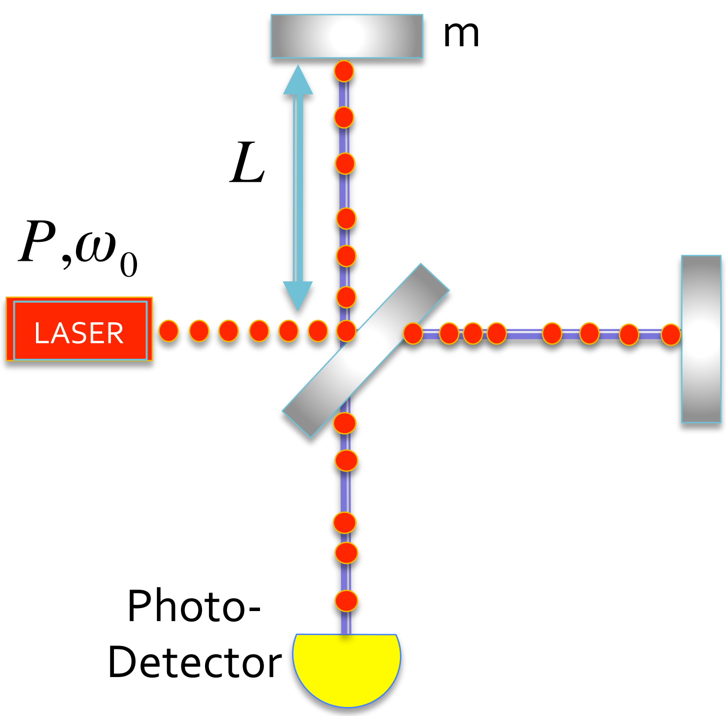
LIGO-G140147-v1

Quantum noise in Gravitational Wave Detectors

Koji Arai / Stan Whitcomb – LIGO Laboratory / Caltech

Introduction ~ Quantum noise?



$$h_{quantum} = \sqrt{h_{rad}^2 + h_{shot}^2}$$

✧ SHOT NOISE:
Photon counting noise

$$h_{shot} \propto \frac{1}{L}\sqrt{\frac{1}{P}}$$

✧ RADIATION PRESSURE NOISE:
Back-action noise caused by random motion of the mirrors

$$h_{rad} \propto \frac{1}{f^2 L}\frac{\sqrt{P}}{m}$$

Measurement frequency

Slide courtesy of L. Barsotti

"Standard Quantum Limit"

$$h_{Quantum} = \sqrt{\frac{4\hbar}{m\Omega^2 L^2}} \sqrt{\frac{1}{2}\left(\mathrm{K} + \frac{1}{\mathrm{K}}\right)}, \qquad \mathrm{K} = \frac{4P\omega_0}{c^2 m\Omega^2}$$

$$h_{Quantum} \geq \sqrt{\frac{4\hbar}{m\Omega^2 L^2}} = h_{SQL}$$

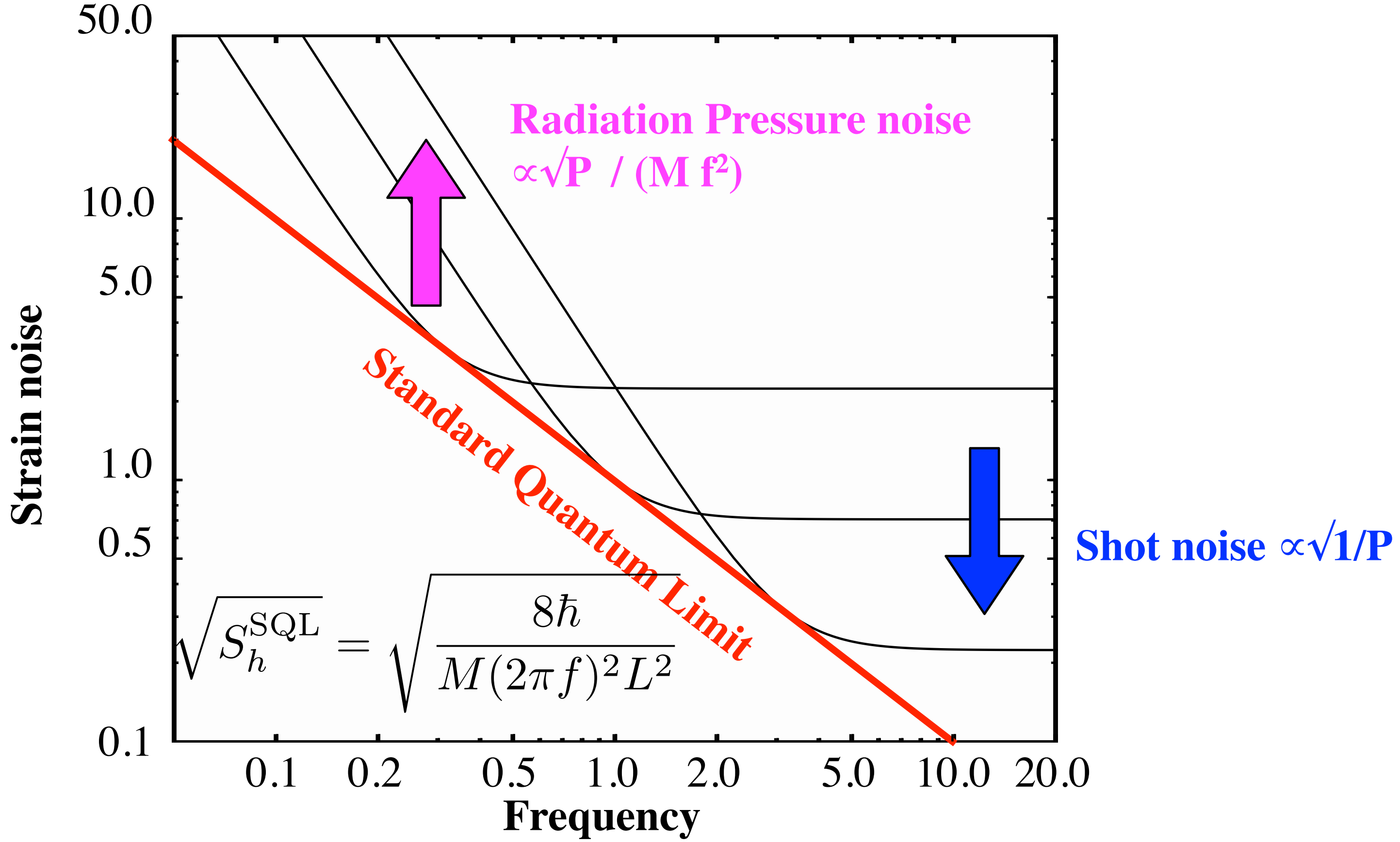
$(m \to m/2 \text{ for FPMI})$

h_{SQL} doesn't depend on the optical parameters of the interferometer, just on the quantum mechanics of a **harmonic oscillator** mass

Slide courtesy of L. Barsotti

Optical noises

- **Quantum noises**
  - Standard Quantum Limit (SQL)



- Trade-off Between Shot Noise and Radiation-Pressure Noise
- Uncertainty of the test mass position due to observation

Introduction ~ Quantum noise?

- **Quantum noise in Advanced LIGO**
  - **Photon shot noise and radiation pressure noise will limit the detector sensitivity in the end**

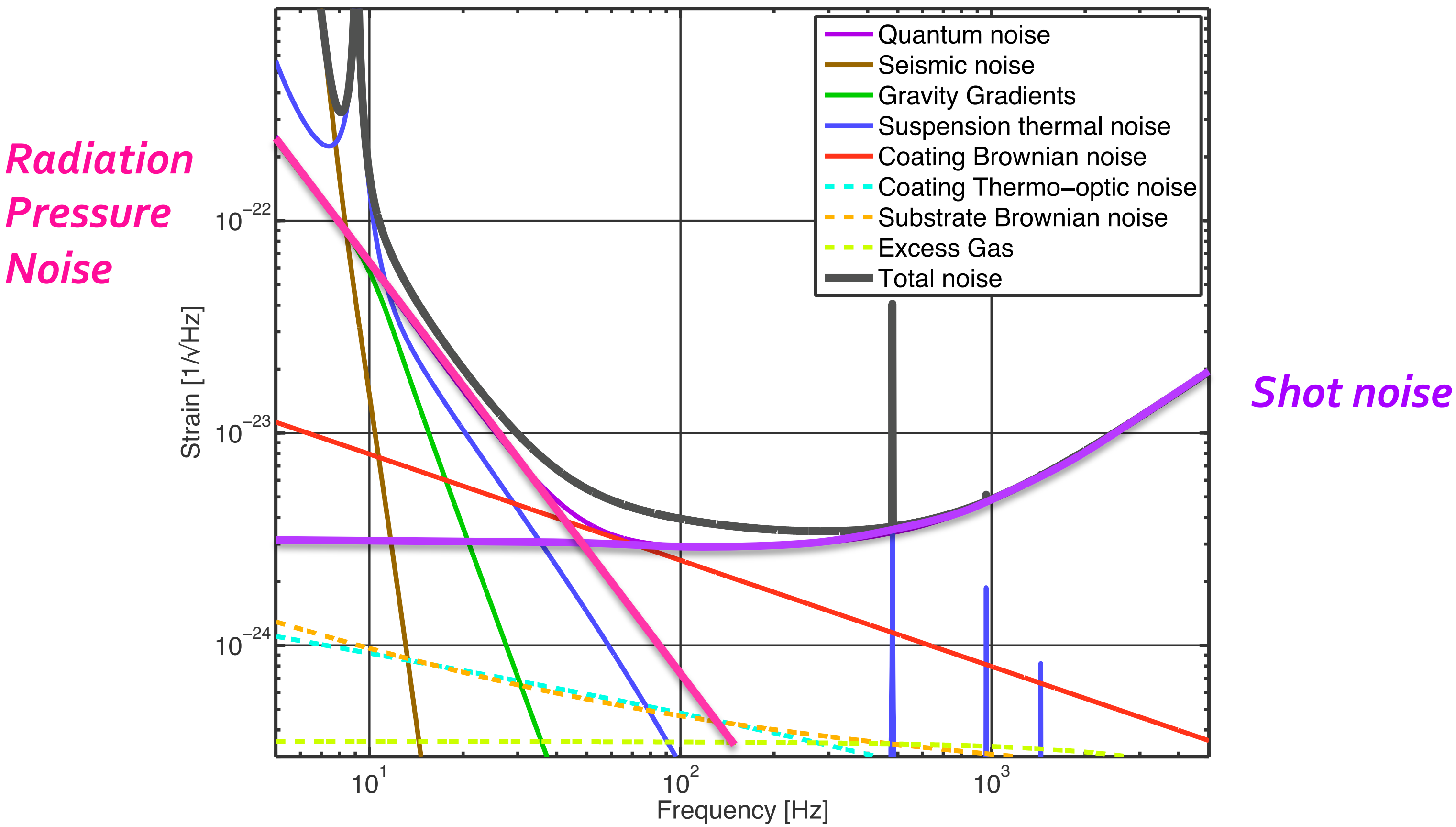


Figure 2: Baseline aLIGO Noise Budget (GWINC v2.0). 125 W input power; broadband RSE tuning.

Introduction ~ Quantum noise?

- **Quantum noise reduction**

$$h_{Quantum} = \sqrt{\frac{4\hbar}{m\Omega^2 L^2}}\sqrt{\frac{1}{2}\left(\mathrm{K}+\frac{1}{\mathrm{K}}\right)}, \qquad \mathrm{K} = \frac{4P\omega_0}{c^2 m\Omega^2}$$

  - Make the interferometer longer
    => Needs new facility
  - Heavier test masses & more optical power
    => Stored power of aLIGO will be 800kW
    Have to deal with thermal effects / instabilities
  - More complex optical configuration to shape optical response

Injection of squeezed states of vacuum

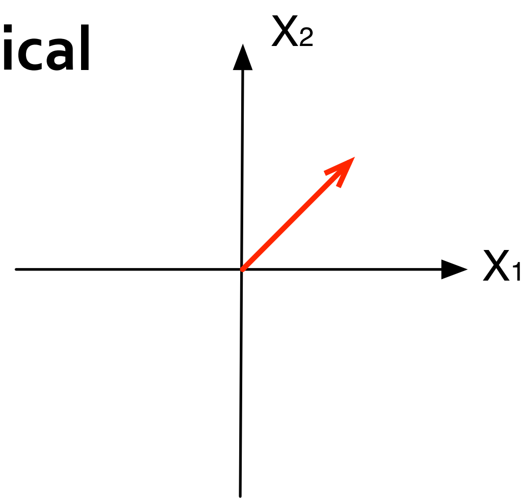
Introduction ~ Quantum noise?

- **What is "squeezing"?**
- **Quantized Electromagnetic Fields**

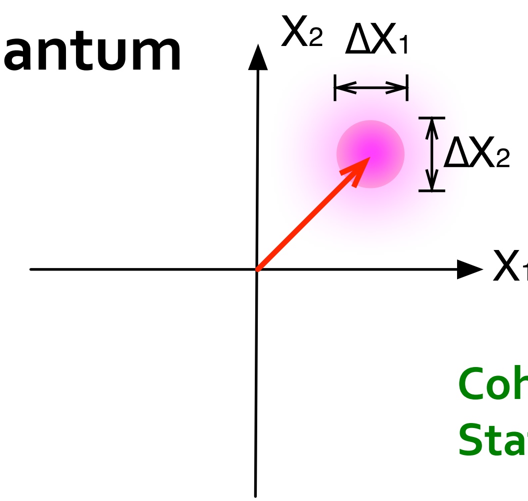
  Quadrature Field Amplitudes

$$\hat{E} = \hat{X}_1 \cos\omega t + i\hat{X}_2 \sin\omega t$$

Classical



Quantum



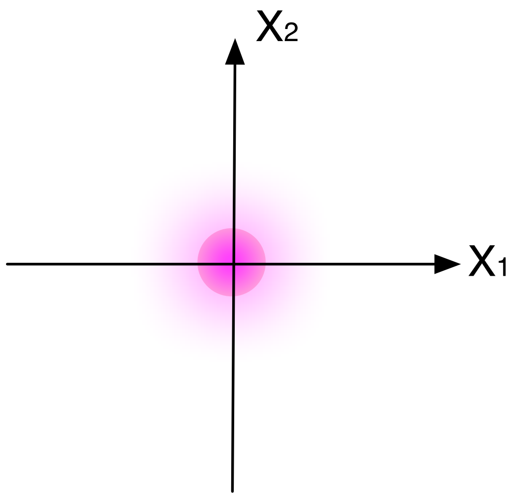
Coherent State

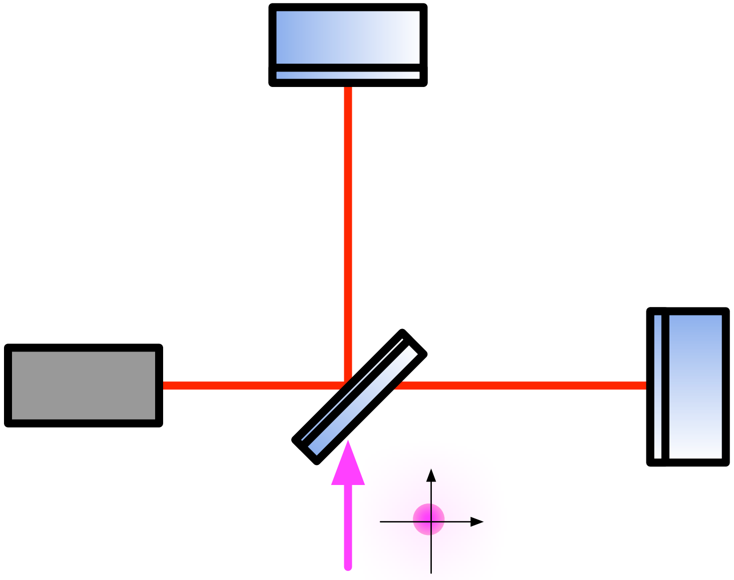
Heisenberg's uncertainty principle

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

Introduction ~ Quantum noise?

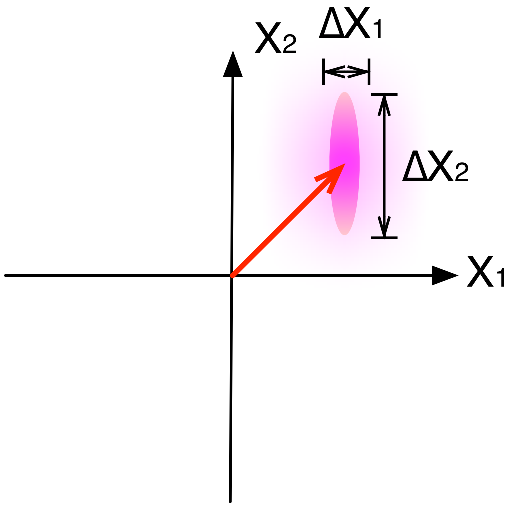
- Even when average amplitude is zero, the variance remains
  => Zero-point "vacuum" fluctuation
- Vacuum fluctuations are everywhere
  => Comes into the interferometer
  from the open optical port and
  cause shot and radiation pressure noises





Squeezing

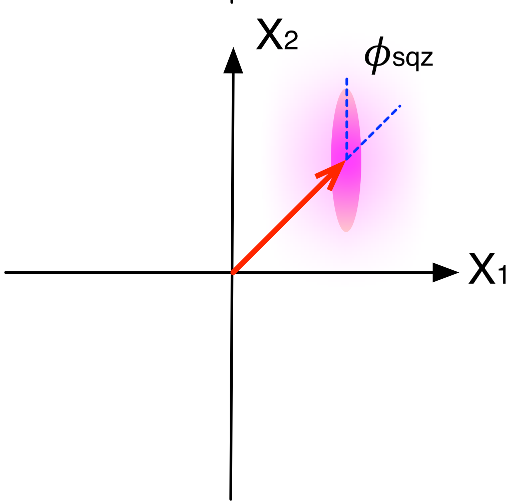
- **The noise can be redistributed while keeping the minimum uncertainty product $\Delta X_1 \Delta X_2 = 1$**
  = Squeezed light



- **Squeezed light is characterized by**
  - **Squeezing factor *r***
    How much the noise is squeezed

$$\Delta X_1 = e^{-r}, \Delta X_2 = e^{r}$$

  - **Squeezing angle ϕ_{sqz}**
    Which quadrature is squeezed

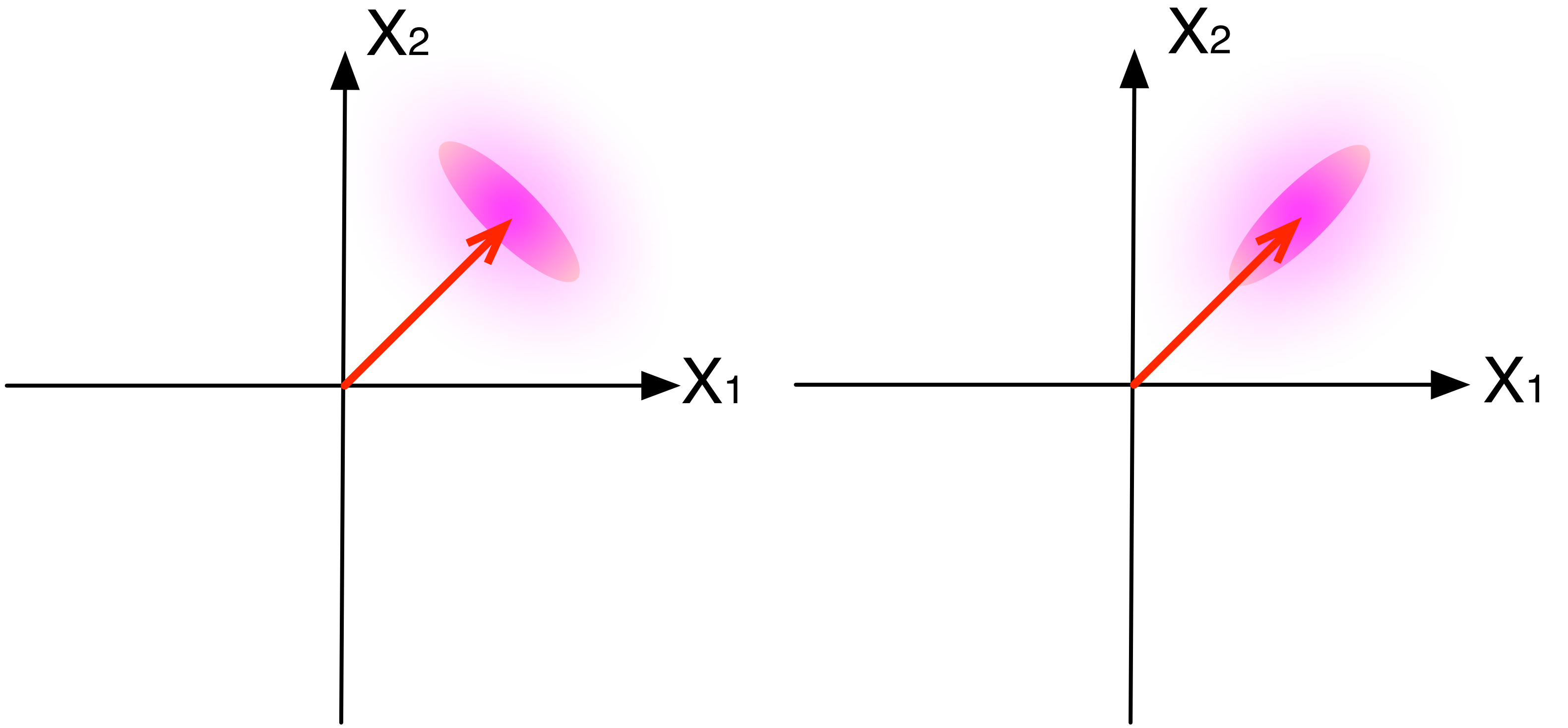


Squeezing

- **Particularly useful two states**

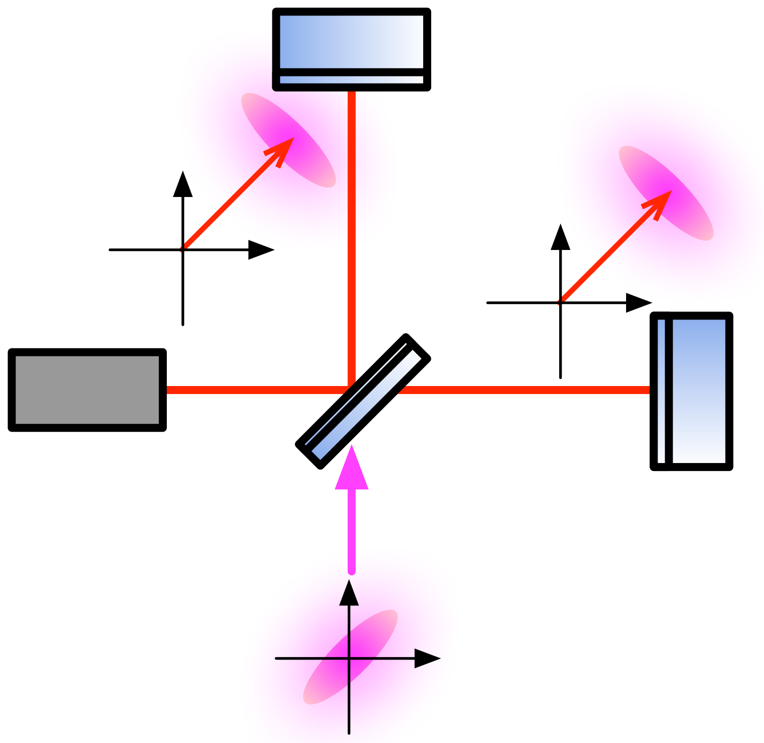
Amplitude squeezing (Phase anti-squeezing)

Phase squeezing (Amplitude anti-squeezing)



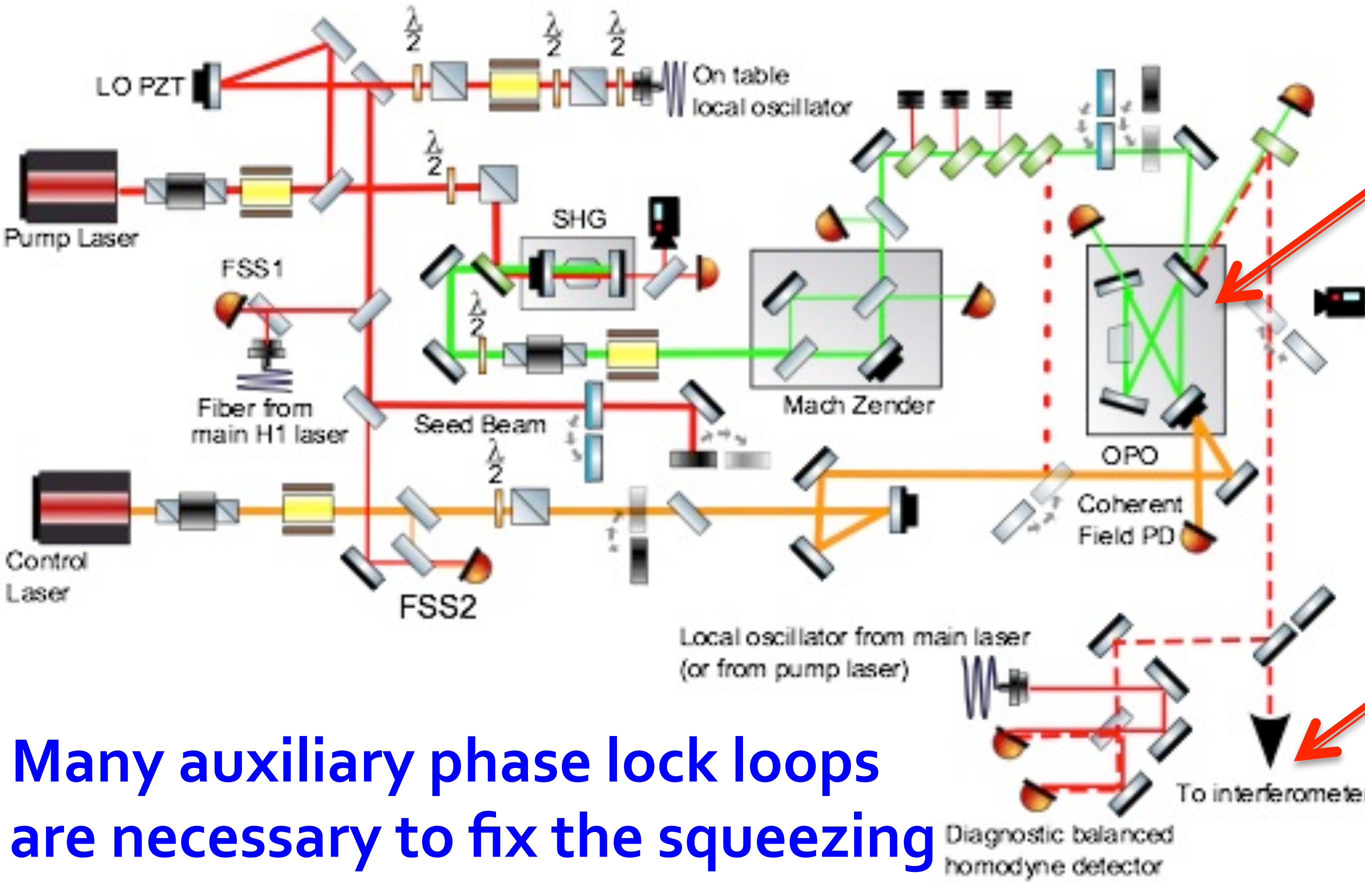
Squeezing

- In practice, we inject squeezed "vacuum" from the dark port
  - Squeezing angle needs to be fixed by a feedback control loop with regard to the field in the interferometer



Squeezing in action

- Actual squeezer (LIGO H1 squeezer)



OPO is here!

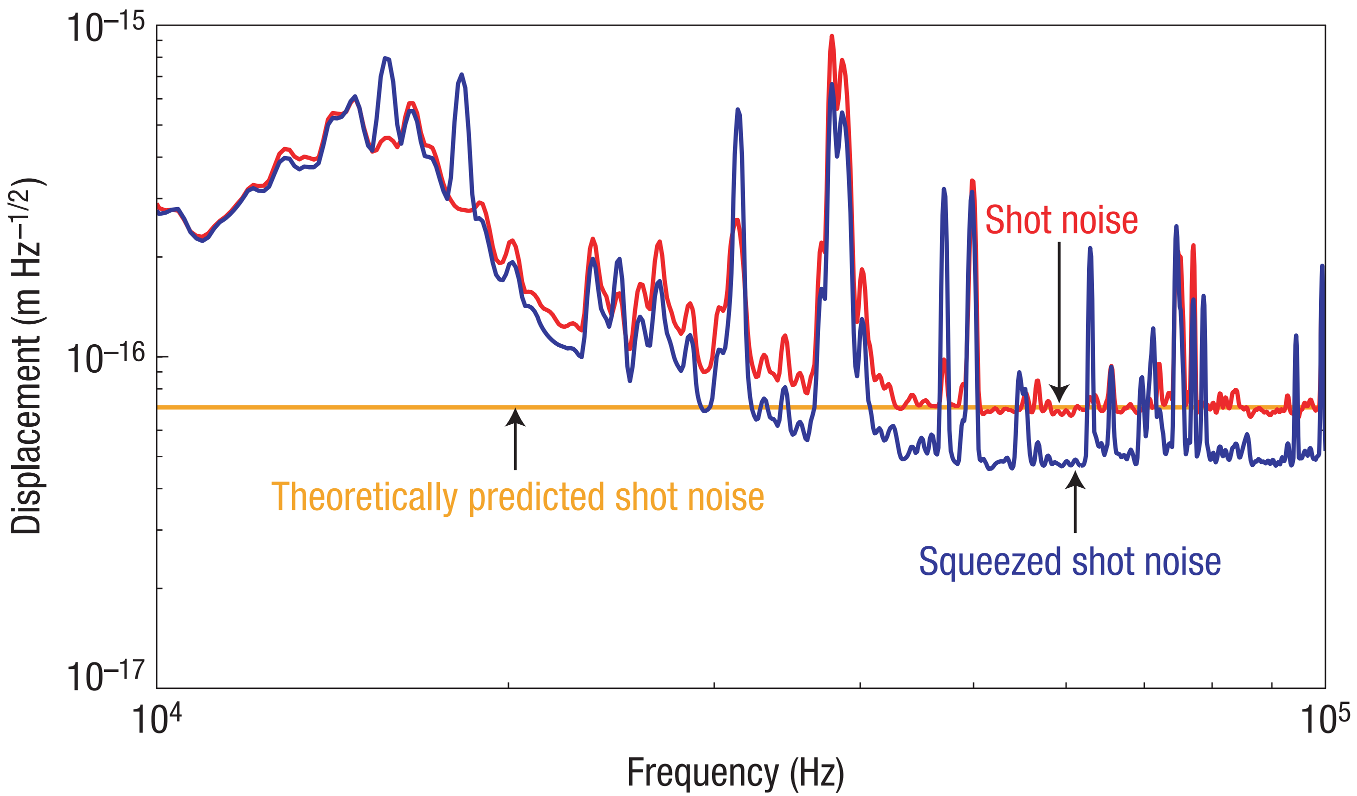
Squeezed vacuum is here!

- Many auxiliary phase lock loops are necessary to fix the squeezing angle

Sheila Dwyer PhD Thesis (2013)

Squeezing in action

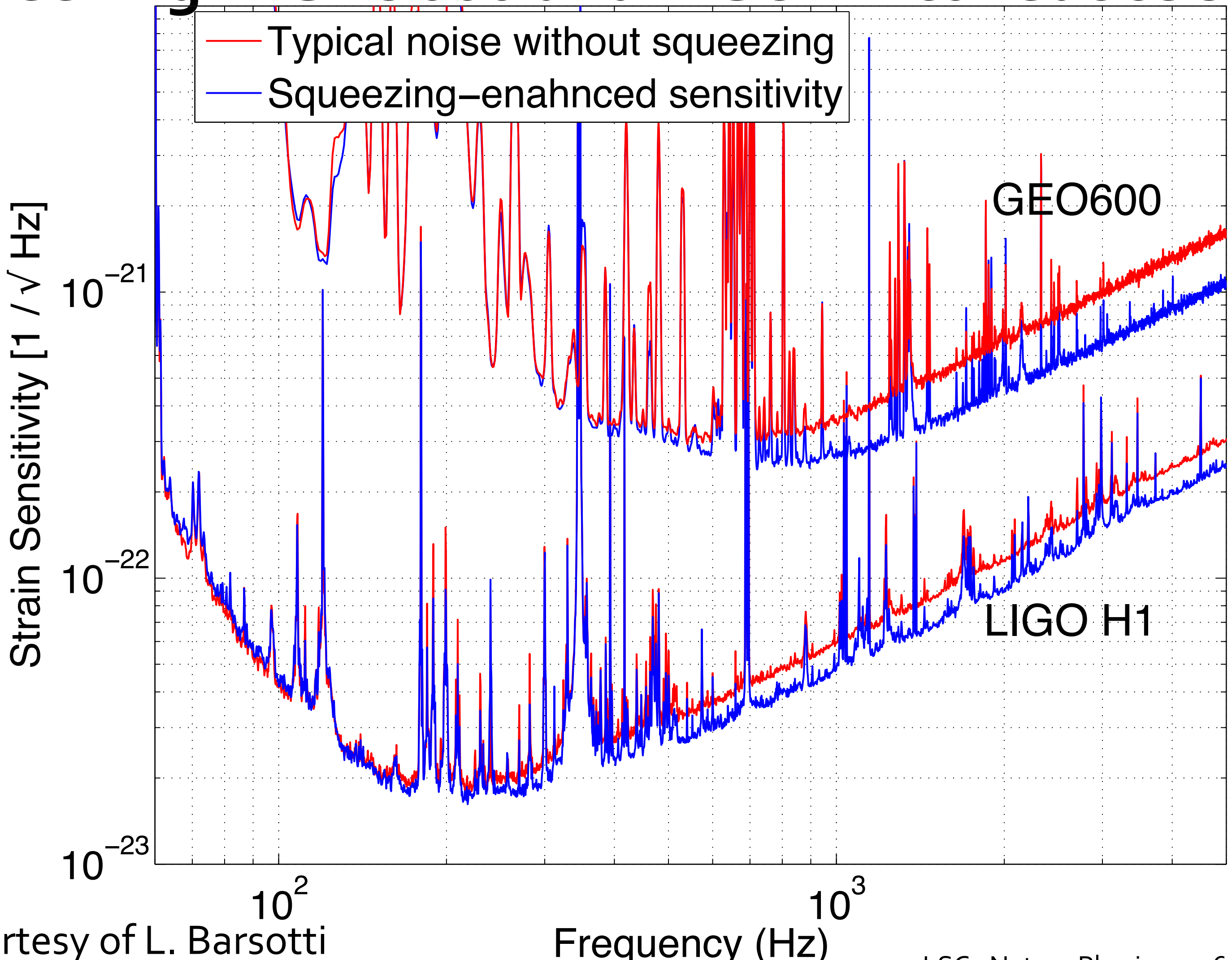
- **Shot noise reduction in GW detectors has already been realized since 2007**
- **Squeezed light injection experiment at the LIGO 40m**



K.Goda et al, Nature Physics 4, 472 - 476 (2008)

Squeezing in action

- **Squeezing in GEO600 and LIGO H1 to reduce shot noise**



3.5 dB (1/1.5)

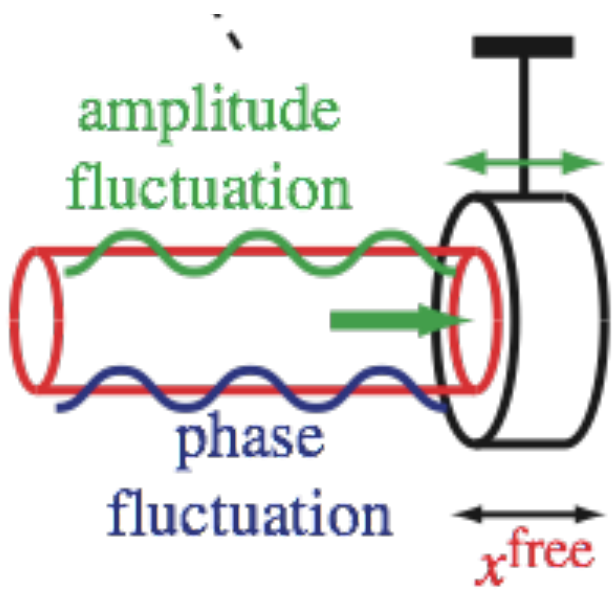
2.1 dB (1/1.27)

Slide courtesy of L. Barsotti
GEO data are courtesy of H. Grote

LSC, Nature Physics 7, 962 (2011)
LSC, Nature Photonics 7, 613–619 (2013)

Quantum noise in an interferometer

- Ponderomotive effect
  - Vacuum fluctuations from the dark port produce amplitude and phase fluctuations in the arm cavities
  - Radiation pressure
    The test mass mechanical system work as a converter from the amplitude fluctuation to the phase fluctuation



Quantum noise in an interferometer

- **Ponderomotive effect**
  - **Radiation pressure:**
    The test mass mechanical system work as a converter from the amplitude fluctuation to phase fluctuation

Output fluctuation

amplitude

phase

amplitude fluctuation in the arm

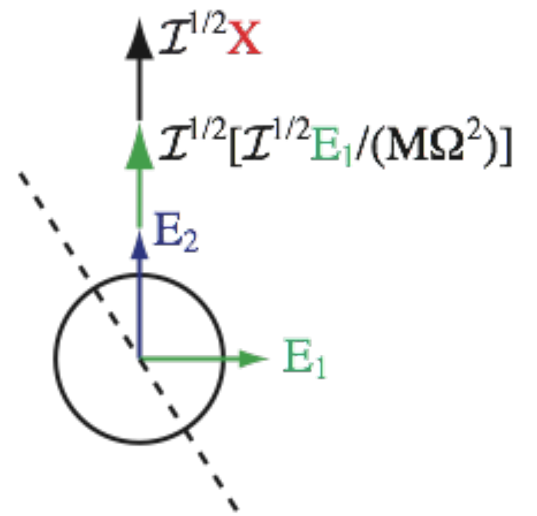
$$E_1^{\text{out}} = E_1^{\text{in}}$$

$$E_2^{\text{out}} = E_2^{\text{in}} - \frac{\mathcal{I}}{M\Omega^2} E_1^{\text{in}} + \sqrt{\mathcal{I}} G$$

phase fluctuation in the arm

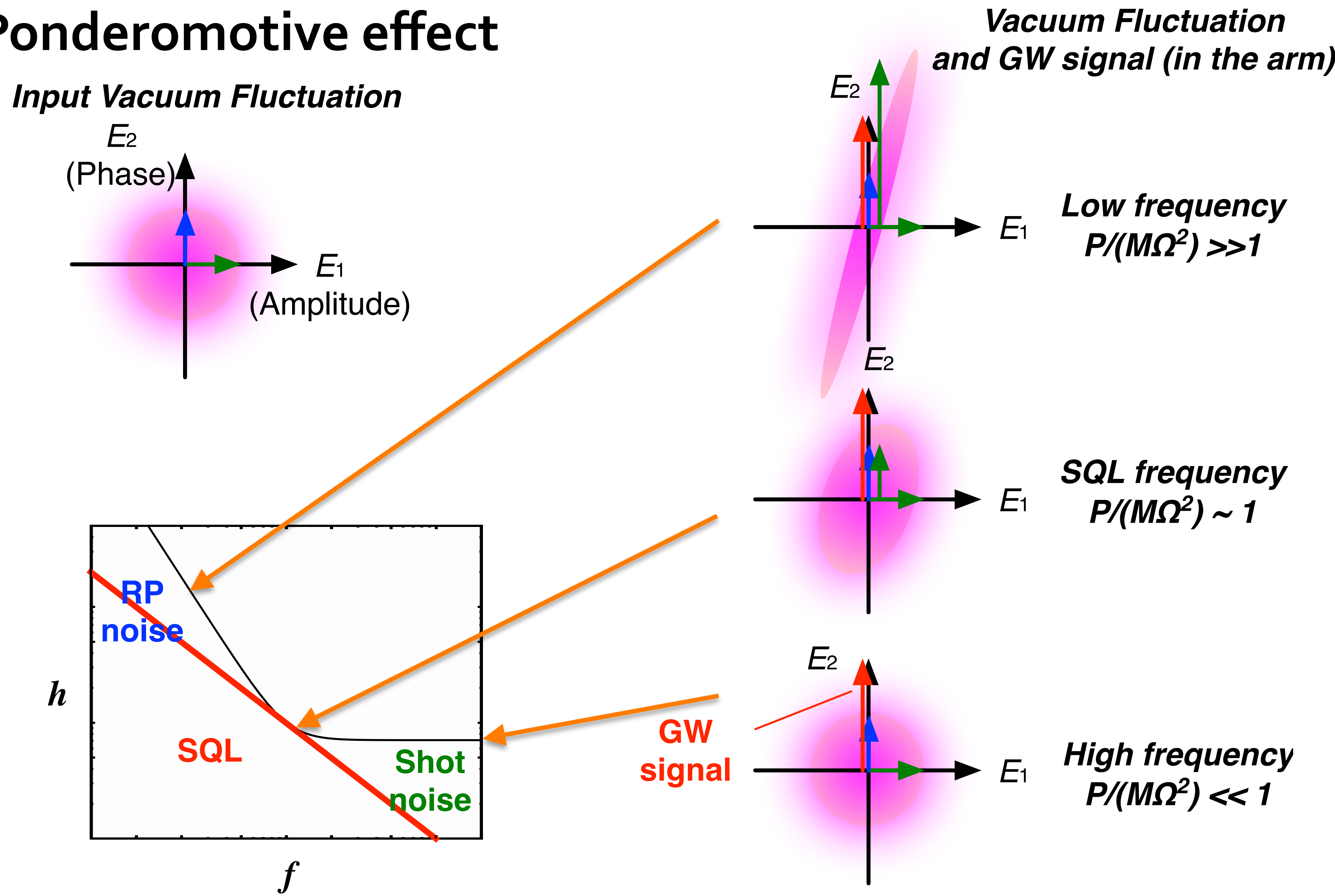
radiation pressure

GW signal



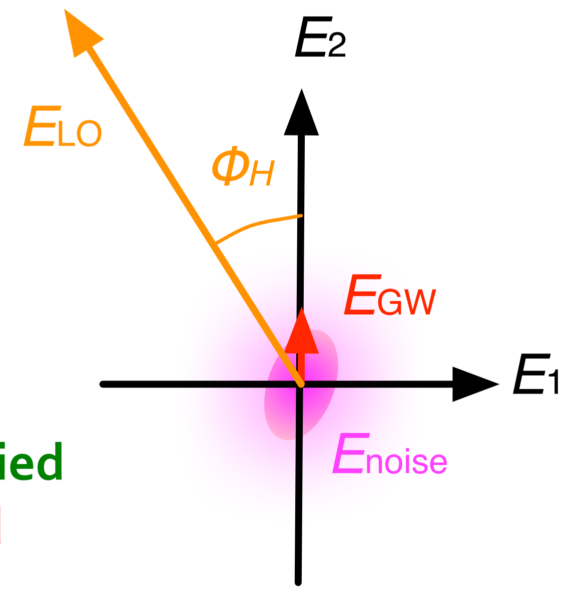
Quantum noise in an interferometer

- **Ponderomotive effect**



Quantum noise in an interferometer

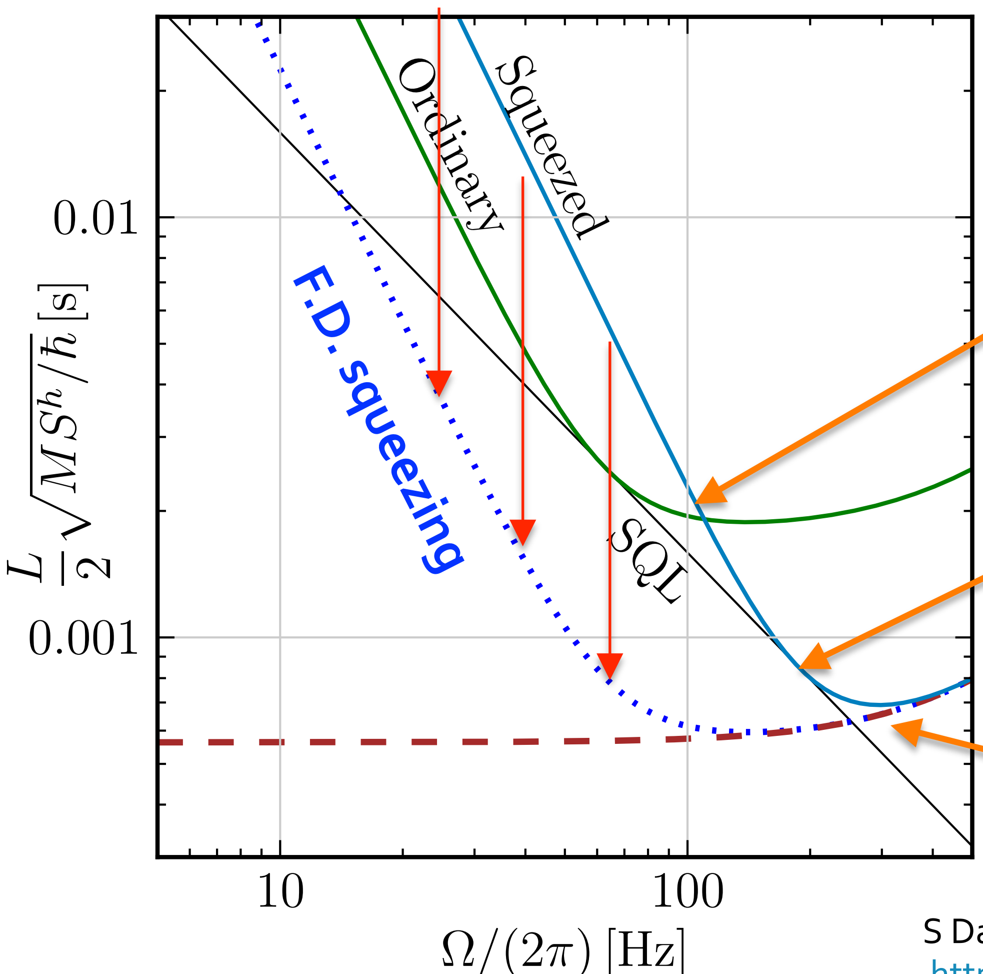
- **Homodyne detection**
  - In order to detect the signal (and noise) with a photodetector
    The output field needs to be mixed with a local oscillator field.
    cf. RF (or heterodyne) detection using RF sidebands

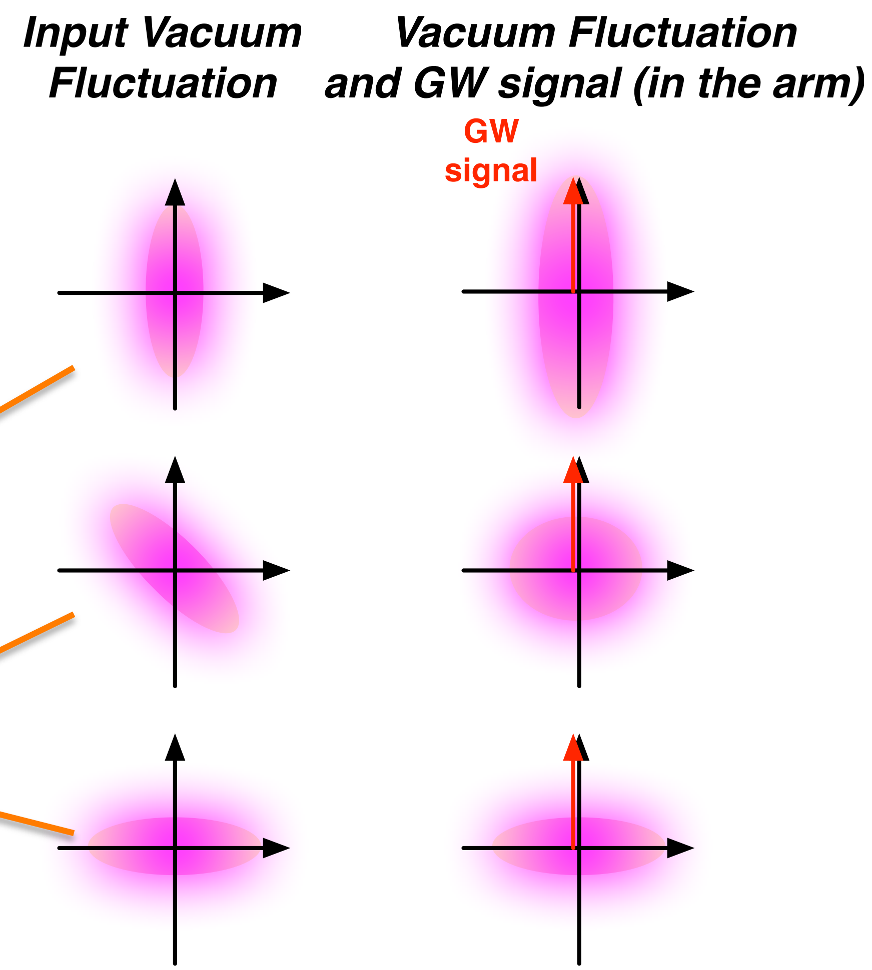


  - Homodyne angle:
    Changes the projection of the GW signal field
    and output noise fields into the detection signal
  - DC Readout
    A small (1~10pm) offset from the dark fringe is applied
    => Useful: The IFO beam itself becomes the LO field
    Φ_H is fixed at zero

Squeezed vacuum injection

- **Frequency dependent squeezing**
  - Rotate squeezing angle to optimize the output noise field



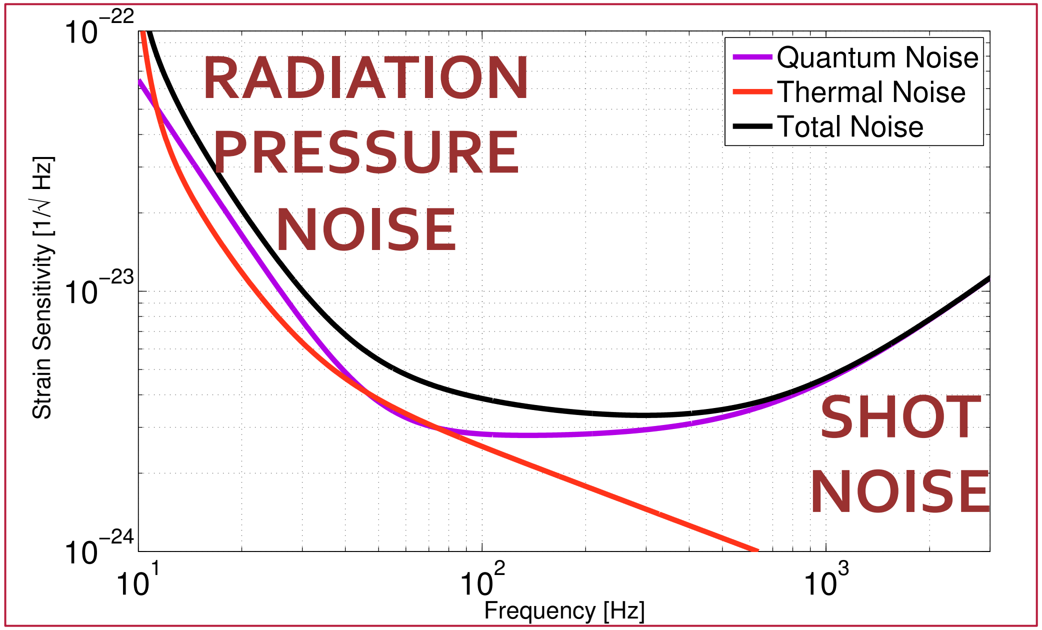


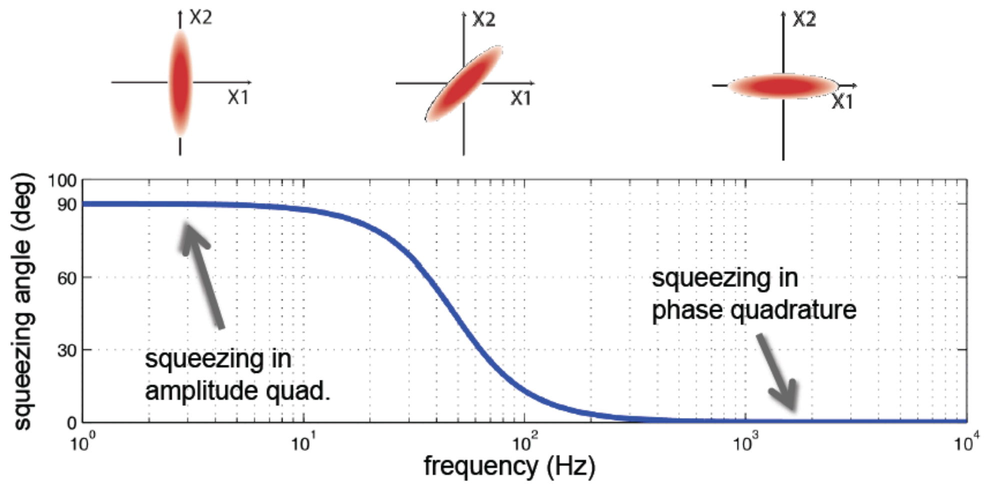
S Danilishin, F Khalili, Living Rev. Relativity, 15, (2012), 5
http://www.livingreviews.org/lrr- 2012- 5

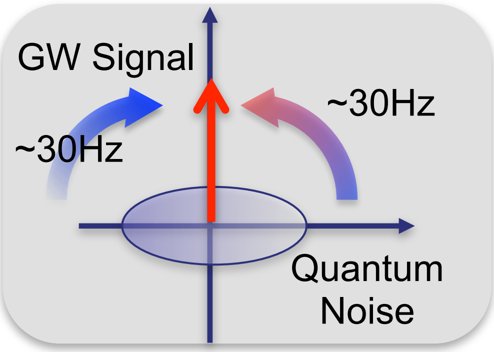
Squeezed vacuum injection

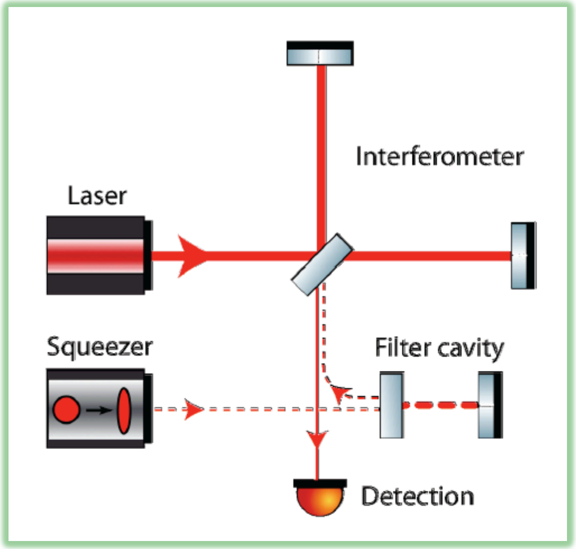
Slide courtesy of L. Barsotti

- **Frequency dependent squeezing**





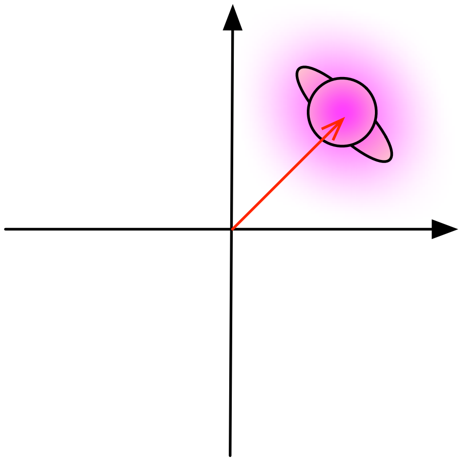




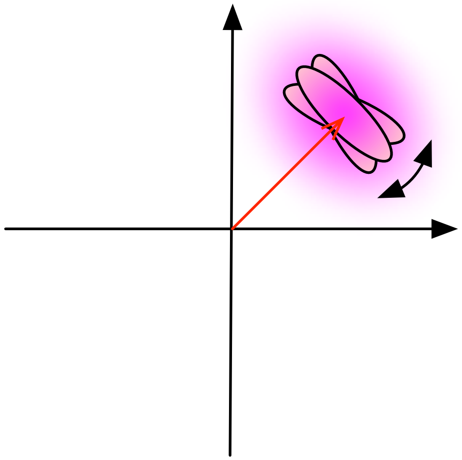
High finesse detuned **"filter cavity"** which rotates the squeezing angle as function of frequency

Squeezed vacuum injection: technical issues

- The enemies of the squeezing
  - Optical Loss
    Optical losses works as beamsplitters
    to introduce normal vacuum fluctuation

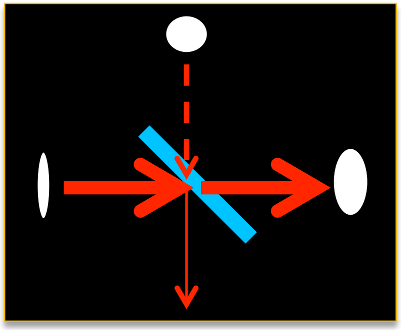


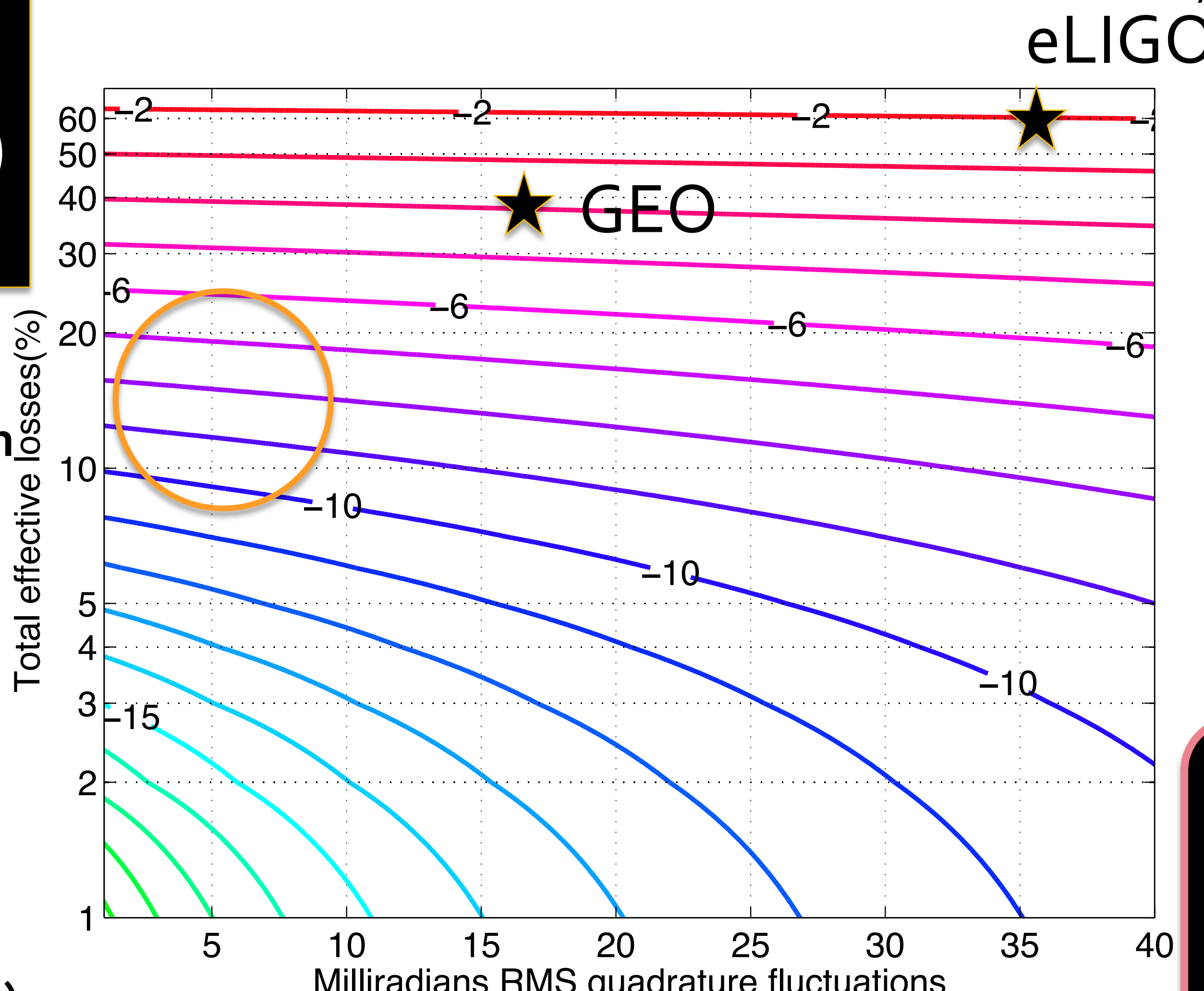
  - Phase noise
    Wobbling of the squeezing angle causes
    leakage of the other quadrature into the
    squeezed quadrature



Optical loss & Squeezing phase noise

Slide courtesy of L. Barsotti

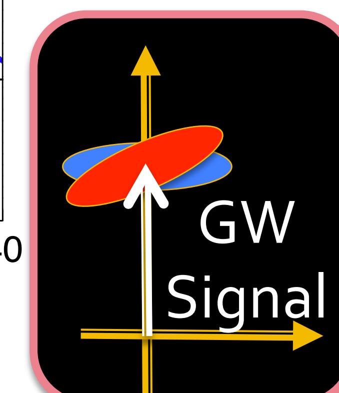




Target: -10dB noise reduction

We need less than 20% total losses

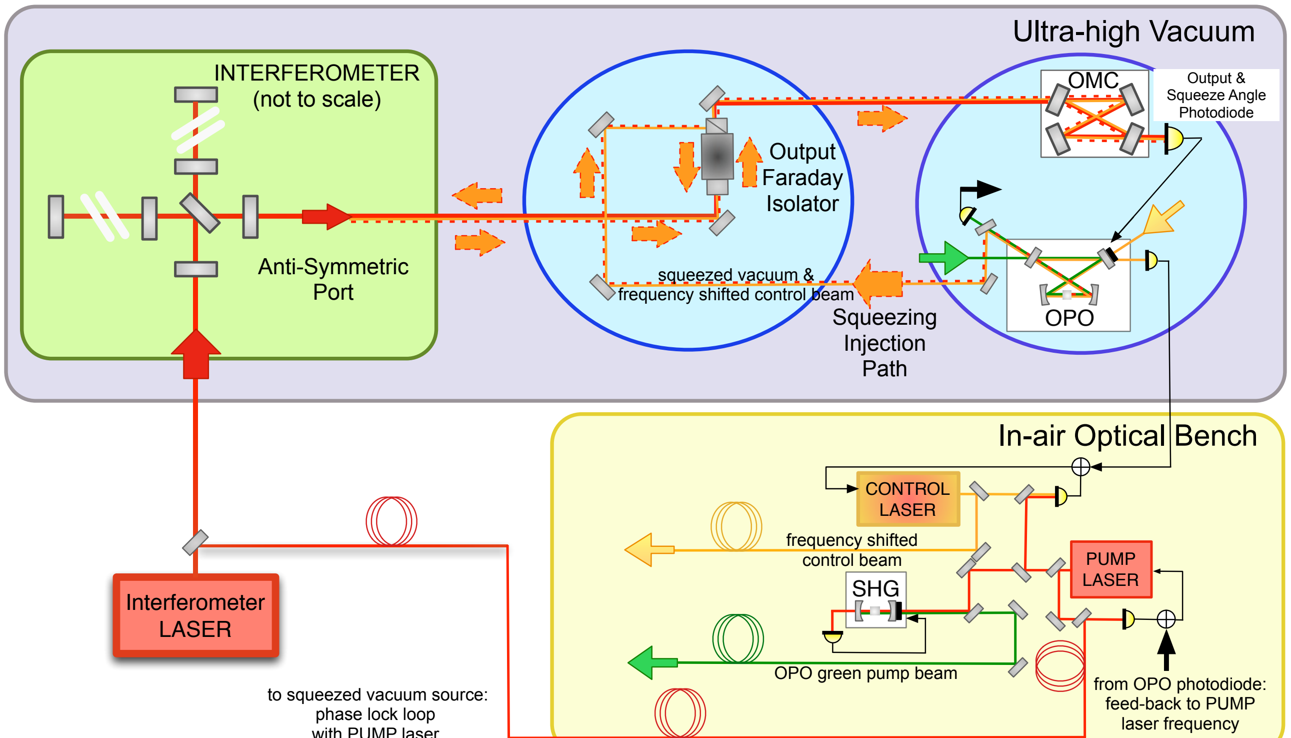
aLIGO readout now has ~30% (w/o squeezing) => Need to reduce!



Phase noise mitigation

Slide courtesy of L. Barsotti

- **Invac OPOfor aLIGO**



Let's move the **OPO into the vacuum envelope** on seismic isolated tables!

E. Oelker et al., Optics Express, Vol. 22, Issue 17, pp. 21106-21121 (2014) (P1400064)

Summary

- Quantom noise in GW detectors
  - Shot noise & Radiation pressure noise

- Squeezed vacuum injection
  - Shot noise reduction already demonstrated.

- Radiation pressure
  - Will eventually limit the sensitivity
  - Frequency Dependent squeezed vacuum injection will mitigate the radiation pressure noise

- Technical Issues: Optical loss & phase fluctuation
  - R&D on going