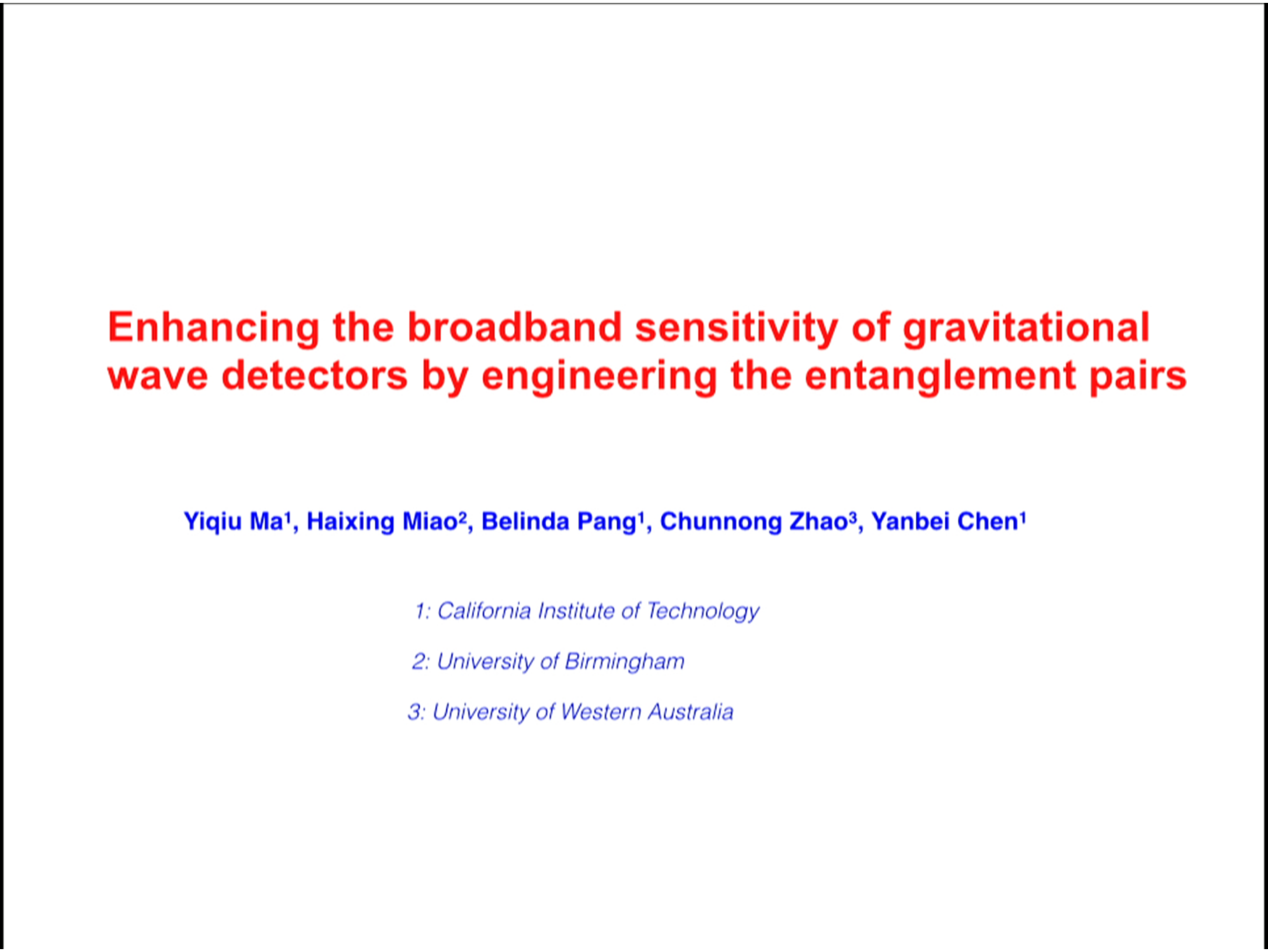
Title: Enhancing the broadband sensitivity of gravitational wave detectors by engineering the entanglement pairs

Date: Jun 23, 2016 01:00 PM

URL: http://pirsa.org/16060123

Abstract: <p>Improving the broadband quantum sensitivity of an advanced gravitational wave detector is one of the key steps for future updating of gravitational wave detectors. Reduction of the broadband quantum noise needs squeezed light with frequency dependent squeezing angle. Current designs for generating frequency dependent squeezed light are based on an ultra-high finesse filter cavity, therefore optical loss will serious contaminate the squeezed light. To circumvent this problem, we propose an new method for generating a frequency dependent squeezing of quantum noise field quadrature by engineering the quantum entangled field pairs which are filtered through the interferometer arm cavity. This new method may have the potential to beat the quantum noise by 7dB in recent future.</p>



Enhancing the broadband sensitivity of gravitational wave detectors by engineering the entanglement pairs

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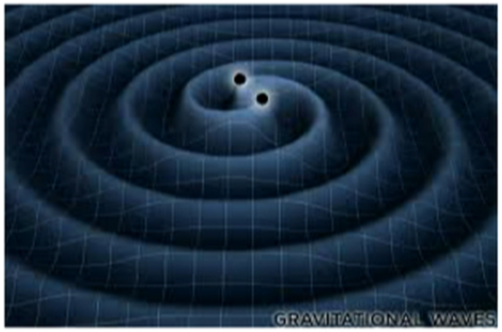
Gravitational Wave Detection



GWs carry unique information
about sources

GWs may allow further test of GR,
in strong curvature region

Km scale detectors around the world

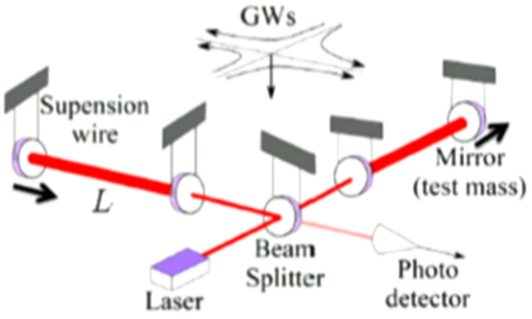

LIGO Hanford


LIGO Livingston


KAGRA Hida


VIRGO Pisa

Gravitational Wave Detection



Arm length $4km$

Mirror mass $40kg$

Target frequency $100 - 1000Hz$

Small motion:

Typical magnitude of strain: $h \sim \delta L/L \sim 10^{-22}$ Distant change: $10^{-19}m$

Current displacement sensitivity: $\Delta x \sim L\sqrt{S_{hh}\Delta f} \sim 10^{-19}m$

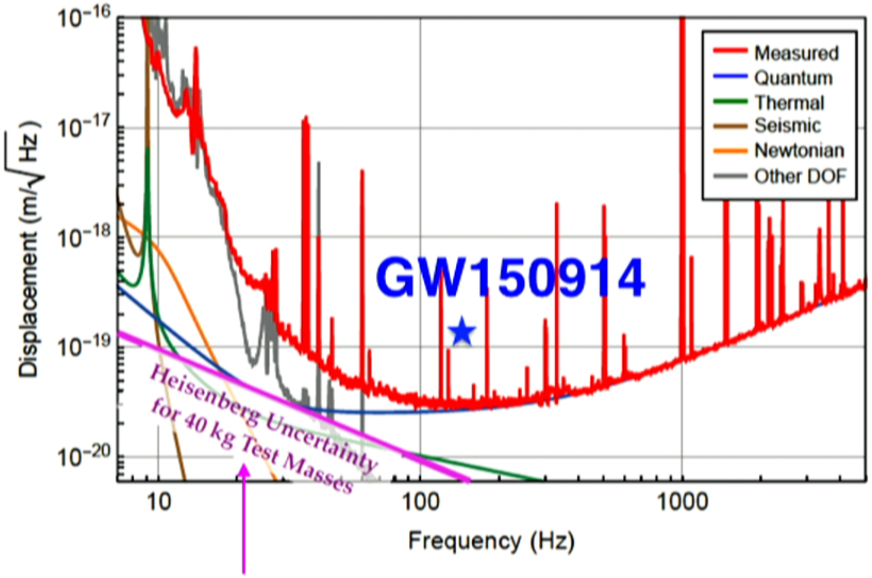
Quantumness :

"Heisenberg product" $\Delta x \Delta p \sim 2\pi m f \Delta x^2 \sim 2\hbar$

Mirror de-Broglie wavelength $\lambda_{\rm de} \sim \sqrt{\hbar/(2\pi m f)}|_{\rm 100Hz} \sim 10^{-19}m$

Sensitivity

$\frac{\text{noise}}{\text{signal}}$



This is also called "Standard Quantum Limit"

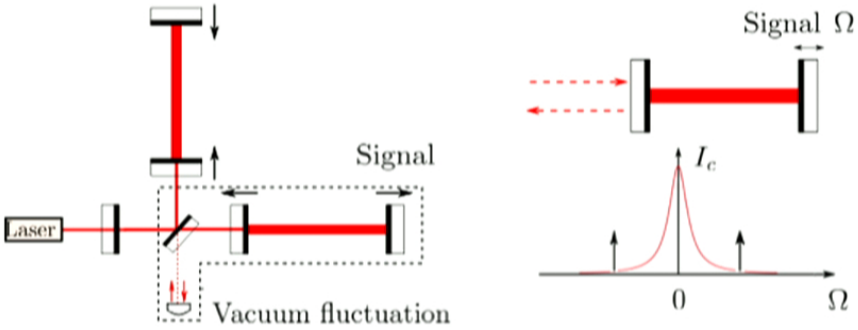
Further improvement of sensitivity (A+):

Reduce quantum noise: squeezing technique

Reduce thermal noise: bigger mirror, bigger laser beam size, better mirror coating

Quantum noise Limited Sensitivity

Signal



Resonance structure of F-P cavity

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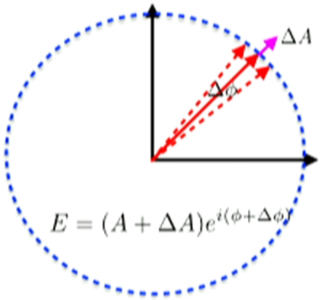
Signal amplitude decreases when Ω increases

Quantum noise Limited Sensitivity



Noise

Amplitude fluctuation

Photon number fluctuation: $\Delta N \sim \sqrt{N}$

➡ Radiation Pressure Noise

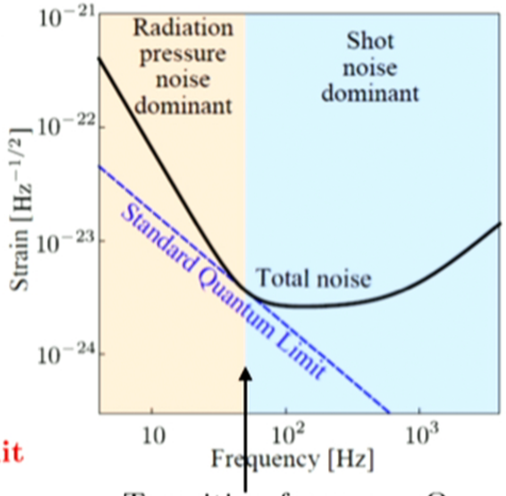
Number-Phase uncertainty relation:

$\Delta N \Delta\phi \sim 1 \rightarrow \Delta\phi \sim 1/\sqrt{N}$

➡ Shot Noise

Trade-off: **Standard Quantum Limit**

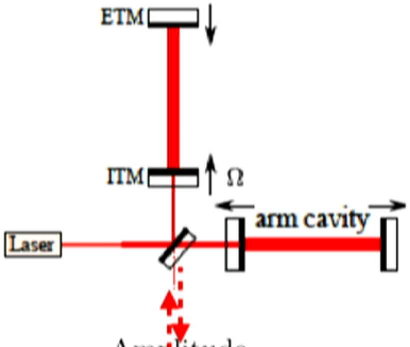
$$S_{\mathrm{hh}}^{\mathrm{SQL}}(\Omega) = \frac{8\hbar}{m\Omega^2 L^2}$$



Transition frequency Ω_q

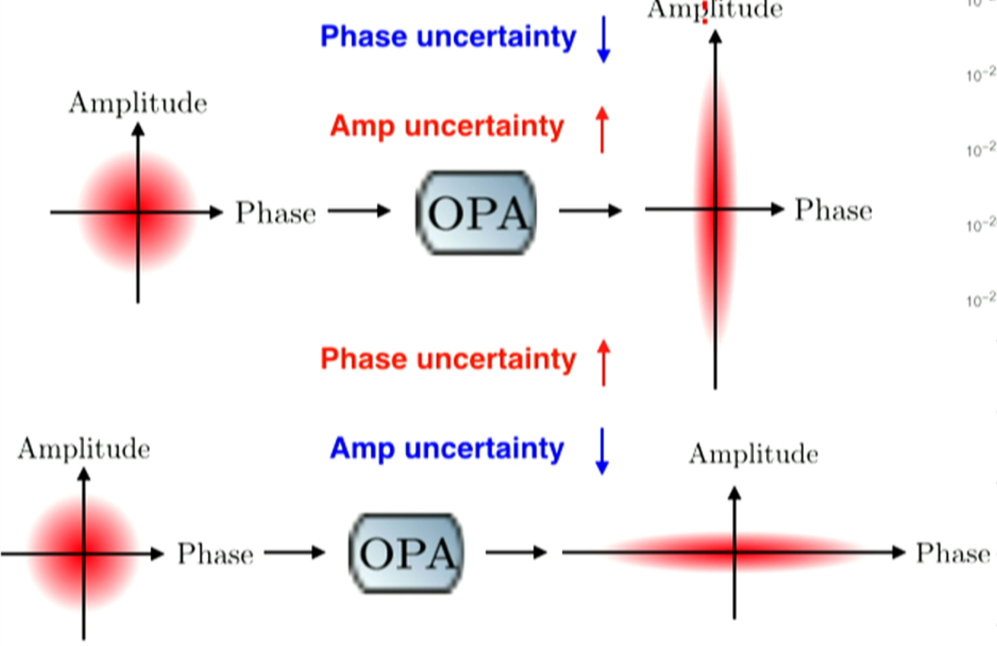
Improving the sensitivity: Redistributing the uncertainty

Carlton Caves



Can not have a broadband improvement !

Need a frequency dependent squeezing

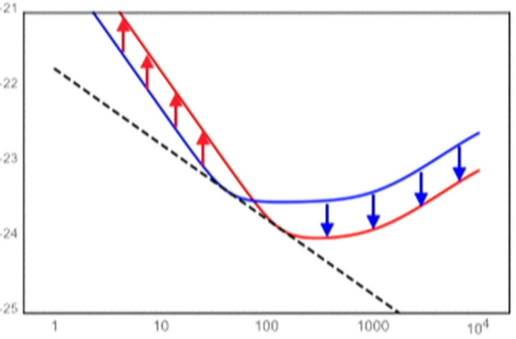


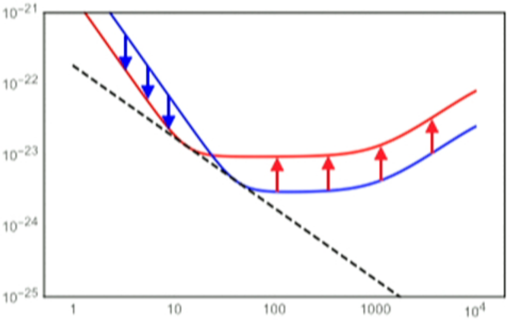
Phase uncertainty ↓

Amp uncertainty ↑

Phase uncertainty ↑

Amp uncertainty ↓

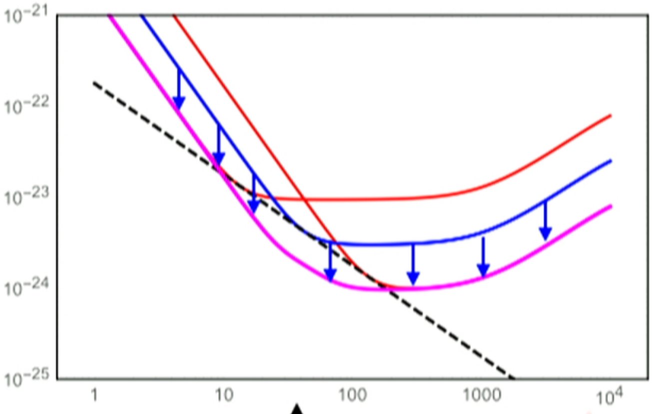




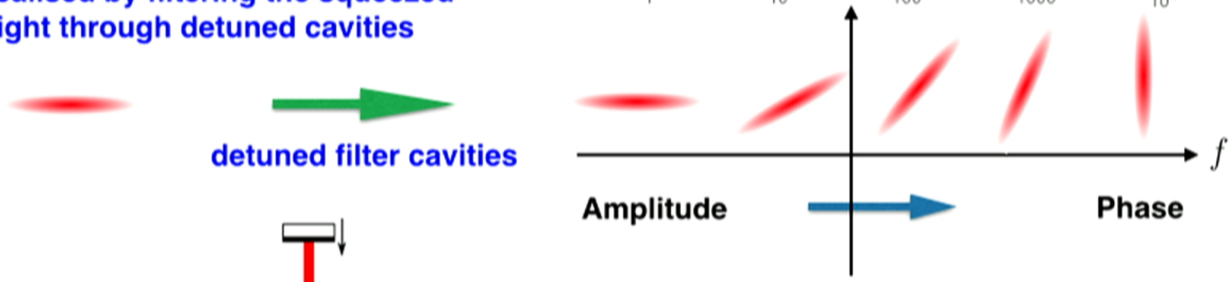
Improving the broadband sensitivity: rotate the field!

H J Kimble

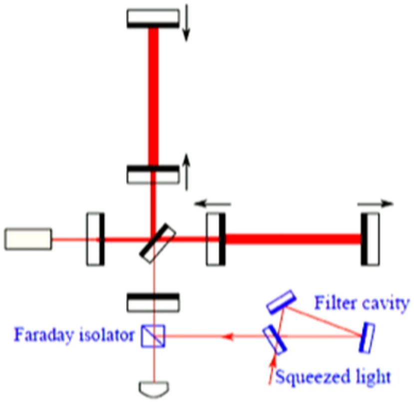
K S Thorne

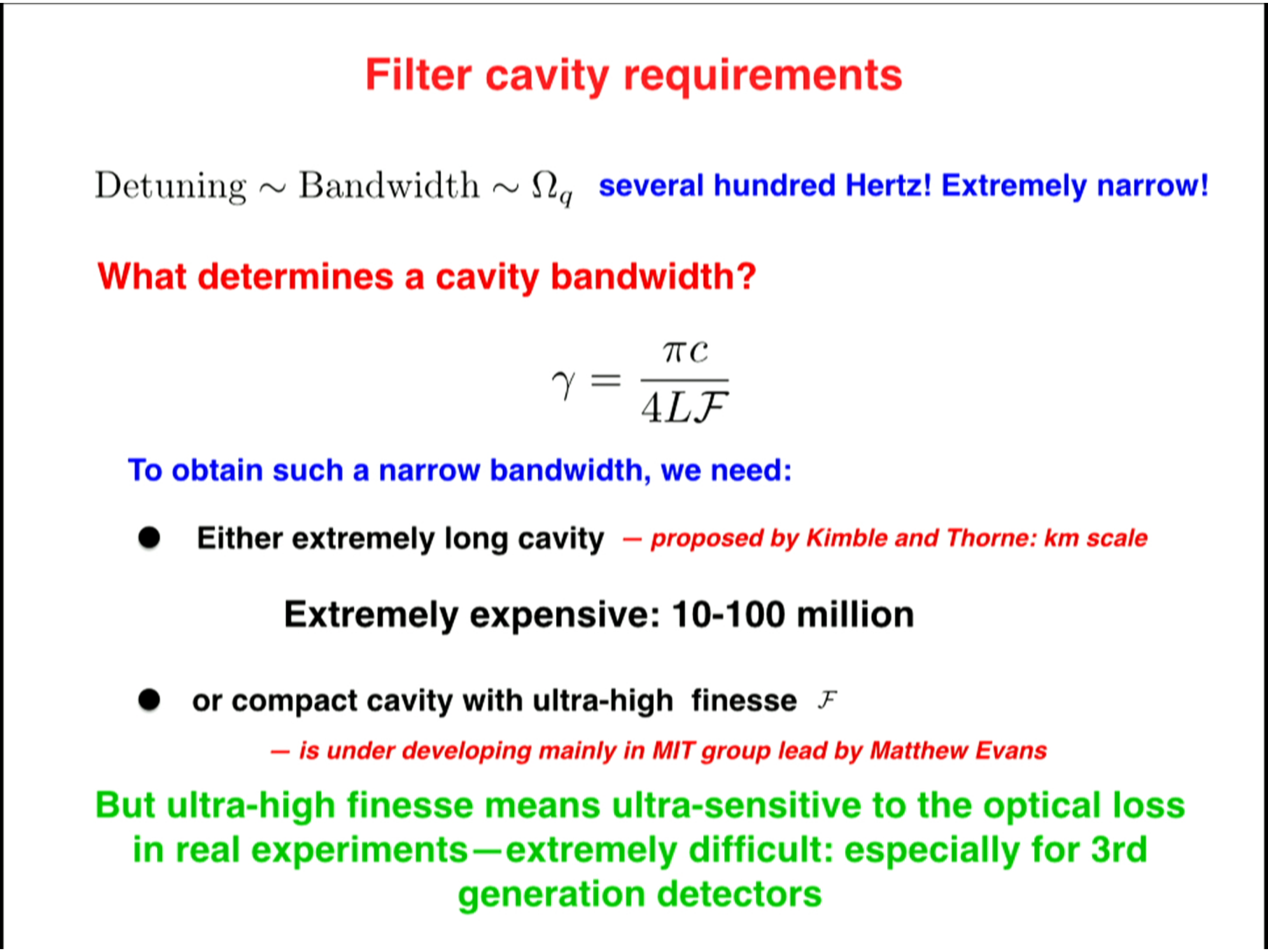


Frequency dependent rotation angle can be realised by filtering the squeezed light through detuned cavities



Transition frequency Ω_q





Filter cavity requirements

$\text{Detuning} \sim \text{Bandwidth} \sim \Omega_q$ **several hundred Hertz! Extremely narrow!**

What determines a cavity bandwidth?

$$\gamma = \frac{\pi c}{4L\mathcal{F}}$$

To obtain such a narrow bandwidth, we need:

- **Either extremely long cavity** ***— proposed by Kimble and Thorne: km scale***

Extremely expensive: 10-100 million

- **or compact cavity with ultra-high finesse** $\mathcal{F}$

— is under developing mainly in MIT group lead by Matthew Evans

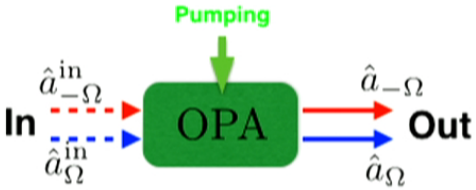
But ultra-high finesse means ultra-sensitive to the optical loss in real experiments—extremely difficult: especially for 3rd generation detectors

Could we use a simpler way to squeeze the noise in a broadband way?

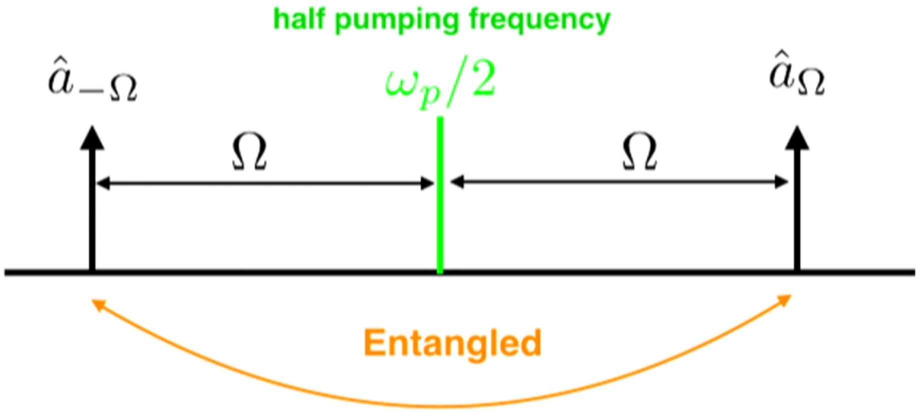
Our alternative proposal:

- ➡ ★ **“Conditional squeezing”**
- ➡ ★ **Arm cavity as filter cavity**

Traditional squeezing



For GW detector: Ω **audioband**



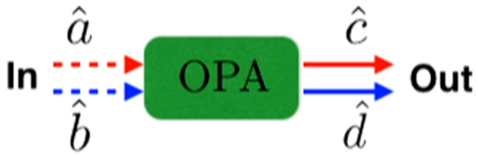
Squeezing $\hat{a}_1 = e^{r}\hat{a}_1^{\rm in}$

Anti-Squeezing $\hat{a}_2 = e^{-r}\hat{a}_2^{\rm in}$

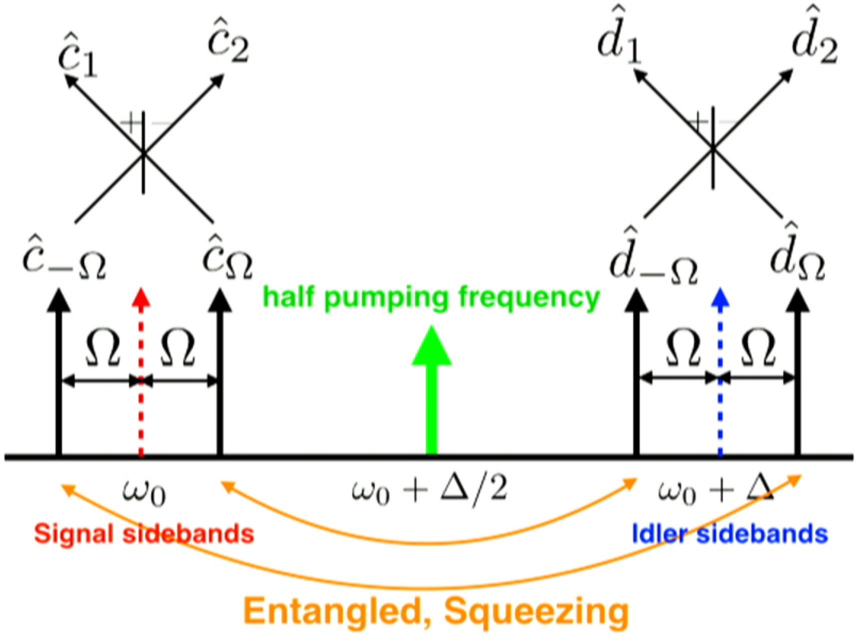
Phase $\hat{O}_1 = \frac{1}{\sqrt{2}}(\hat{O}_\Omega + \hat{O}^\dagger_{-\Omega})$

Amplitude $\hat{O}_2 = \frac{1}{\sqrt{2}i}(\hat{O}_\Omega - \hat{O}^\dagger_{-\Omega})$

Conditional squeezing: MHz band squeezer



$$\Omega/(2\pi) \sim \text{audioband}$$
$$\Delta/(2\pi) \sim \text{MHz}$$



Audioband sidebands

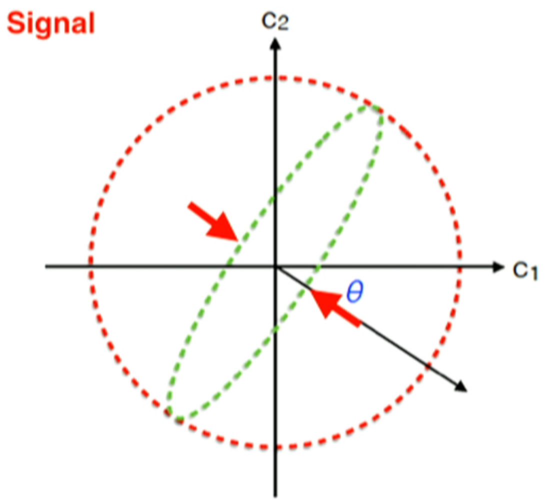
$$\begin{aligned} c_1 &= a_1 \cosh r + b_1 \sinh r \\ c_2 &= a_2 \cosh r - b_2 \sinh r \\ d_1 &= b_1 \cosh r + a_1 \sinh r \\ d_2 &= b_2 \cosh r - a_2 \sinh r \end{aligned}$$

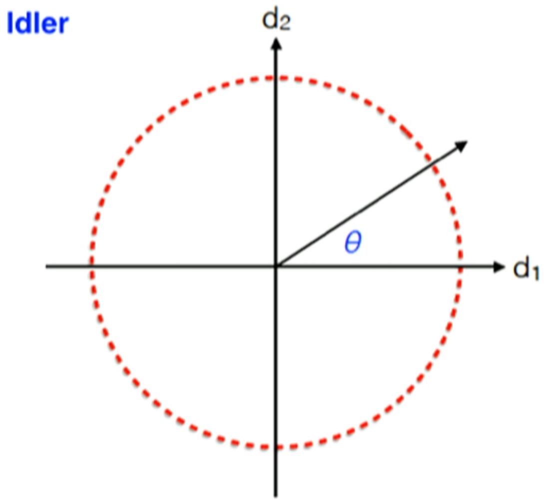
Measuring $\hat{d}_{1,2}$ can obtain information about $\hat{c}_{1,2}$

Conditional squeezing: Conditioning

Bearing in mind: last page:

$\hat{c}_1$ correlate with $\hat{d}_1$ in the same way as $\hat{c}_2$ correlate with $-\hat{d}_2$





can predict $c_{-\theta} = c_1\cos\theta - c_2\sin\theta$

after subtraction: conditionally squeezed!

$$S_{c_{-\theta}c_{-\theta}} = \frac{1}{\cosh 2r}\,,\quad S_{c_{\pi/2-\theta}c_{\pi/2-\theta}} = \cosh 2r$$

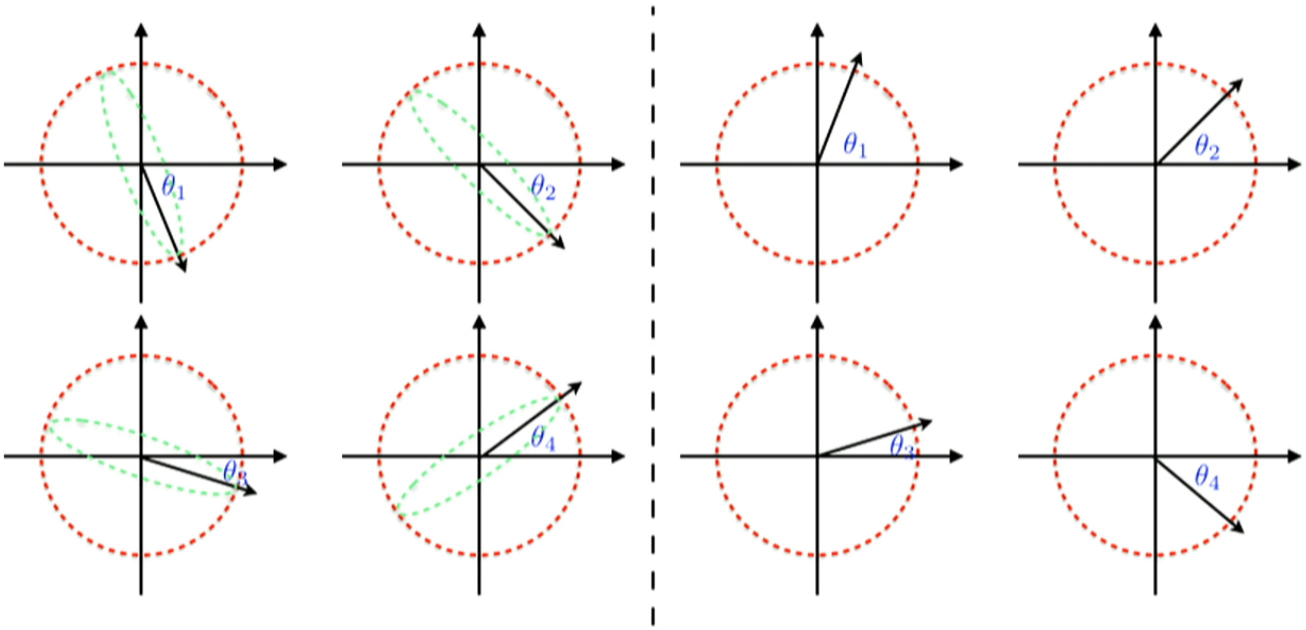
~3dB less than single squeezer

measuring $d_\theta = d_1\cos\theta + d_2\sin\theta$

★ **Measurement of entangled beam produces conditional squeezing**

Frequency Dependent Conditioning

Signal **Idler**



A frequency dependent measurement on d-quadrature

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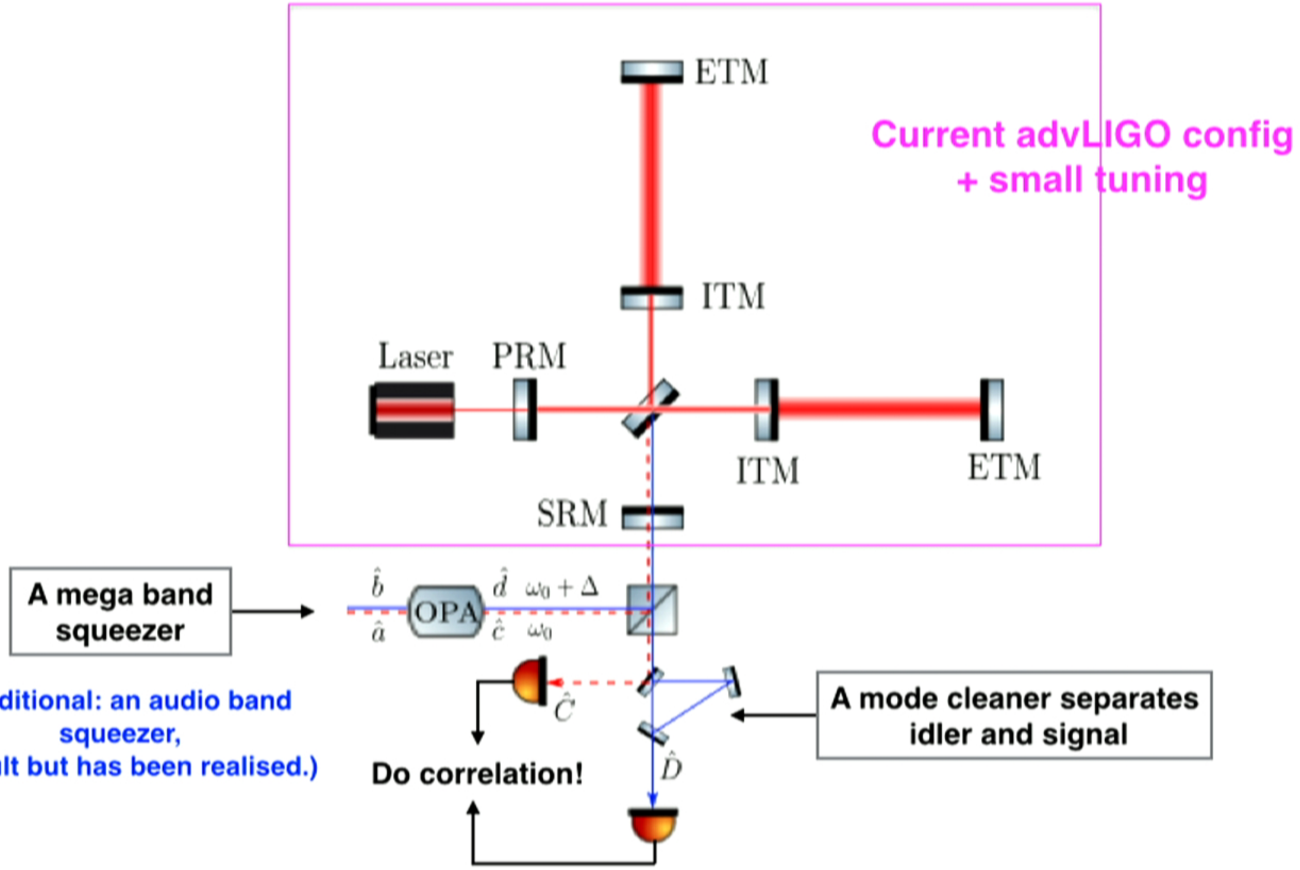
★ **A frequency dependent conditional squeezing of c-quadrature**

Proposed Configuration

KEY: Signal mode and idler mode
see different interferometer response



Current advLIGO config
+ small tuning

A mega band
squeezer

(Traditional: an audio band
squeezer,
difficult but has been realised.)

A mode cleaner separates
idler and signal

Do correlation!

Look into: Proposed Configuration

Effective cavities

Signal: the same as AdvLIGO: pondermotive interaction + GW

Signal recycling cavity is on-resonance

—high transmissivity—broadband

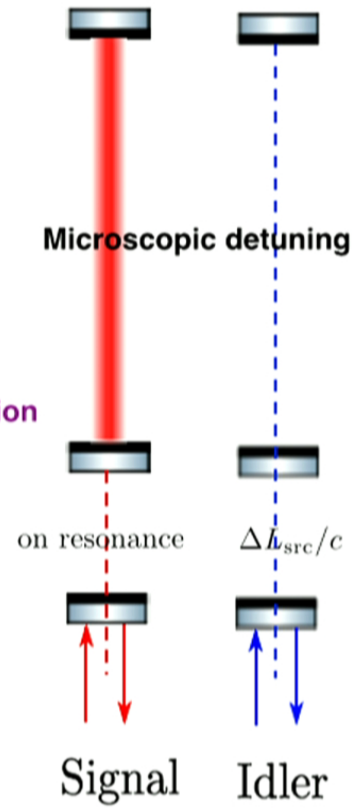
Idler: A rotation

Large detuning $\Delta \longrightarrow$ Does not participate in the pondermotive interaction

Does not carry GW

↓

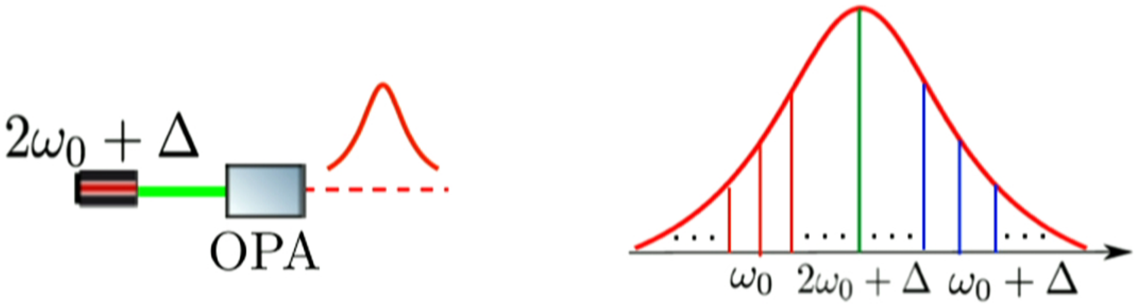
★ Feels that the interferometer is a filter cavity



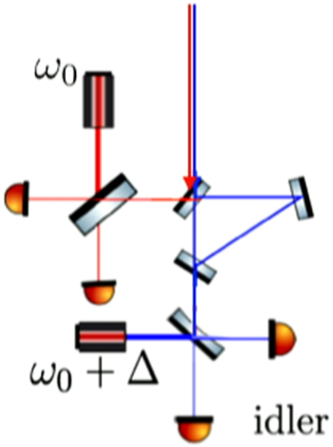
Look into: Proposed Configuration

Input and Readout

- What actually will be injected into the interferometer is a broadband field

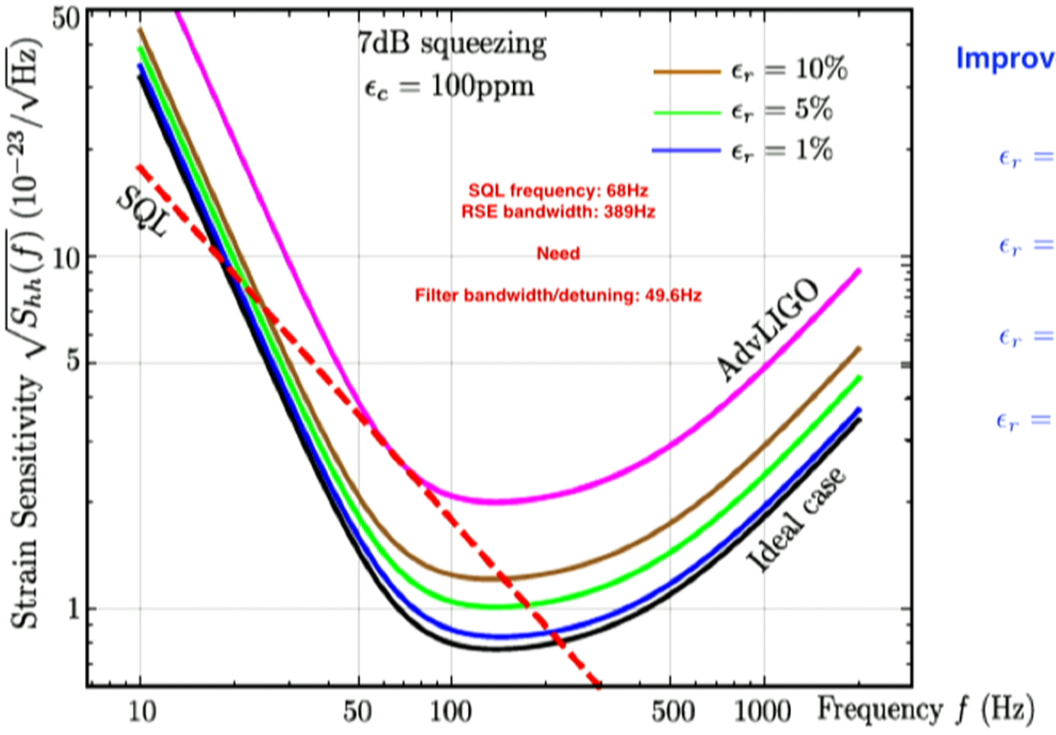


- We pick up the signal/idler fields with precise local oscillator



Theoretical Sample Sensitivity Curves

Including the loss



SQL frequency: 68Hz
RSE bandwidth: 389Hz

Need

Filter bandwidth/detuning: 49.6Hz

Improvement factor (Amp)

$\epsilon_r = 0\%$	2.25
$\epsilon_r = 1\%$	2.15
$\epsilon_r = 5\%$	1.82
$\epsilon_r = 10\%$	1.55

Proposed Configuration

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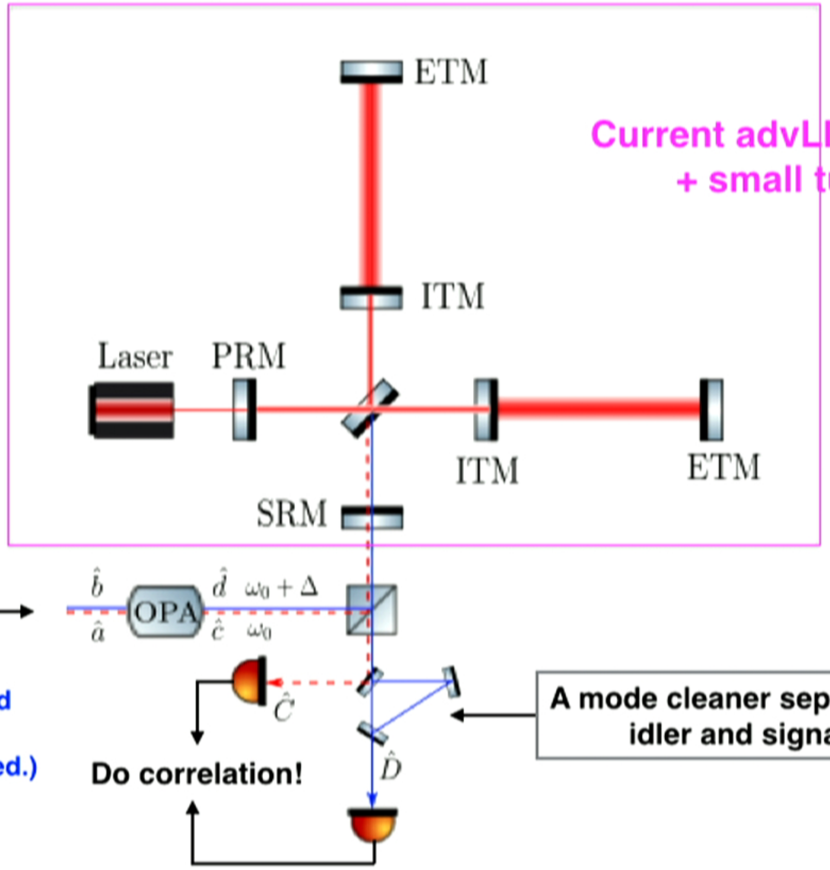

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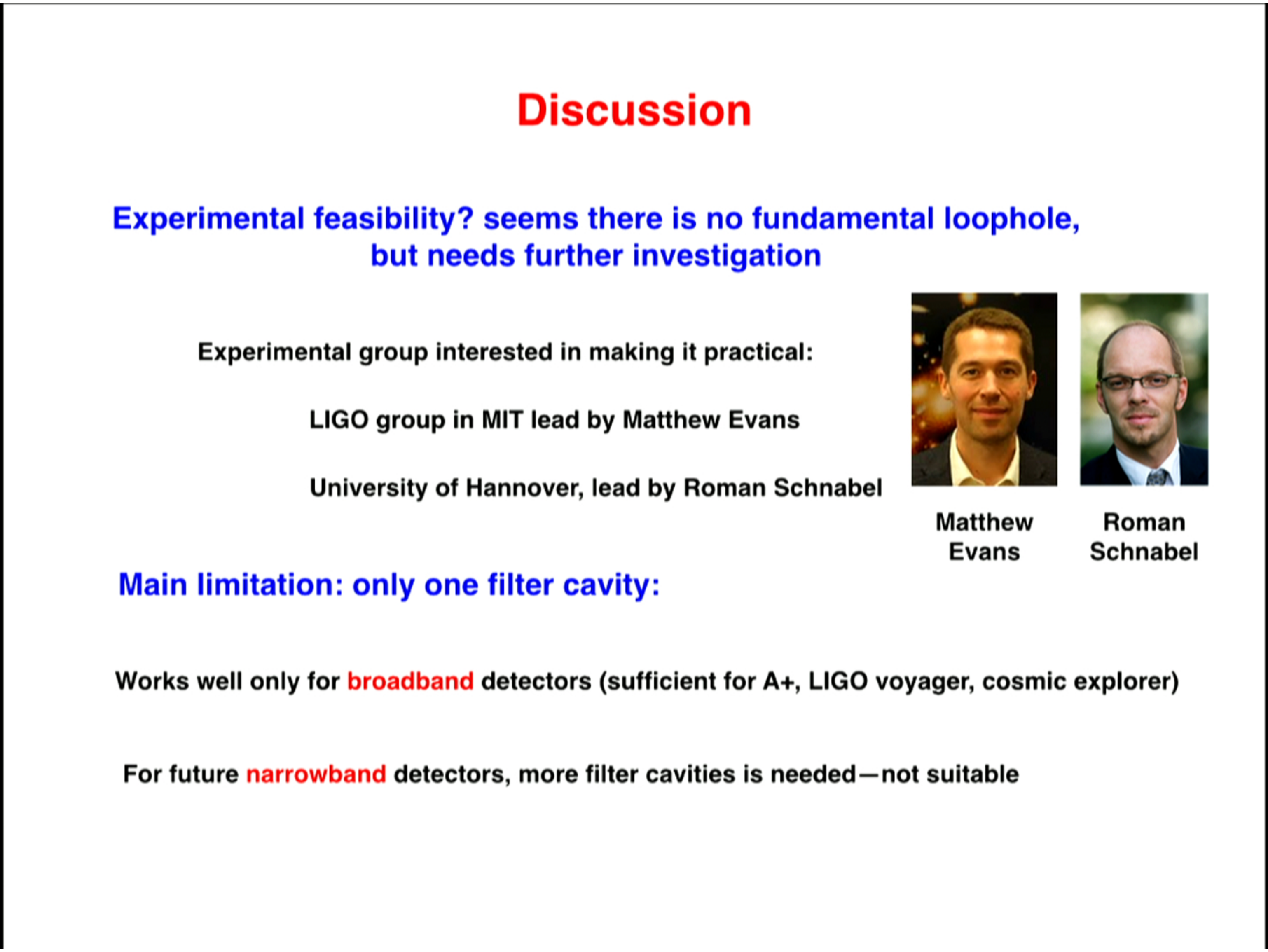


Discussion

Experimental feasibility? seems there is no fundamental loophole, but needs further investigation

Experimental group interested in making it practical:

LIGO group in MIT lead by Matthew Evans

University of Hannover, lead by Roman Schnabel

Matthew Evans

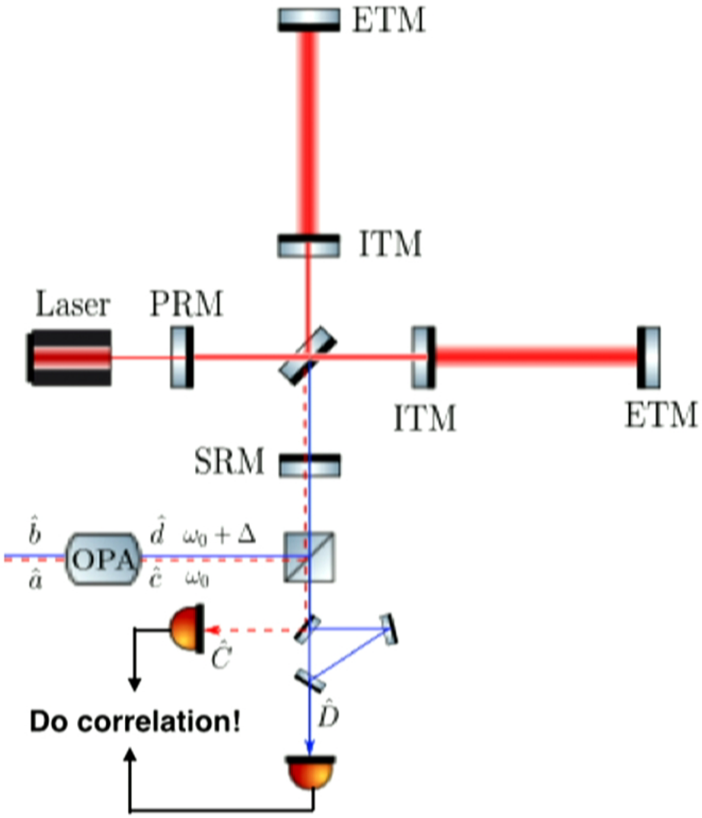
Roman Schnabel

Main limitation: only one filter cavity:

Works well only for broadband detectors (sufficient for A+, LIGO voyager, cosmic explorer)

For future narrowband detectors, more filter cavities is needed—not suitable

Summarise



Do correlation!

- MegaHertz squeezer produce entanglement pairs
- Arm cavity can be used as optical filter
- Conditional squeezing contributes quantum noise reduction
- A possible promising alternative approach