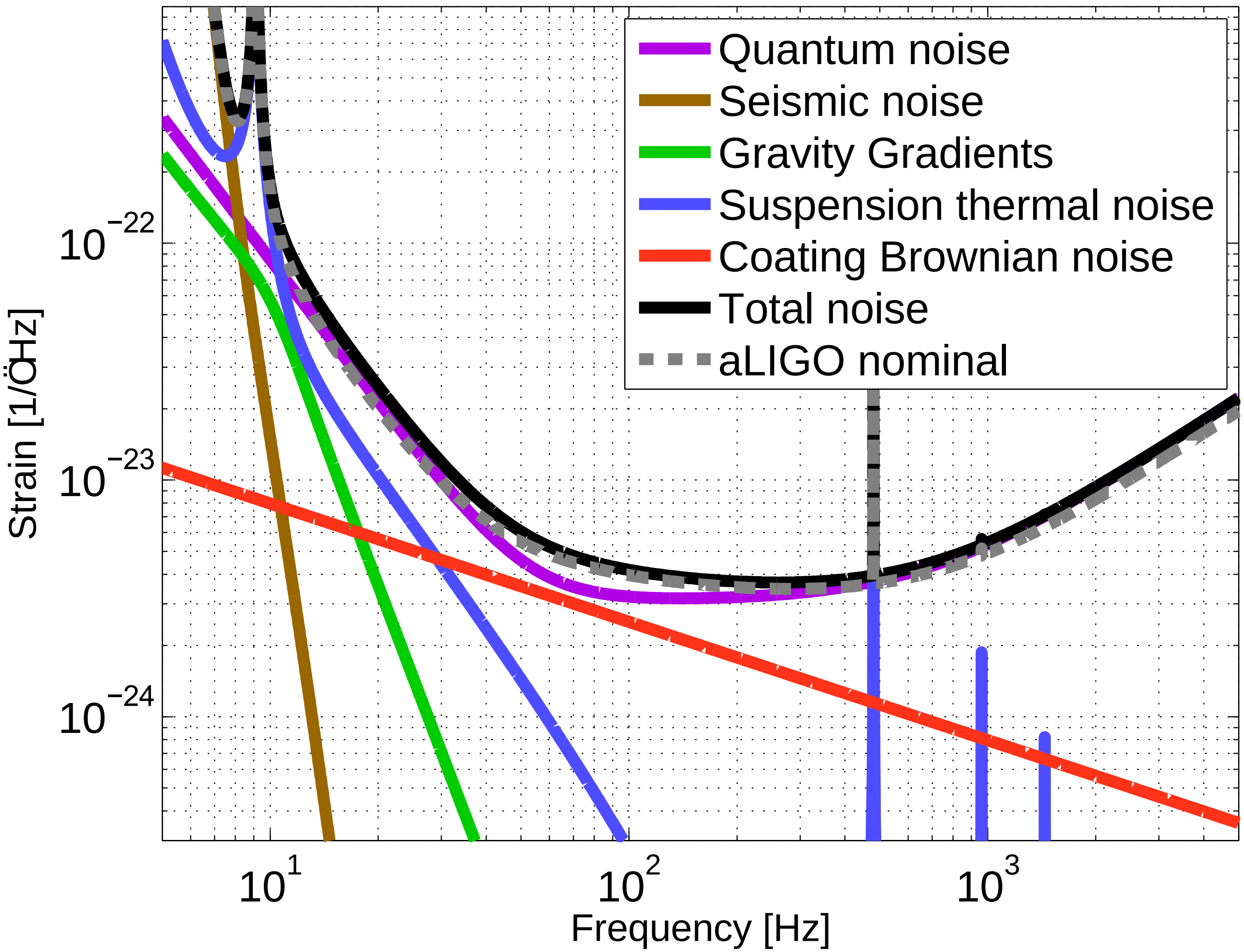


Frequency Independent Squeezing



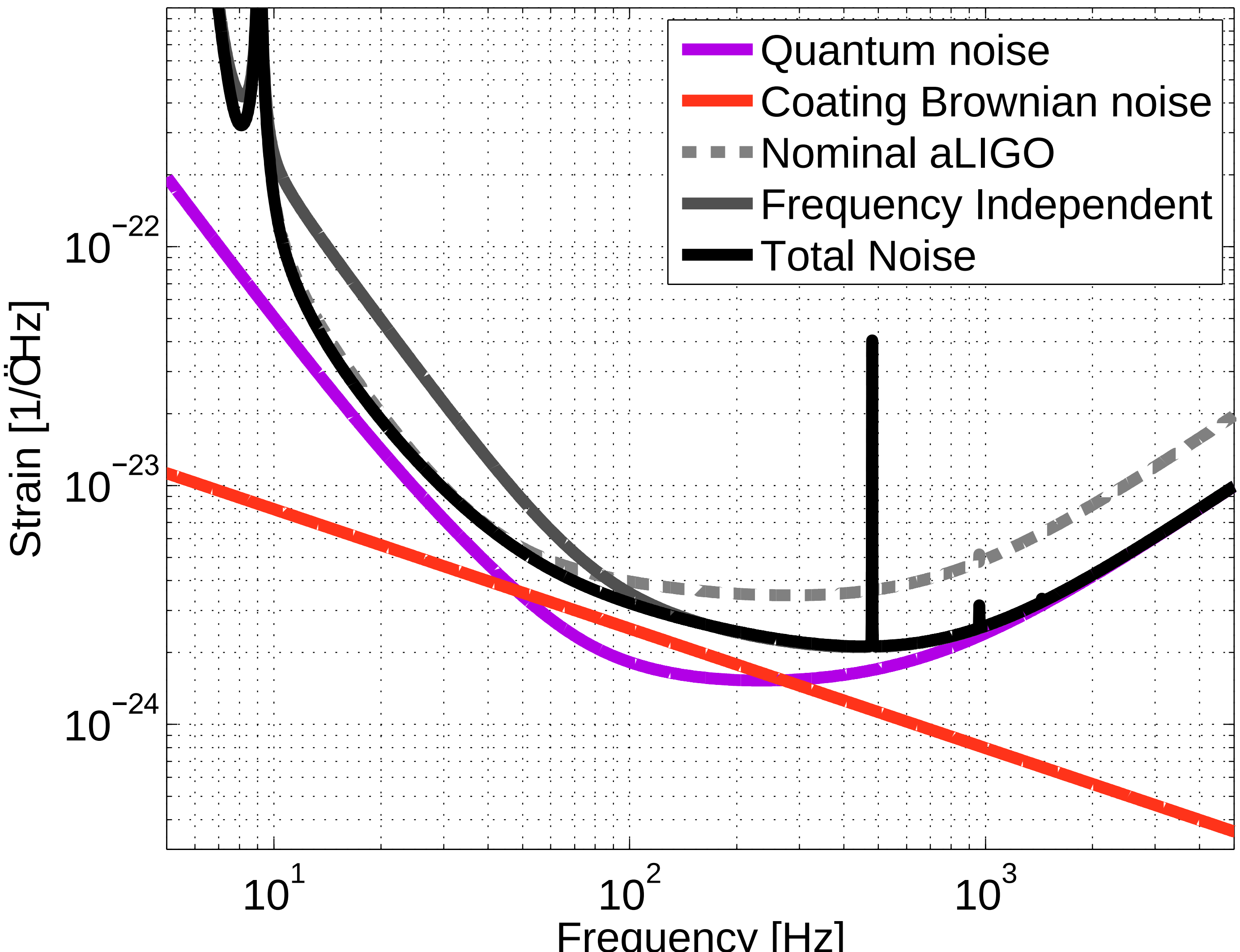
➔ High frequency improvement, no benefit in BNS-BNS range

Frequency Independent Squeezing as risk mitigation for high power operation



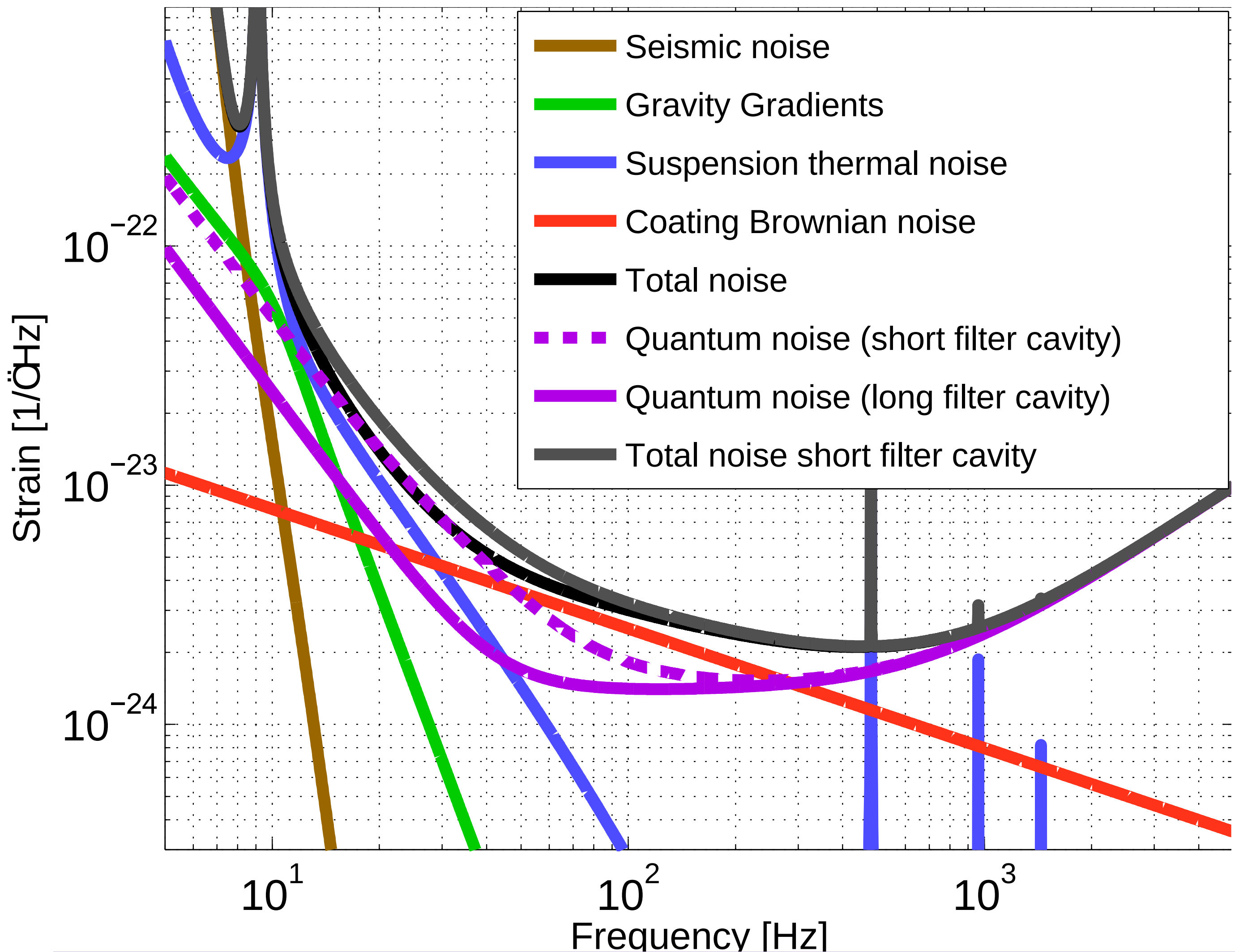
aLIGO @ 4 times less power + squeezing = aLIGO nominal

Frequency Dependent Squeezing (“short” filter cavity)



- ➔ High frequency improvement, + 25% BNS-BNS range (200 vs 250 Mpc)
- ➔ Enables further improvement through coating thermal noise reduction

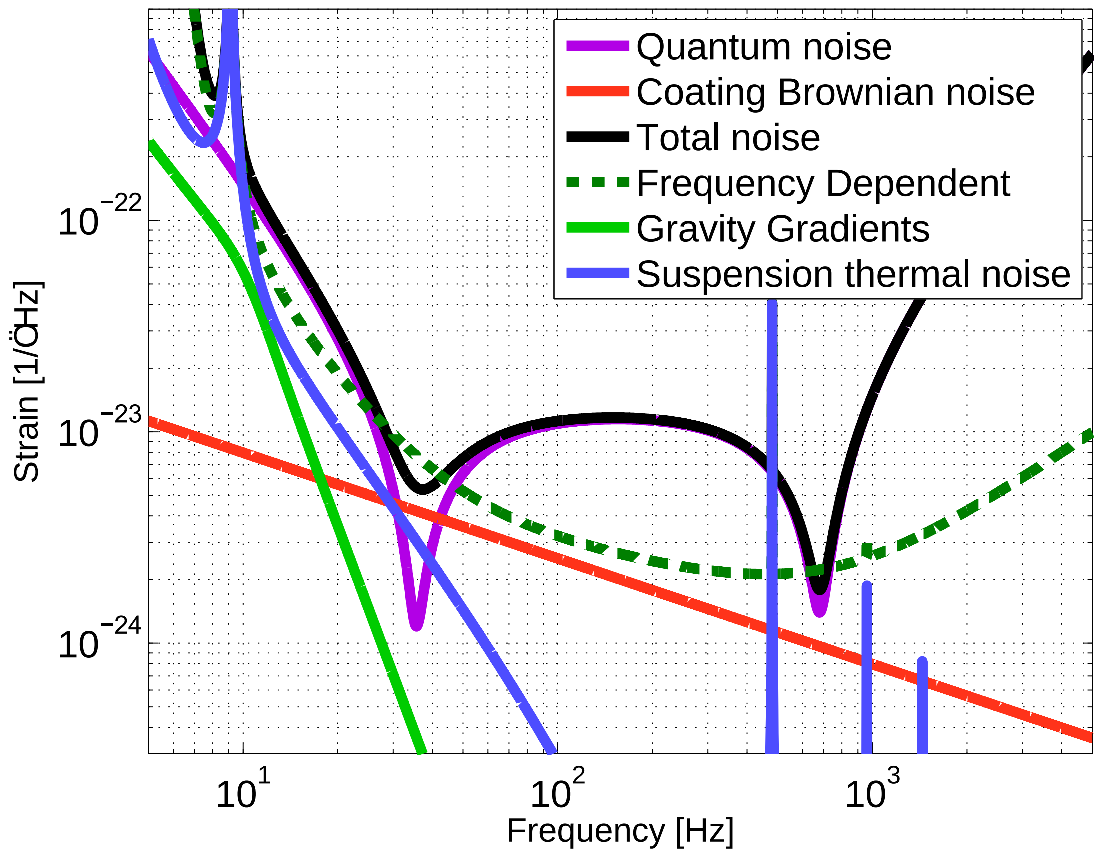
Frequency Dependent Squeezing (“long” filter cavity)



➔ More challenging than “short cavity”; particularly beneficial for targeting low/mid frequency sources, especially when combined with other

Signal Recycling Detuning

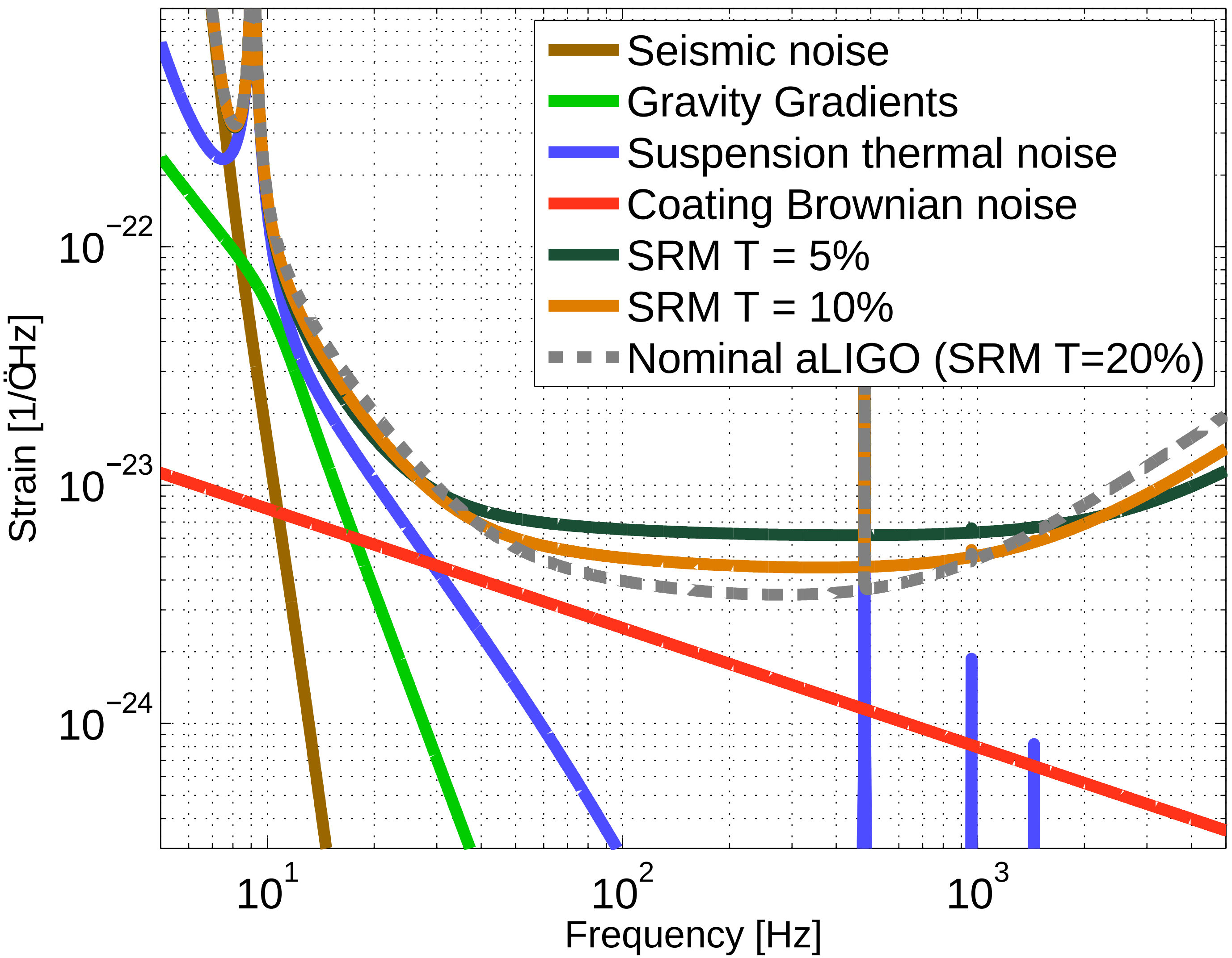
- In principle, ability to target high frequency sources without squeezing, by giving up BNS range completely
- Challenge from the point of view of interferometer control
- Interferometer loss limits how deep we can go



➔ Signal recycling detuning not particular beneficial for high frequency sources (compared to squeezing)

➔ Interesting cases for low-mid frequencies regions

Change of interferometer bandwidth



Readiness level / cost for Squeezing

- **Frequency independent**
  - ✓ Already applied in large scale interferometers

    Nature Physics 7, 962 (2011), Nature Photonics 7, 613–619 (2013)
  - ✓ Conceptual design for application in Advanced LIGO:

    Optics Express Vol. 22, Issue 17, pp. 21106-21121 (2014)
  - ✓ Mature technology: system development phase
  - ✓ High frequency improvement, **risk mitigation** for high power operation in aLIGO
  - ✓ Tentative cost estimate: $1M per interferometer

Readiness level / cost for Squeezing

✧ Frequency dependent (“short cavity”)

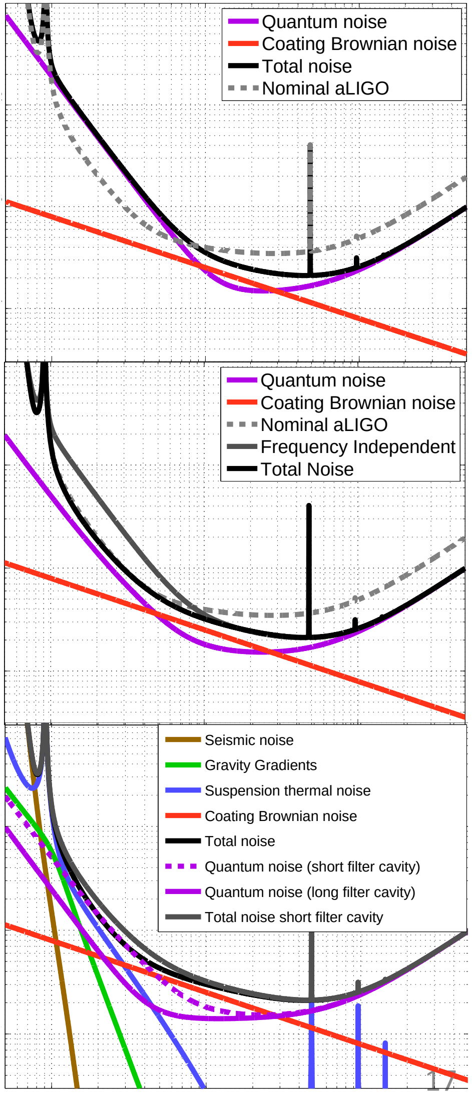
- ✓ Recent demonstration with table top experiment (P1500062)
- ✓ Mature technology: system development phase
- ✓ +25% improvement in BNS-BNS range (~260 Mpc)
- ✓ Greater benefit when combined with reduced coating thermal noise (see Stefan’s talk, and Phys. Rev. D 91, 062005)
- ✓ Tentative estimate: additional $0.5M per interferometer

✧ Frequency dependent (“long cavity”)

- ✓ Particular beneficial for low frequency sources, when combined with other noise improvements (see Rana’s talk)
- ✓ Technology development phase; more costly

Summary of Squeezing Options

Option	Benefit & Cost	Readiness
Frequency Independent Squeezing	x2 improvement at HF, worse low frequency $1M / IFO	system development
Frequency Dependent Squeezing (short cavity)	x2 improvement at HF, preserve low frequency add $500k / IFO	system development
Frequency Dependent Squeezing (long cavity)	x2 improvement at HF, improvement at low frequency too add $1M / IFO (TBC)	technology development

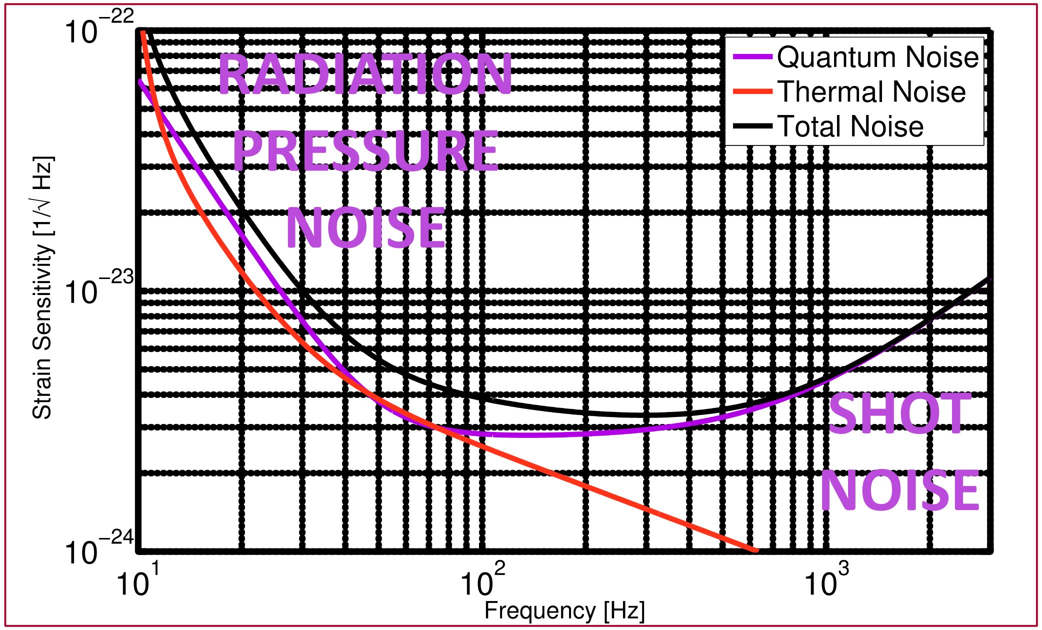


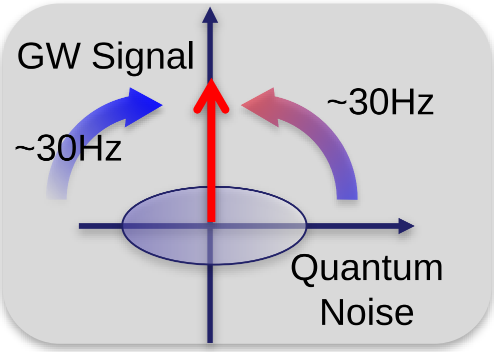
Conclusions

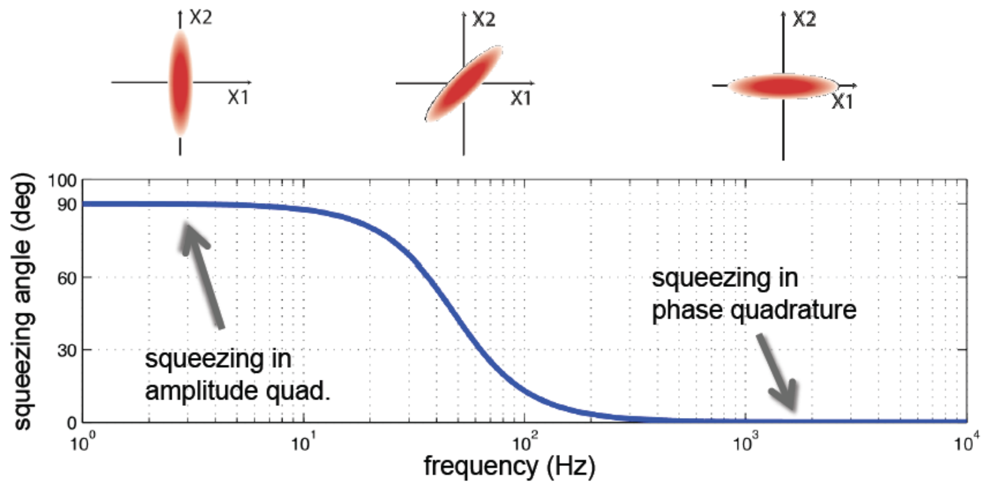
- ✧ Getting a factor of 2 improvement at high frequency is within reach
- ✧ More than a factor of 2 is harder, but doable
- ✧ What we do at high frequency does impact the low-mid frequency region
- ✧ Benefit in terms of BNS range is "only" +25%, but that's true with any single improvement we do
  ➔ need to attack multiple noise sources at the same time

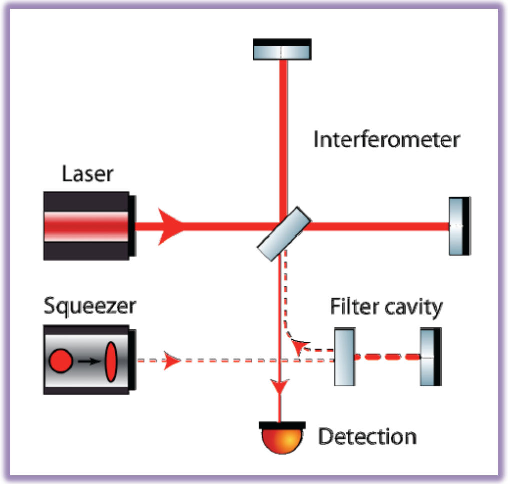
Extra Slides

Frequency Dependent Squeezing - I



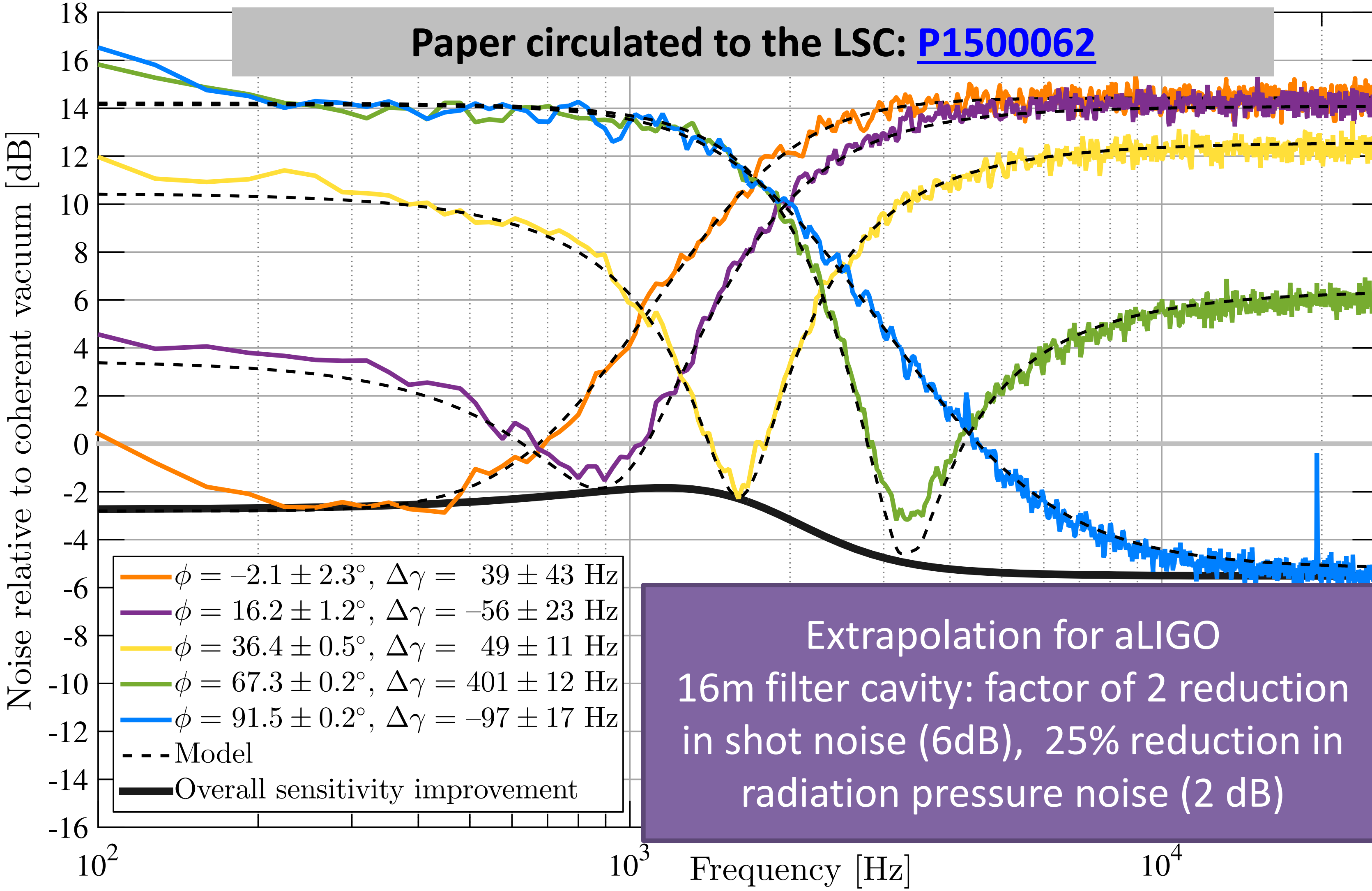






High finesse detuned **"filter cavity"** which rotates the squeezing angle as function of frequency

Frequency dependent squeezing with a 2 m filter cavity @ MIT



Paper circulated to the LSC: P1500062

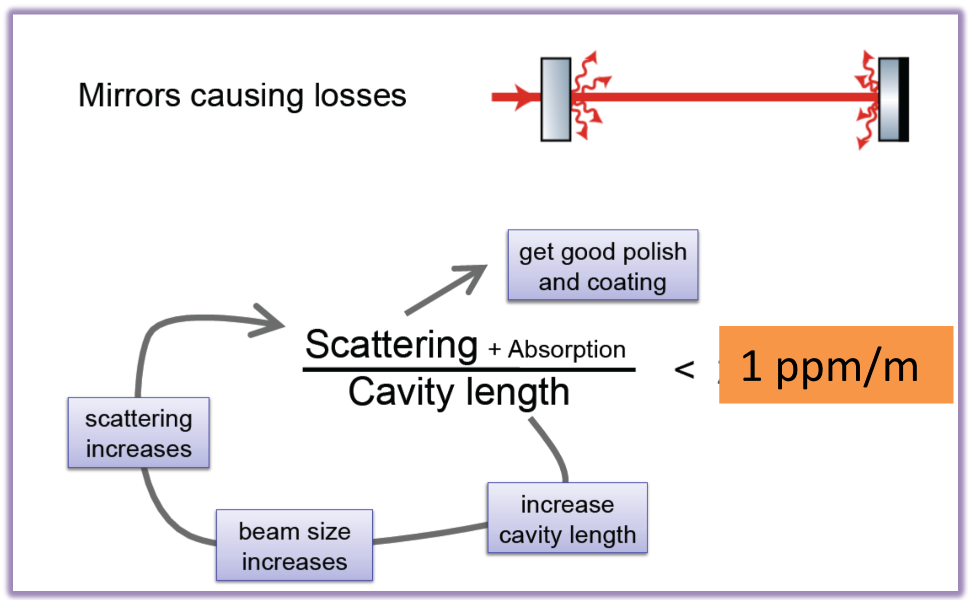
Extrapolation for aLIGO
16m filter cavity: factor of 2 reduction in shot noise (6dB), 25% reduction in radiation pressure noise (2 dB)

Long vs Short filter cavity
(Nothing comes cheap)

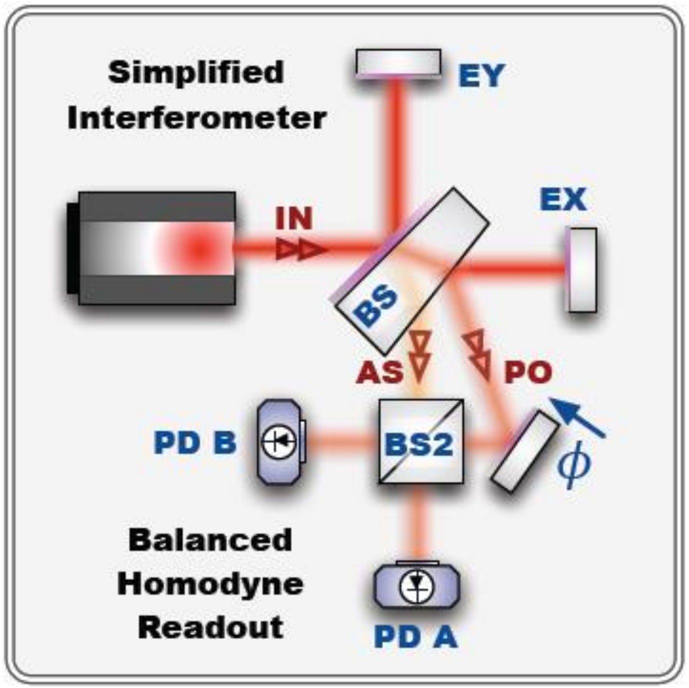
- ✧ Advanced LIGO needs a a filter cavity with 50 Hz bandwidth
- ✧ Losses in a filter cavity deteriorate, if too high, make the filter cavity useless…

$$\text{Total Loss } E = \frac{4\epsilon}{T} = \frac{\epsilon}{L}\frac{c}{\gamma_{filter}}, \qquad \gamma_{filter} = \frac{Tc}{4L}$$

Per-round-trip loss depends on the beam spot size (big beam size → higher scatter losses), which depends on L



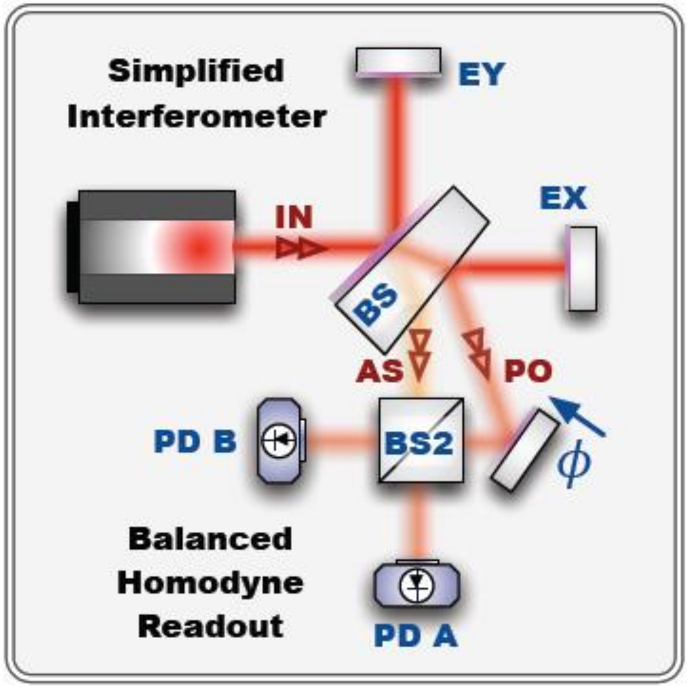
Balanced Homodyne Detection



Optics Express Vol. 22, Issue 4, pp. 4224-4234 (2014)

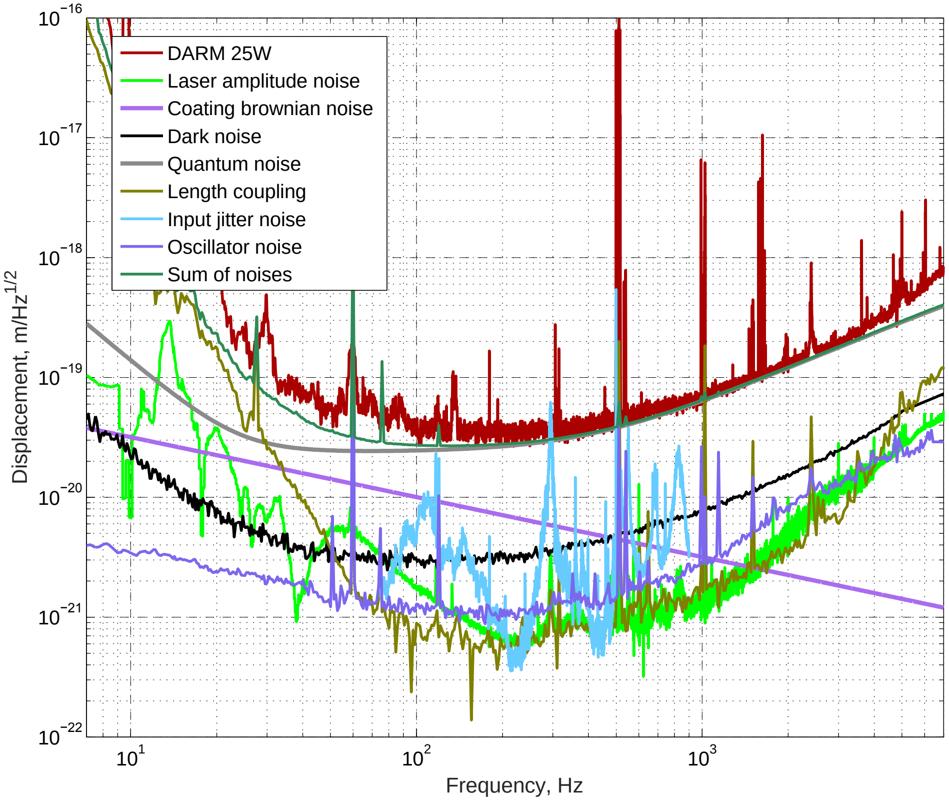
- ✧ Standard technique in table top squeezing experiments
- ✧ It has advantages compared to DC readout when applied to large scale interferometers
- ✧ Main advantage: remove static carrier field at the anti-symmetric port

Balanced Homodyne Detection

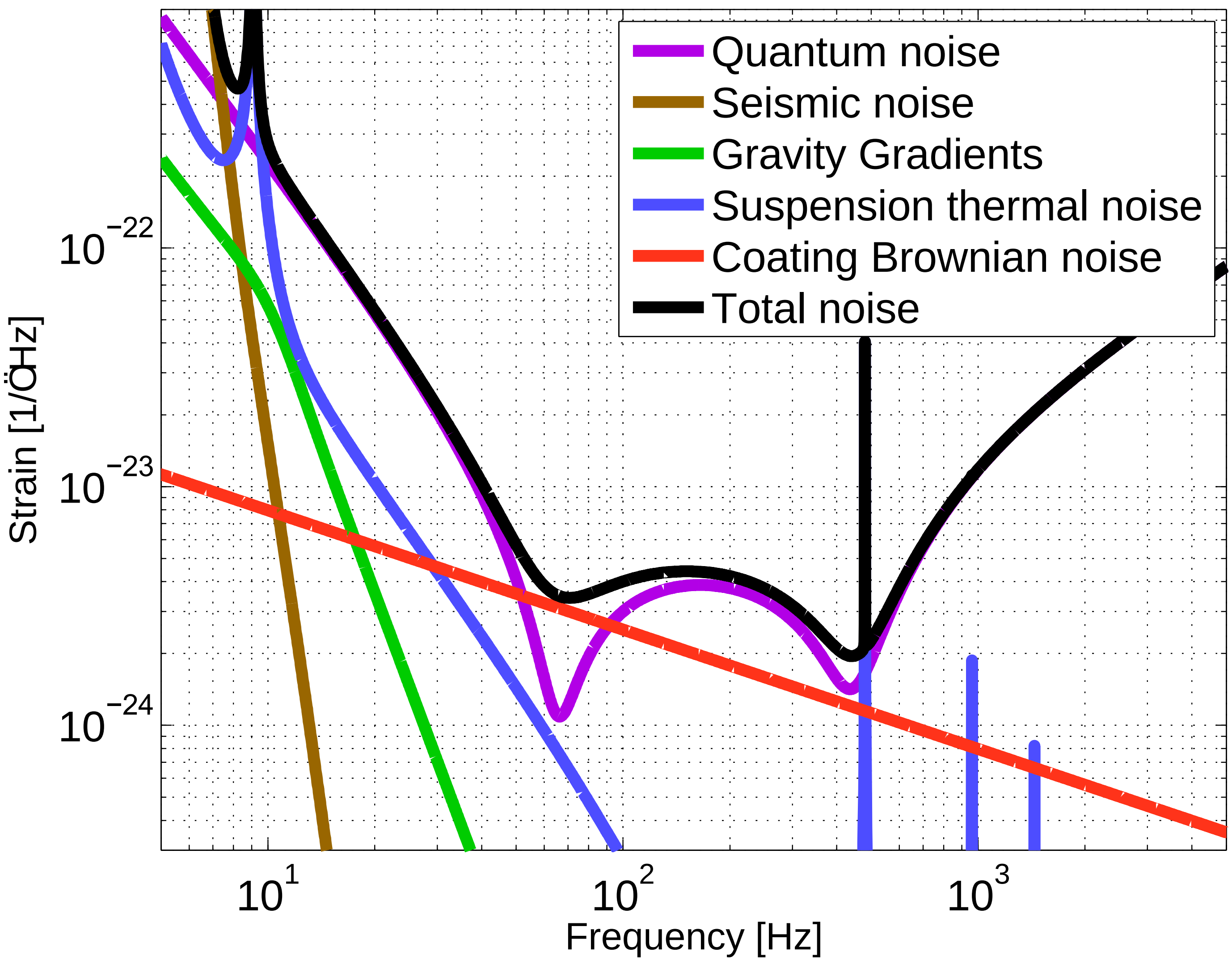


Optics Express Vol. 22, Issue 4, pp. 4224-4234 (2014)

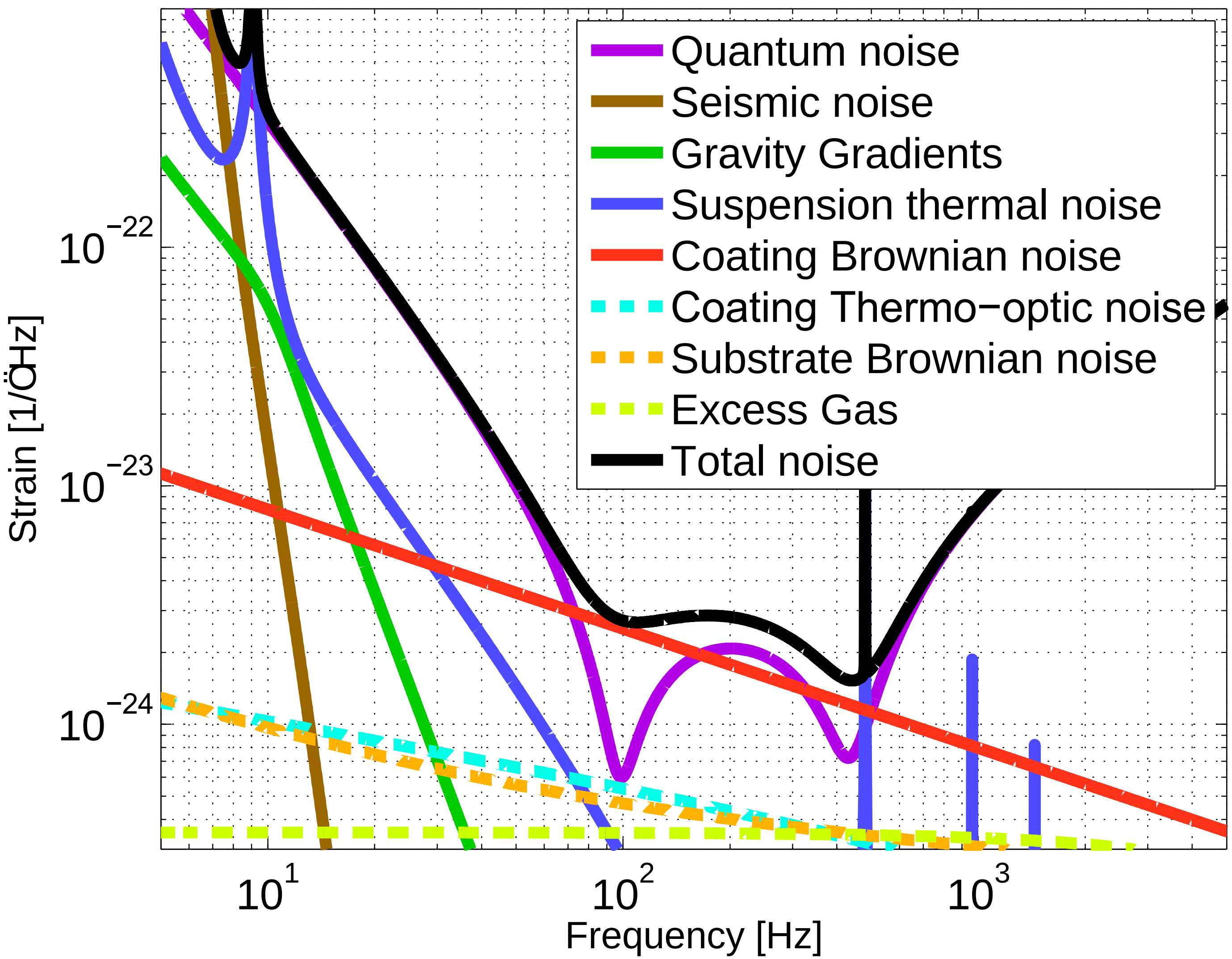
L1 current high frequency noise budget



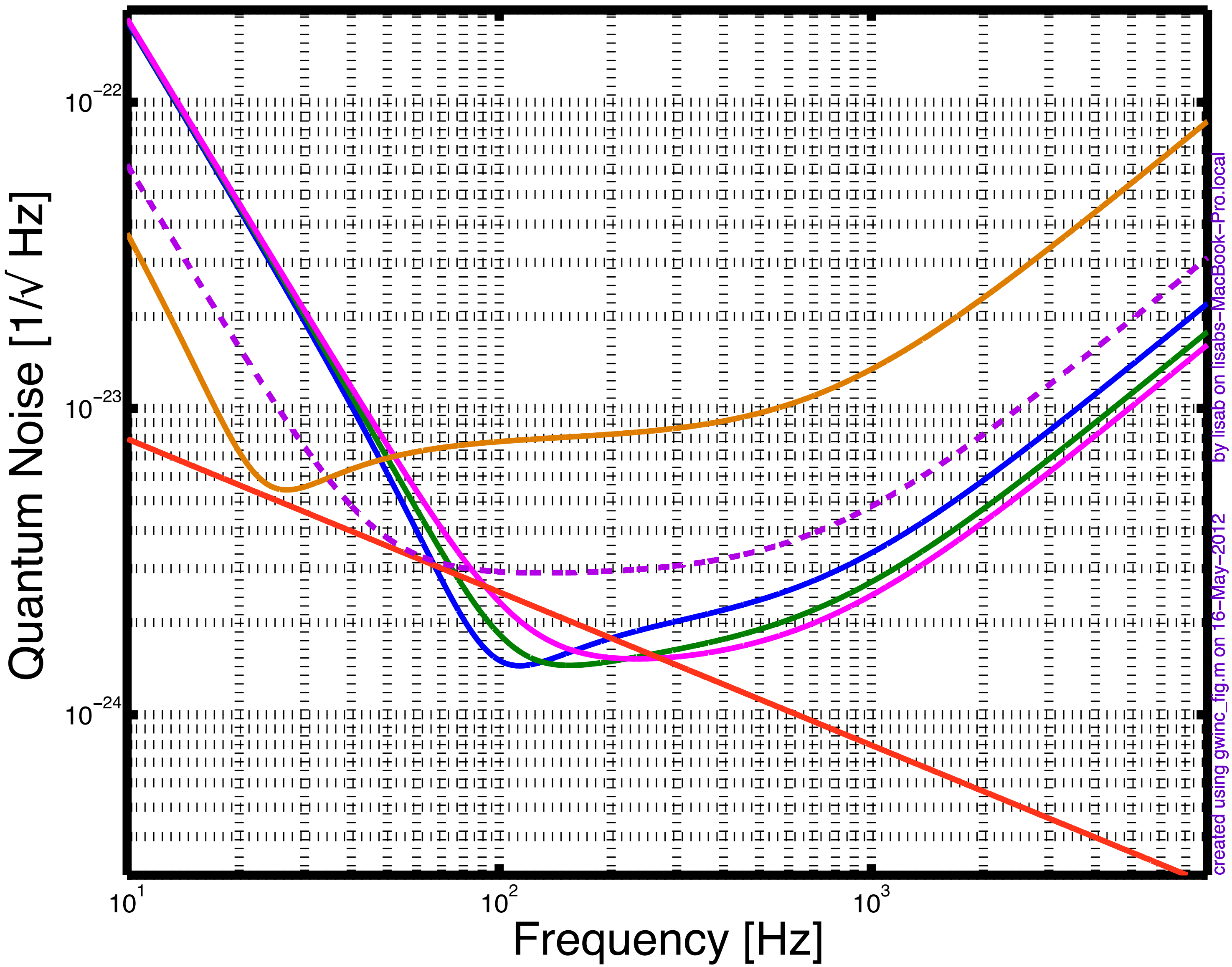
Signal Recycling Detuning with frequency independent squeezing



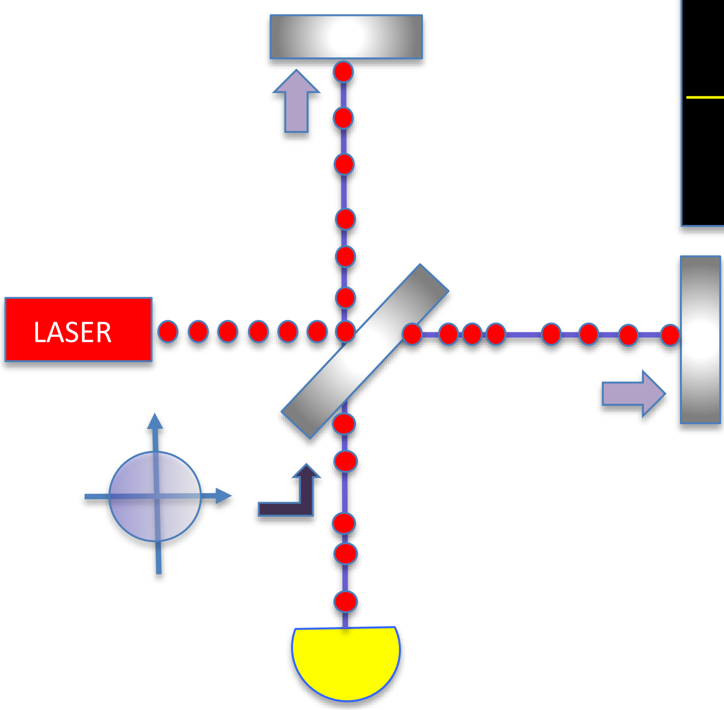
Signal Recycling Detuning with frequency independent squeezing, low loss

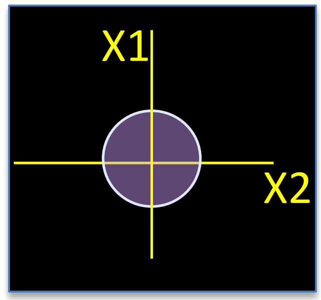


Quantum noise shaped by squeezed angle



Quantum Noise and Vacuum

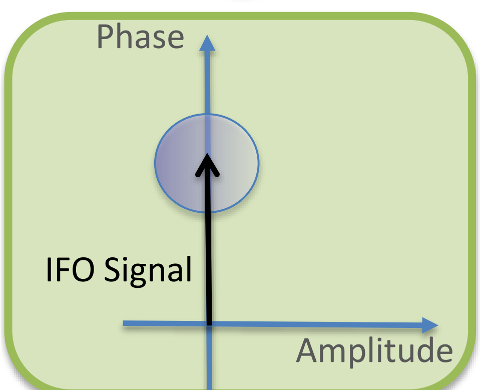




- Quantization of the electro-magnetic field
- When average amplitude is zero, the variance remains
- Heisenberg uncertainty principle:

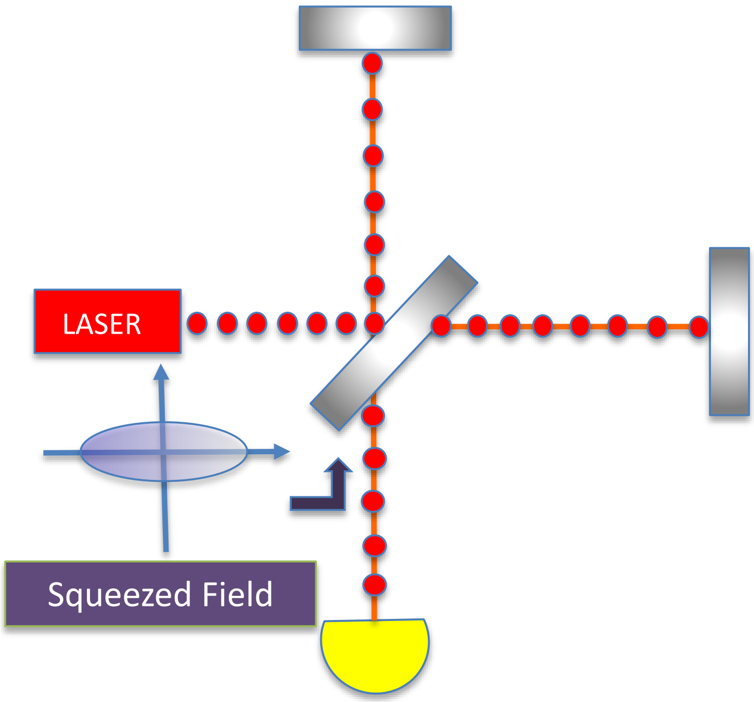
$$\Delta X_1 \, \Delta X_2 \geq 1$$

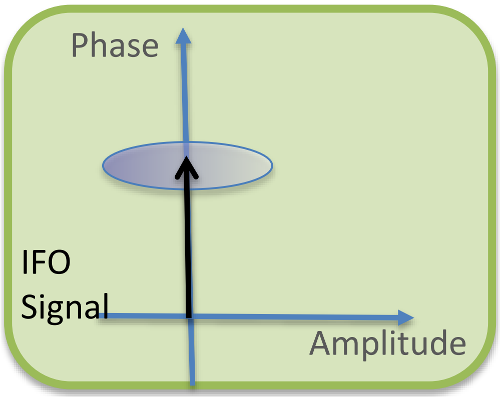
- Vacuum fluctuations are everywhere that classically there is no field….
- …like at the output port of your interferometer!



- Quantum noise is produced by vacuum fluctuations entering the open ports
- Vacuum fluctuations have equal uncertainty in phase and amplitude:
  - Phase: Shot-Noise (photon counting noise)
  - Amplitude: Radiation Pressure Noise (back-action)

Vacuum Getting Squeezed





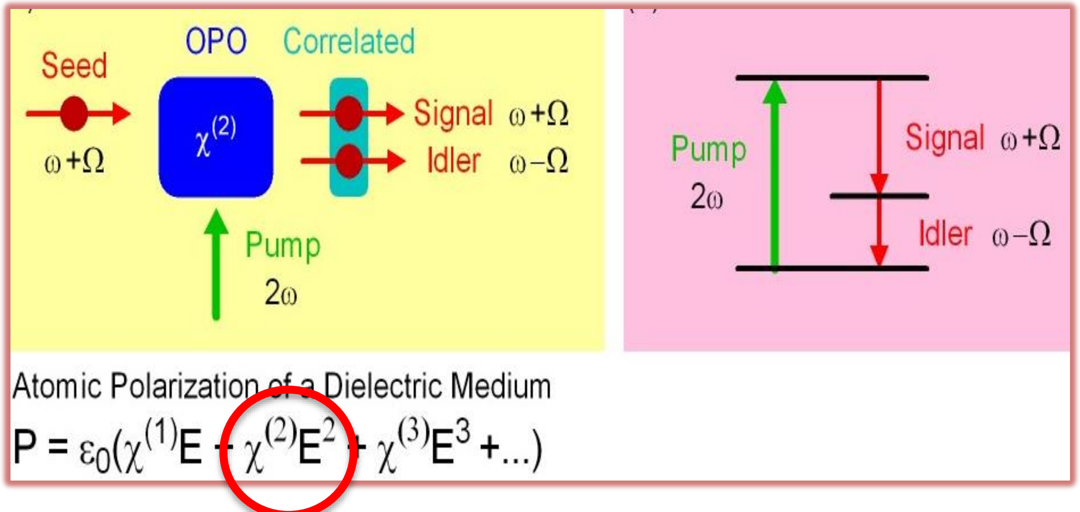
- ✧ Reduce quantum noise by injecting squeezed vacuum: less uncertainty in one of the two quadratures
- ✧ Heisenberg uncertainty principle: if the noise gets smaller in one quadrature, it gets bigger in the other one
- ✧ One can choose the relative orientation between the squeezed vacuum and the interferometer signal (squeeze angle)

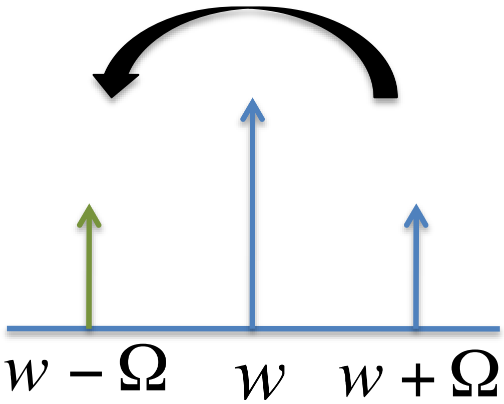
C. M. Caves, Phys. Rev. Lett. 45, 75 (1980).
C. M. Caves, Quantum-mechanical noise in an interferometer. Phys. Rev. D 23, p. 1693 (1981).

How to make squeezed fields..

…. in theory

- ✧ Non linear medium with a strong second order polarization component
- ✧ Correlation of upper and lower quantum sidebands





$$P \propto (Ee^{-i2wt} + Ee^{-i(w+\Omega)t})^2$$

$$\Rightarrow Ee^{-i(w-\Omega)t}$$

The OPO makes a “copy” of the quantum sideband, and it correlates the sidebands

How to make squeezed fields..

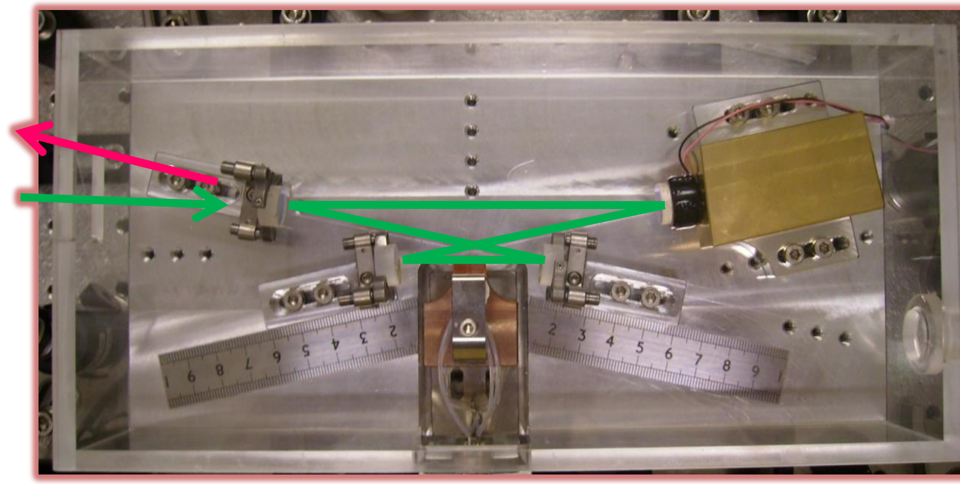
.... in practice

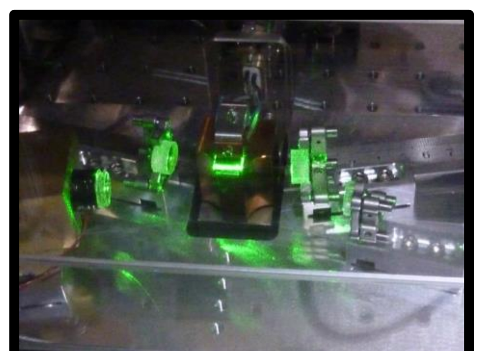
World-wide effort in the last 10 years to make squeezing in the audio-frequency band

✧ Lasers, mirrors, control loops,..

Courtesy of Alexander Khalaidovski (AEI)

The Squeezer of the GEO600 detector





The Optical Parametric Oscillator
of the LIGO squeezer
(ANU design)