Squeezing in Resonantly Enhanced Axion-Photon Regeneration: Pushing the fundamental Limits

Vistas in Axion Physics
Seattle, April 2012

Guido Mueller
University of Florida

Squeezing in

[illegible]

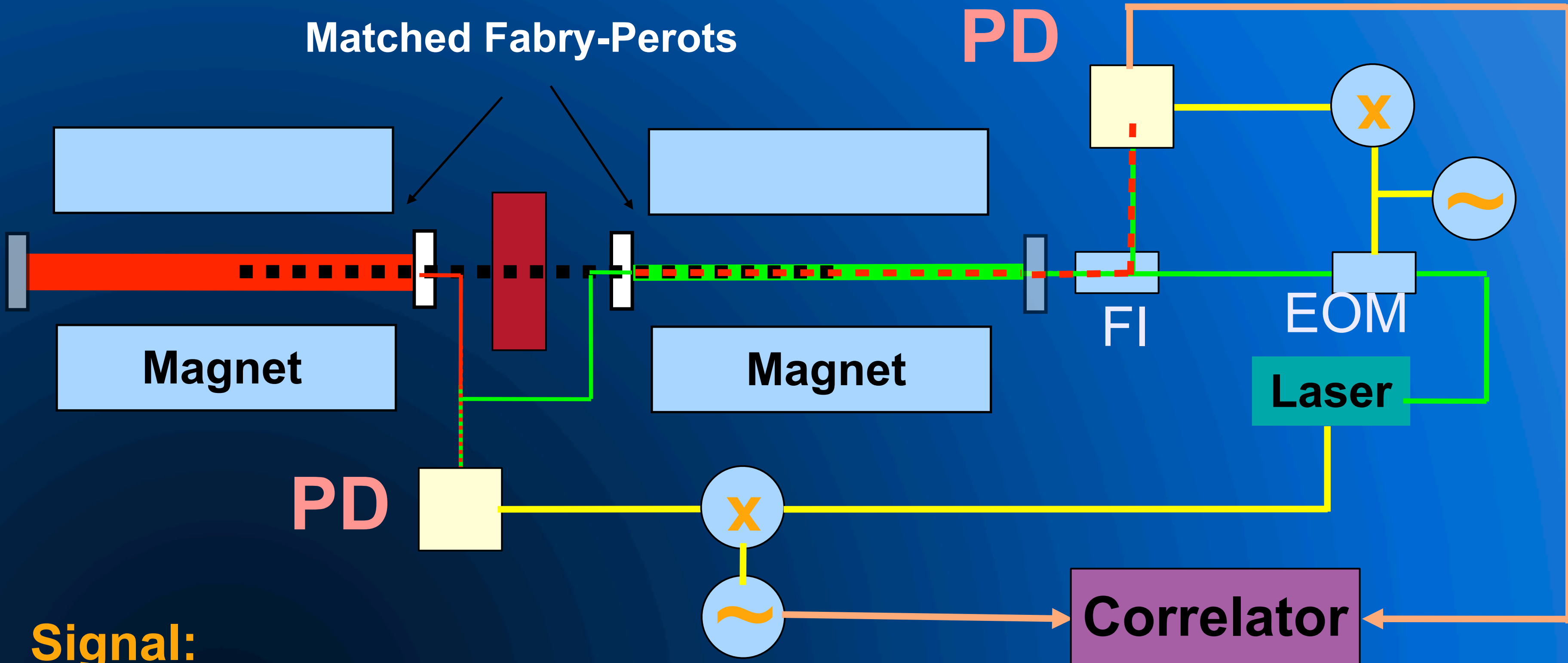
F[illegible]

This is very preliminary!!

Vistas in Axion Physics
Seattle, April 2012

Guido Mueller
University of Florida

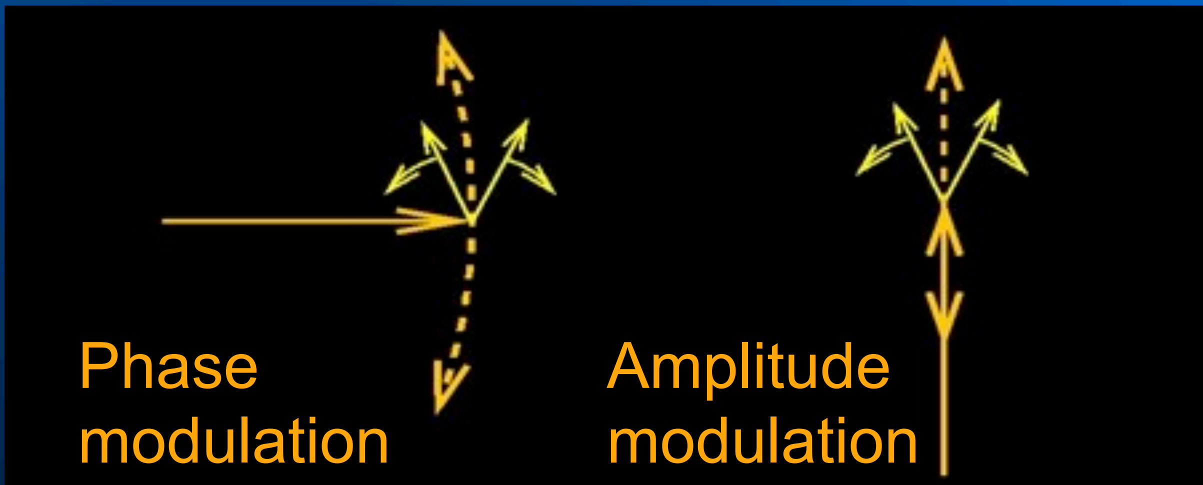
Experimental Setup



Signal:

- Beat signal between a laser field and the newly generated field
- Competes with amplitude modulation of the laser field

Excursion in PM/AM

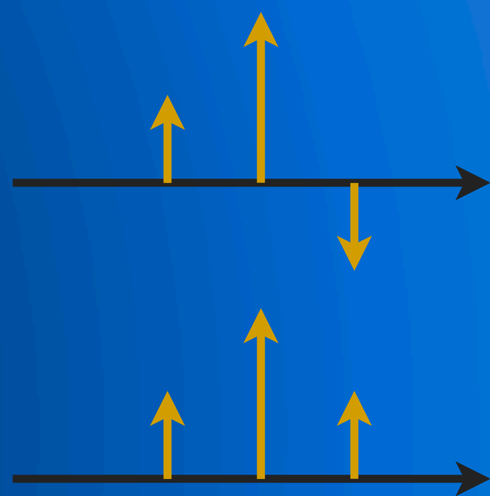


Phasor diagram:

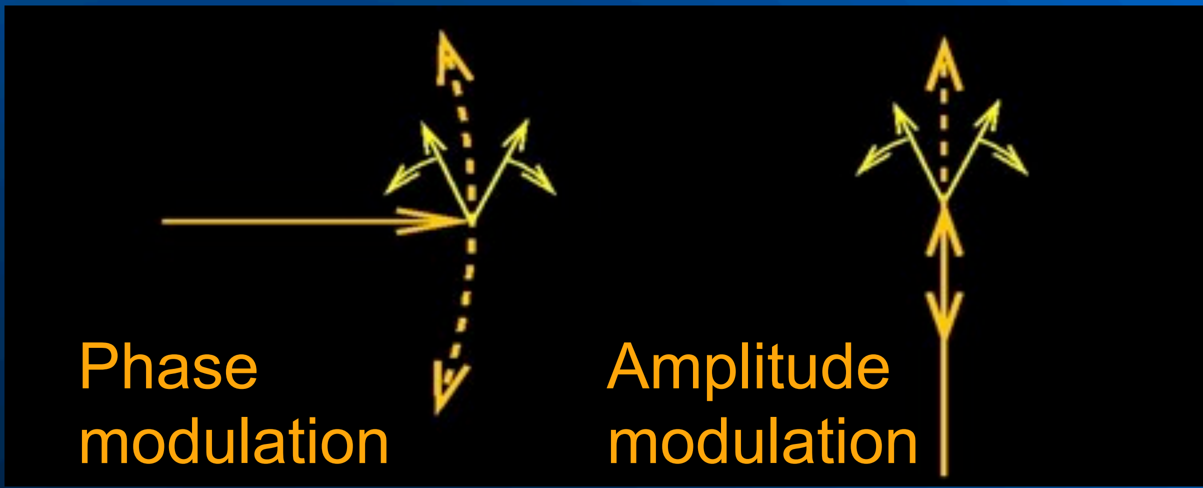
Difference betw. PM and AM:
90º phase shift in carrier or
180º between SB

$$E_{PM} = E_O \left(1 + m e^{i\Omega t} - m^* e^{-i\Omega t}\right) e^{i\omega t}$$

$$E_{AM} = E_O \left(1 + m e^{i\Omega t} + m^* e^{-i\Omega t}\right) e^{i\omega t}$$



Excursion in PM/AM



Phasor diagram

Both are super-positions of carrier and two sideband fields

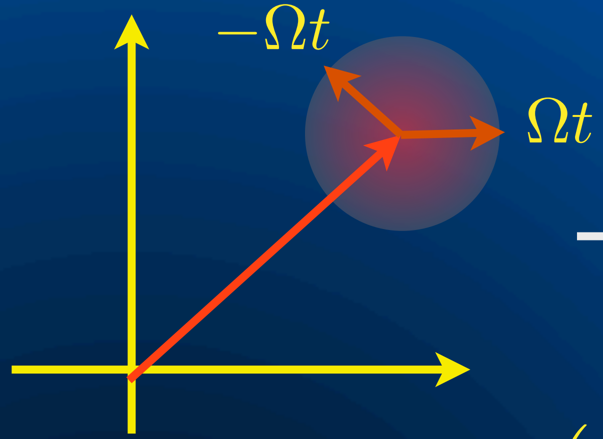
Phase modulation does not change length of phasor

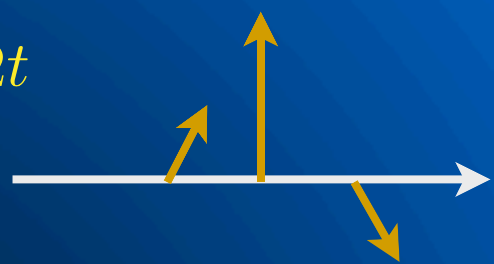
➡ Not detectable with photo detector

Amplitude modulation does change length of phasor

➡ Modulates photo current at modulation frequency

Vacuum Noise





'Vacuum fluctuations' at Ω and -Ω create AM and PM at Fourier frequency Ω on the field

$$E = \left(\sqrt{\bar{N}} + v_+ e^{i\Omega t} + v_- e^{-i\Omega t}\right) e^{i\omega t}$$

- Amplitude: Gaussian distr. with standard dev. √1/2
- Phase: Random between 0 and 2π

$$v_+ \approx \sqrt{\frac{1}{2}} e^{i\phi_+} \qquad v_- \approx \sqrt{\frac{1}{2}} e^{i\phi_-}$$

Signal vs. Noise

$$E = \left(\sqrt{\bar{N}} + \sqrt{\bar{n}}e^{i\Omega t} + v_+ e^{i\Omega t} + v_- e^{-i\Omega t}\right) e^{i\omega t}$$

Local Oscillator + Signal + Noise sidebands

Power at Ω $$P(\Omega) = Q\cos(\Omega t) + I\sin(\Omega t)$$

Expectation value/Signal: $$< Q >_{\phi_\pm} = 2\sqrt{\bar{N}\bar{n}}$$

Variance/Noise: $$< \Delta Q >_{\phi_\pm} = \sqrt{2\bar{N}}$$

$$\Big\} \quad SNR = \sqrt{2\bar{n}}$$

If signal phase is not known: $$< \Delta P >_{\phi_\pm} = 2\sqrt{\bar{N}} \quad \Rightarrow \quad SNR = \sqrt{\bar{n}}$$

Signal vs. Noise

$$E = \left(\sqrt{\bar{N}} + \sqrt{\bar{n}}e^{i\Omega t} + v_+ e^{i\Omega t} + v_- e^{-i\Omega t}\right) e^{i\omega t}$$

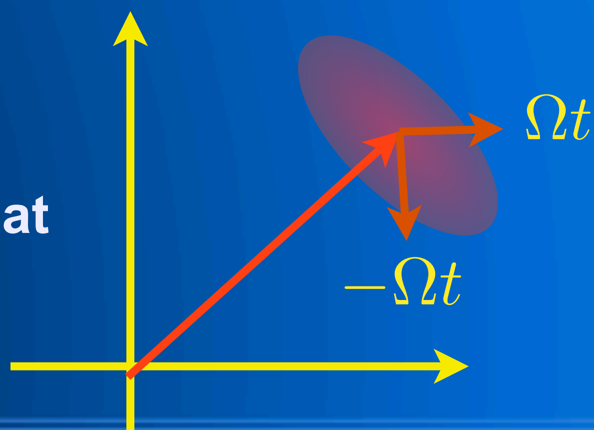
Local Oscillator + Signal + Noise sidebands

Interpretation:

- **Uncorrelated vacuum fluctuations modulate amplitude at Ω**

Solution:

- **As we can't turn them off, correlate them**
  - **Will increase phase noise in field**
    - **But we should be insensitive to that (Details: TBC)**



The QO picture

Two mode squeezing operator:

$$|\zeta >_2 = \hat{S}_2(\zeta)|0,0> = exp\left[\left(\zeta^* \hat{v}_+ \hat{v}_- - \zeta \hat{v}_+^\dagger \hat{v}_-^\dagger\right)\right]|0,0>$$

generates ‘photons’ in pairs (sort off ...)

Non-linear Optics process: $\vec{P} = \chi_2 E^2$

Optical parametric oscillator (OPO):

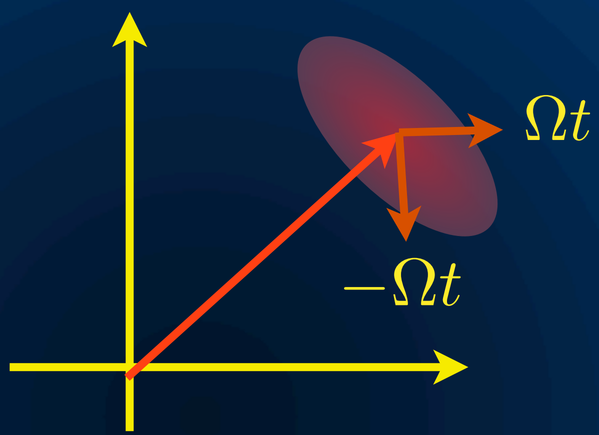
$$\nu = \nu_+ + \nu_-$$

The QO picture

Two mode squeezing operator:

$$|\zeta >_2 = \hat{S}_2(\zeta)|0,0> = exp\left[\left(\zeta^* \hat{v}_+ \hat{v}_- - \zeta \hat{v}_+^\dagger \hat{v}_-^\dagger\right)\right]|0,0>$$

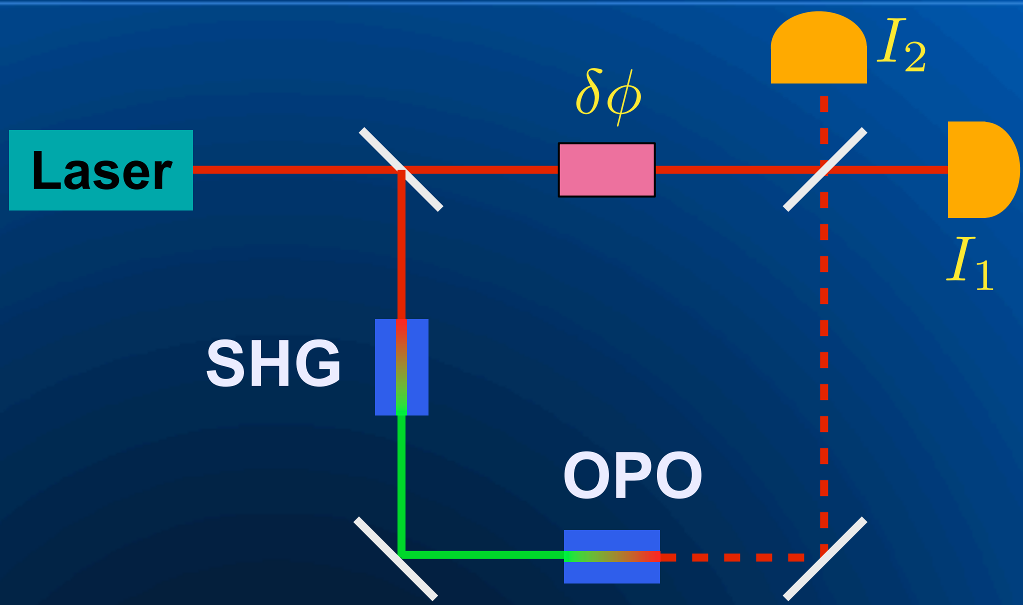
generates 'photons' in pairs (sort off ...)

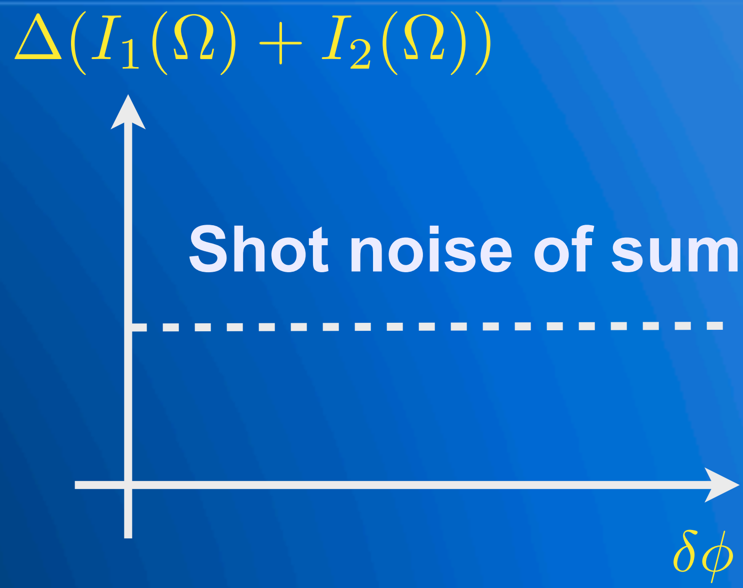


Operate OPO below threshold:

- No photons generated
- Correlates vacuum fluctuations
  - Oscillating Polarization inside OPO couples phases of both fields

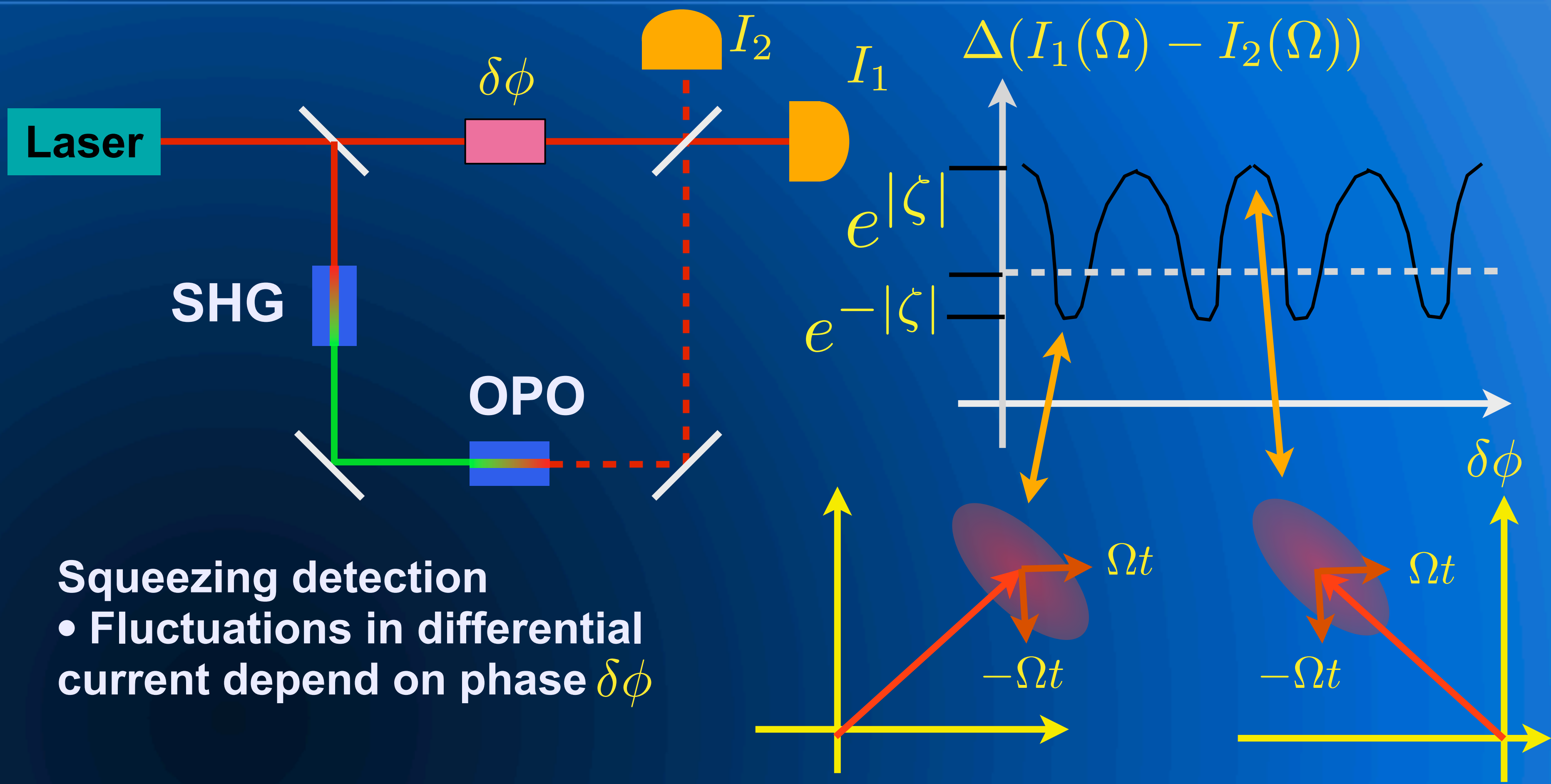
Typical Setup





- Sum senses vacuum from ‘bright port’
  - Not sensitive to squeezed light

Typical Setup



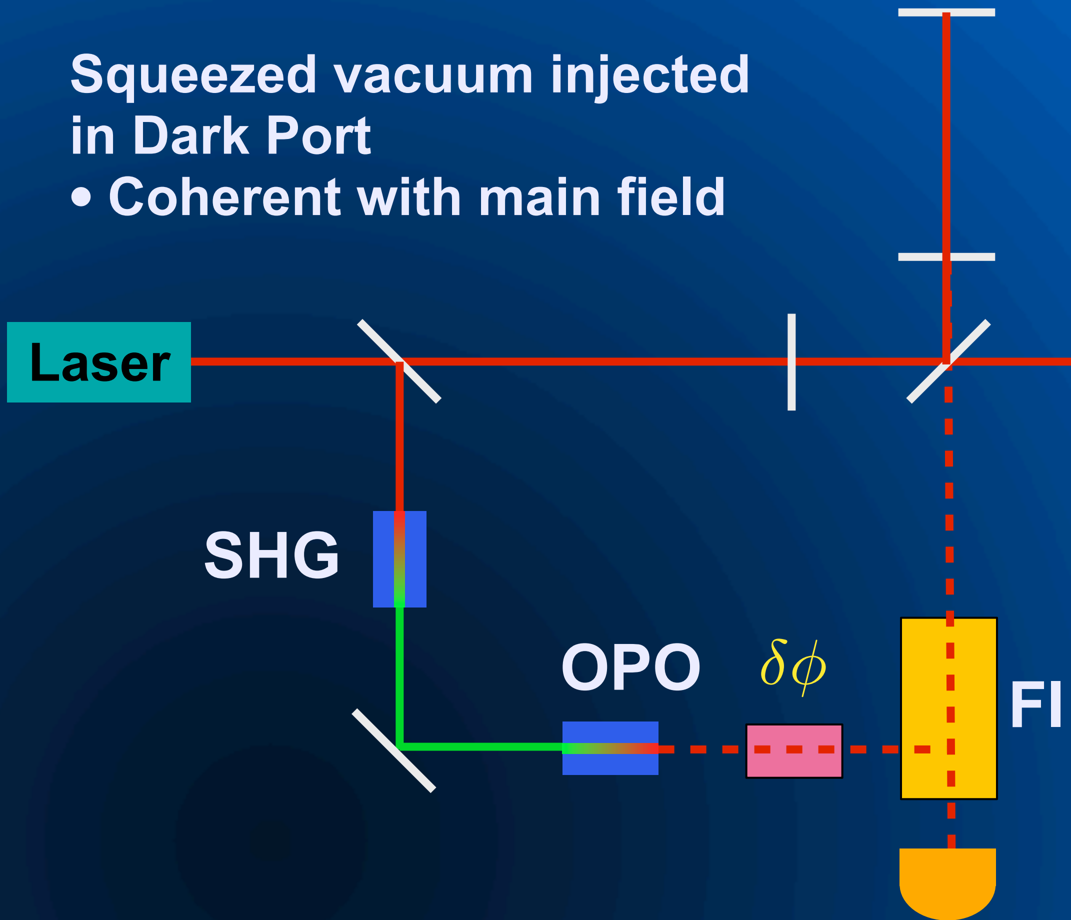
Squeezing detection

- **Fluctuations in differential current depend on phase** $\delta\phi$

In LIGO

Squeezed vacuum injected in Dark Port
- Coherent with main field

GEO 600 & LIGO has seen ~2-3 dB noise reduction above ~150 Hz
See for example:
Nature Physics 7, 962–965 (2011)

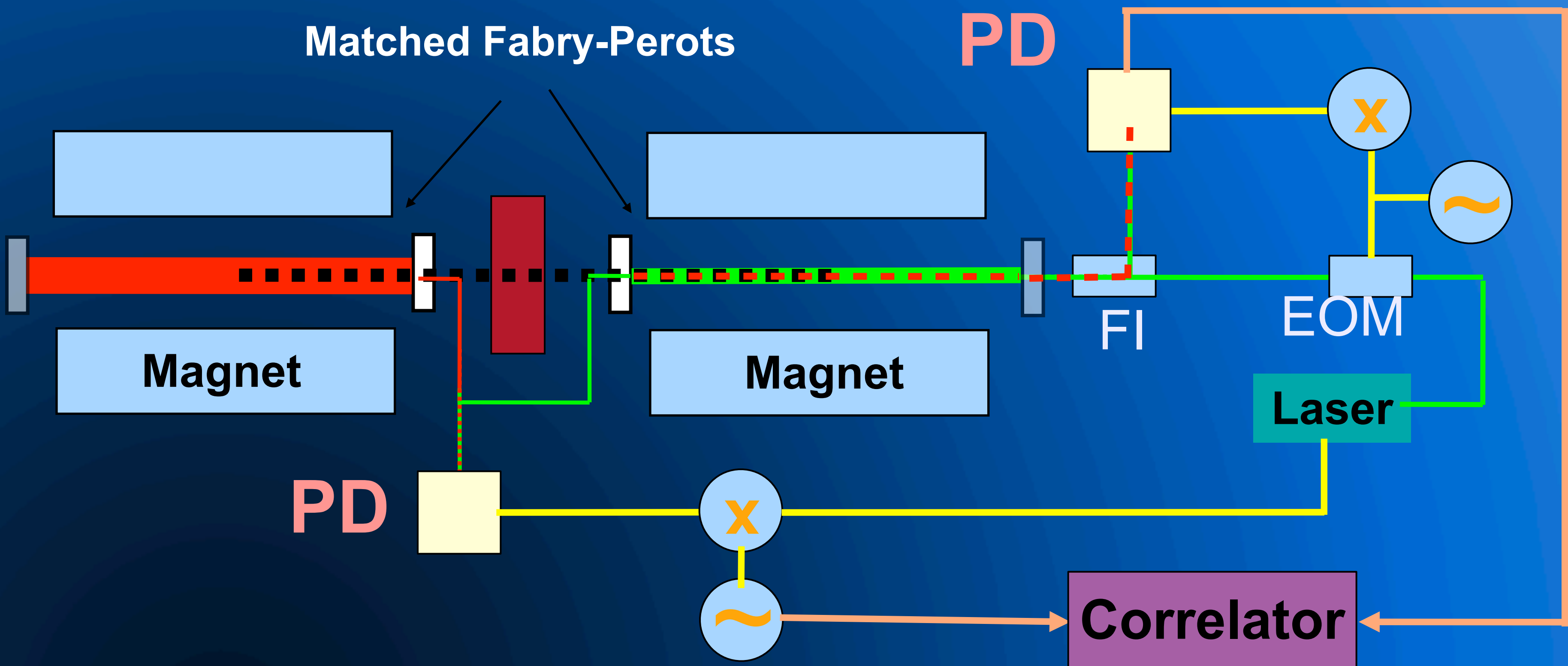


Reduces

- differential radiation pressure noise or
- differential phase noise (shot noise in read out)

depending on phase

Our Experimental Setup

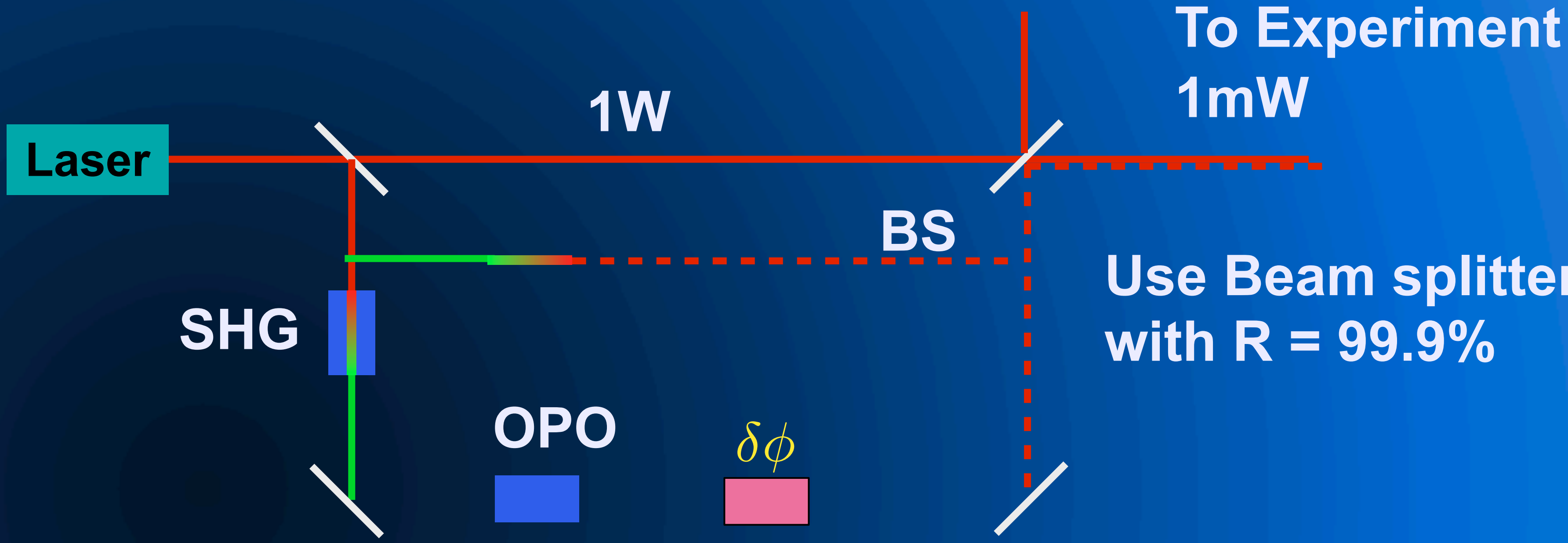


- How can we inject squeezed vacuum??

Squeezing vs. Losses

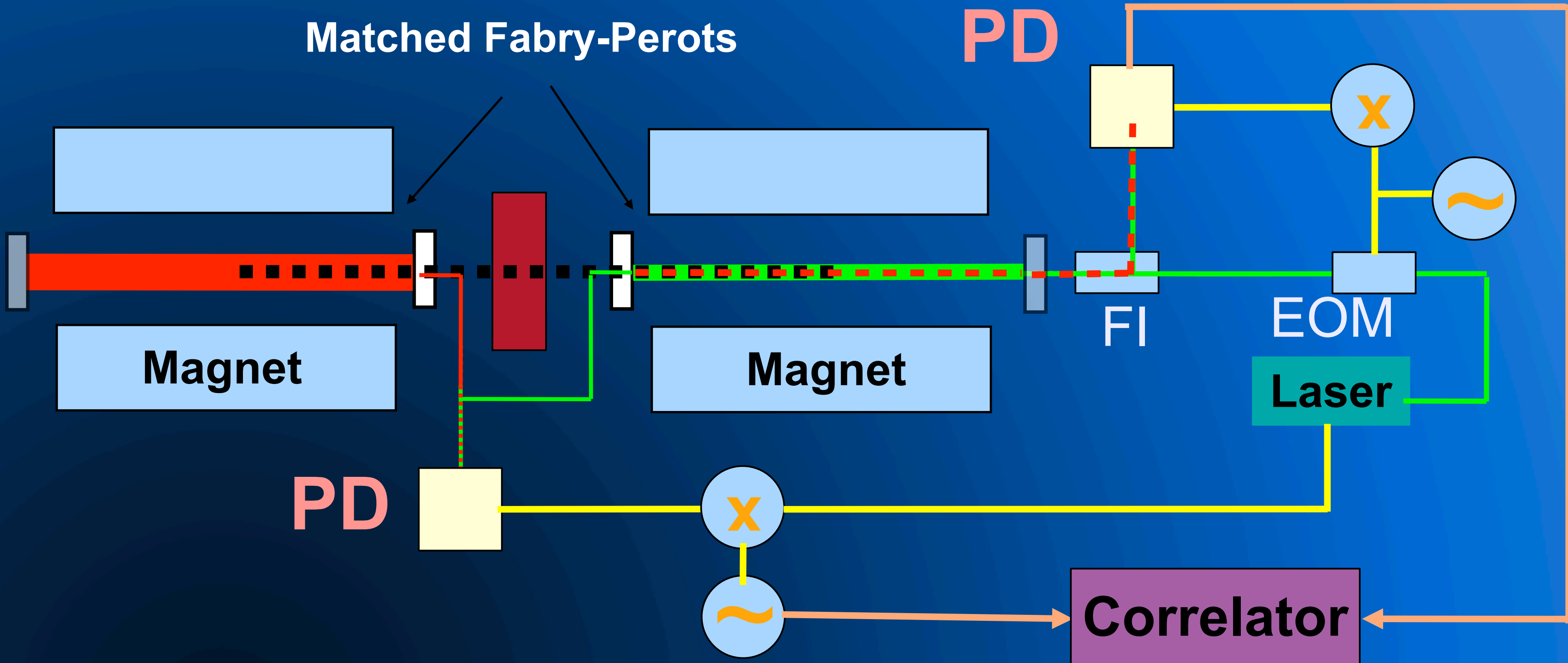
$$\sqrt{< (\Delta X_1)^2 >} = \frac{\sqrt{(1-L)}}{2} e^{-|\zeta|} + \frac{\sqrt{L}}{2}$$

L: Power loss



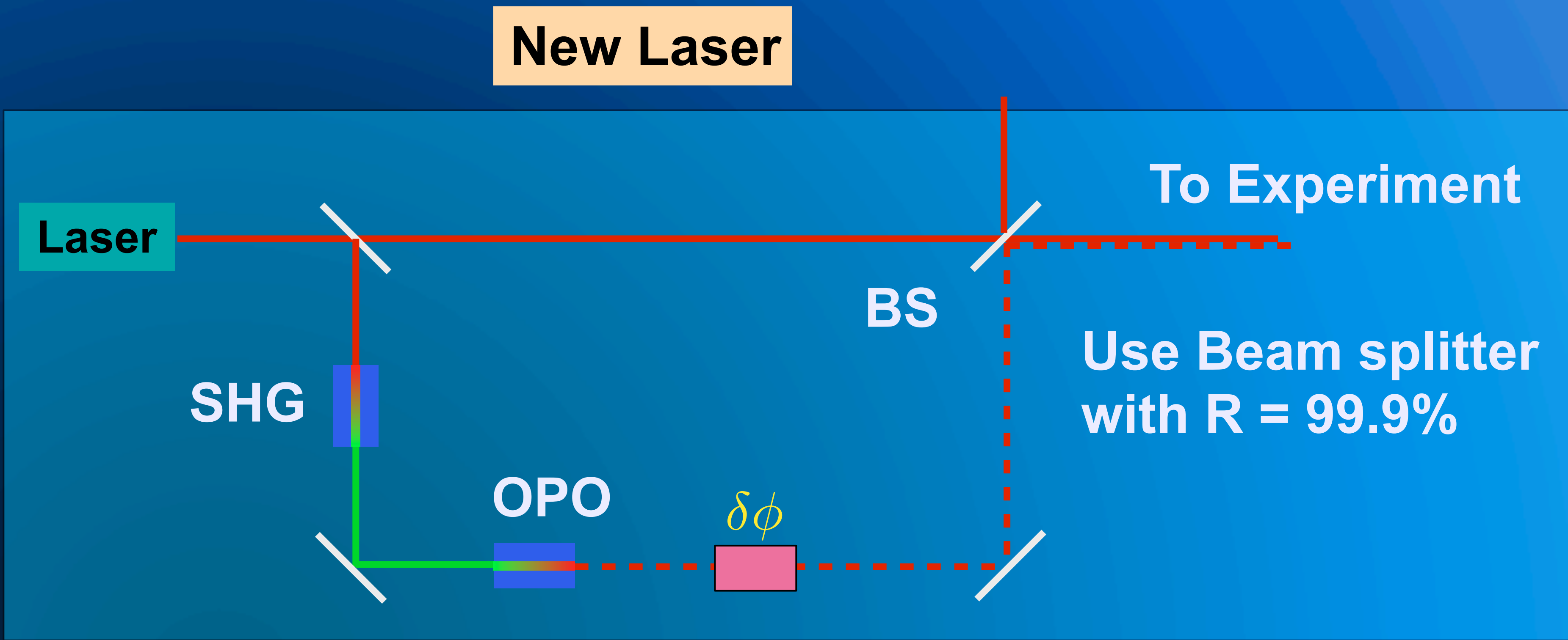
Use Beam splitter with R = 99.9%

Experimental Setup

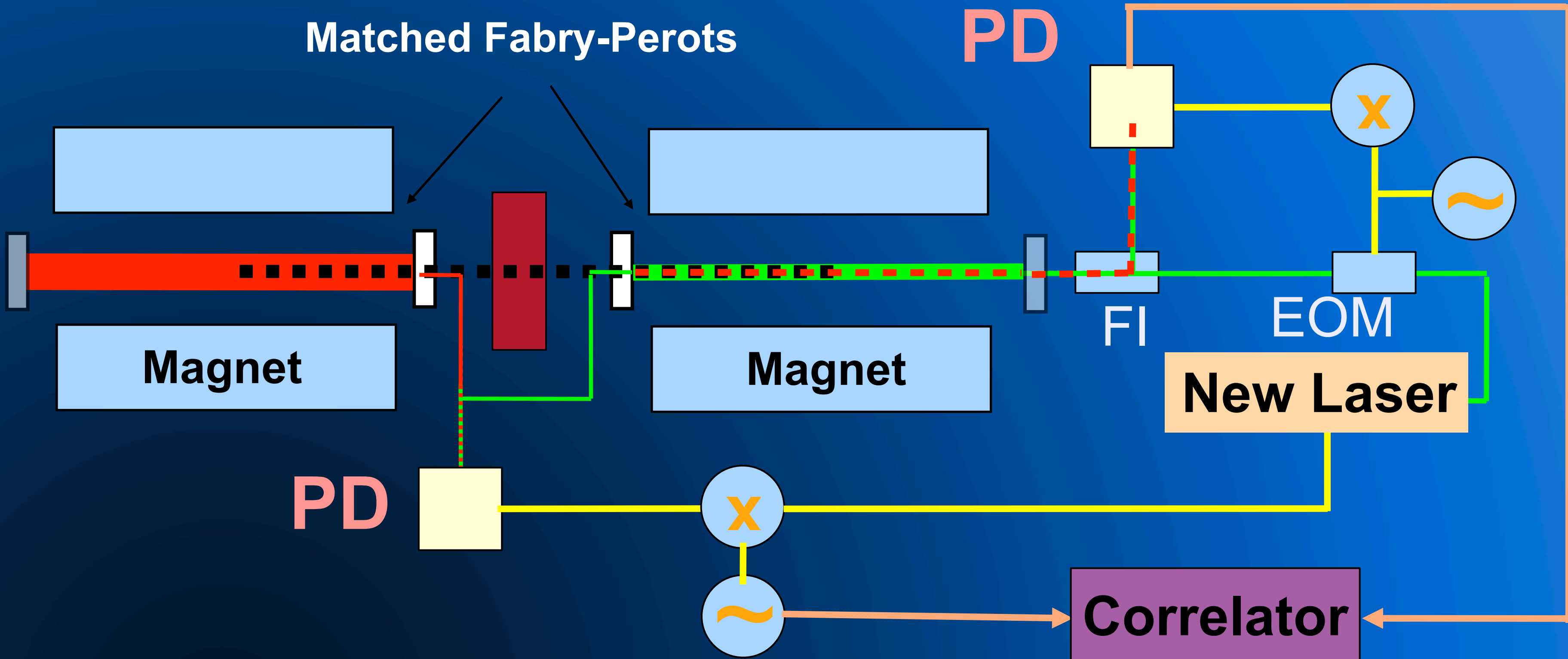


Integration into experiment?

‘New Laser’


New Laser
Laser
To Experiment
BS
SHG
OPO
$\delta\phi$
Use Beam splitter
with R = 99.9%

Experimental Setup



Integration into experiment? No problem

Signal vs. Noise

$$E = \left(\sqrt{\bar{N}} + \sqrt{\bar{n}}e^{i\Omega t} + v_+ e^{i\Omega t} + v_- e^{-i\Omega t}\right) e^{i\omega t}$$

Local Oscillator + Signal + Noise sidebands

Power at Ω $$P(\Omega) = Q\cos(\Omega t) + I\sin(\Omega t)$$

Expectation value/Signal: $< Q >_{\phi_\pm} = 2\sqrt{\bar{N}\bar{n}}$

Variance/Noise: $< \Delta Q >_{\phi_\pm} = \sqrt{2\bar{N}}e^{-|\zeta|}$

$$\Bigg\} \; SNR = e^{|\zeta|}\sqrt{2\bar{n}}$$

If we know the signal phase or quadrature!!

Signal vs. Noise

$$E = \left(\sqrt{\bar{N}} + \sqrt{\bar{n}}e^{i\Omega t} + v_+ e^{i\Omega t} + v_- e^{-i\Omega t}\right) e^{i\omega t}$$

Local Oscillator + Signal + Noise sidebands

Power at Ω $\quad P(\Omega) = Q\cos(\Omega t) + I\sin(\Omega t)$

Expectation value/Signal: $< Q >_{\phi_\pm} = 2\sqrt{\bar{N}\bar{n}}$

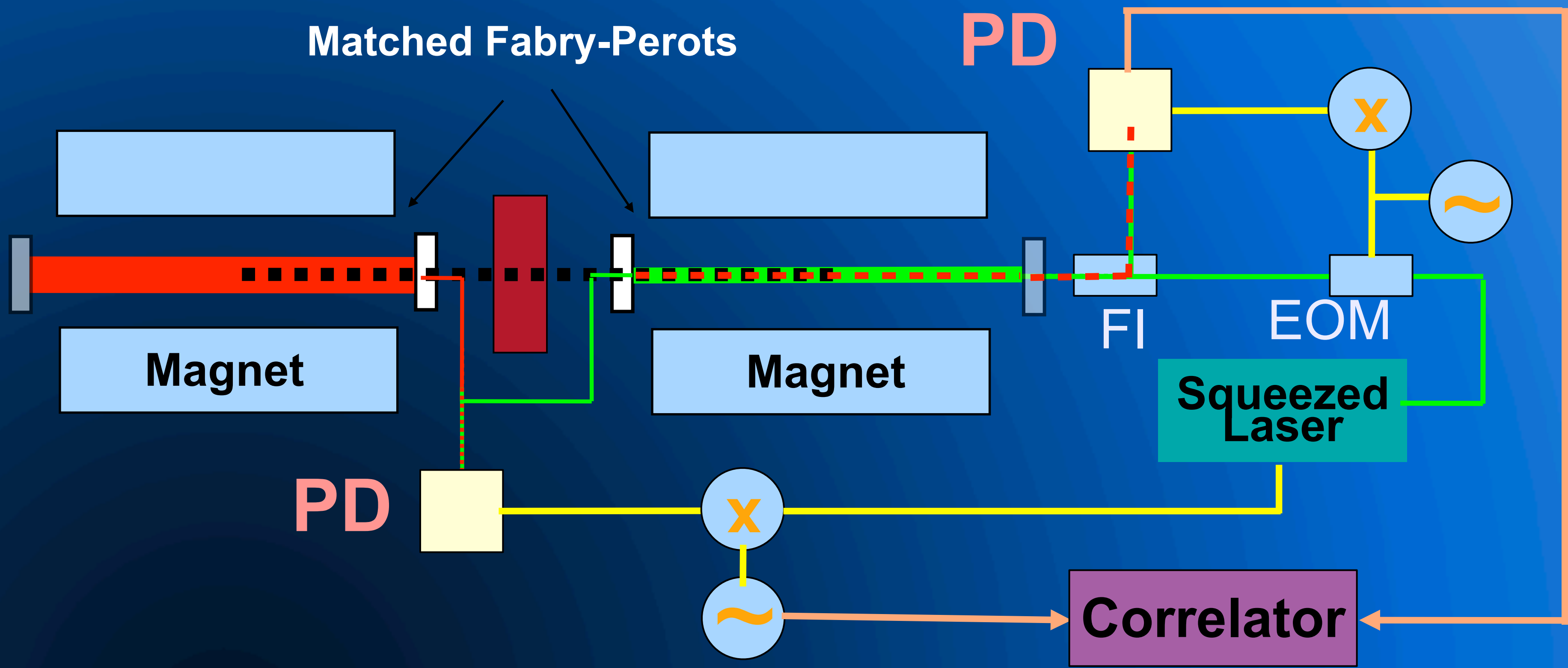
Variance/Noise: $< \Delta Q >_{\phi_\pm} = \sqrt{2\bar{N}}e^{-|\zeta|}$

$$\Big\} \quad SNR = e^{|\zeta|}\sqrt{2\bar{n}}$$

If signal phase is not known: $< \Delta P >= 2\cosh(|\zeta|)\sqrt{\bar{N}}$

Don't squeeze!! $\Rightarrow \quad SNR = \dfrac{\sqrt{\bar{n}}}{\cosh(|\zeta|)} < \sqrt{\bar{n}}$

Problem I



Need to know and control the distance between the two cavities!

Problems I

Need to control the distance between the two cavities!

How well? $|\zeta| \approx 2.3 \quad \Rightarrow \quad \frac{\Delta Q_{SQ}}{\Delta Q_{coh}} = \frac{1}{10}$

$$\frac{\Delta I_{SQ}}{\Delta I_{coh}} = 10 \quad \text{and} \quad S = \Delta I \sin\theta + \Delta Q \cos\theta$$

Signal phase $\theta < 0.01\text{rad}$ **to use 10dB squeezing**

$$\delta l \approx O(1\text{nm})$$

Not yet clear to me how ...
But not a fundamental problem ...

Summary I

REAPR and SQUEEZING:

- Sensitivity can be improved using squeezed light if
  - Losses in the injection path can be nearly eliminated

$$\sqrt{< (\Delta X_1)^2 >} = \frac{\sqrt{(1-L)}}{2} e^{-|\zeta|} + \frac{\sqrt{L}}{2}$$

  - We know and control the demodulation phase and axion/optical paths
    - not sure how ...

Last Question

- How far can we push our standard ‘fundamental’ limit?

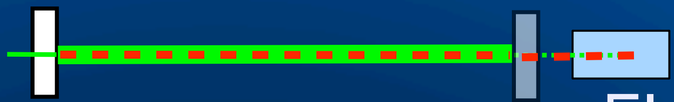
Last Question

- How far can we push the standard ‘fundamental’ limits??

Probably by a factor 1

- Sorry, no ‘0’ missing here ...

Real Problem



Signal build-up: $$\sqrt{\bar{n}} = \frac{t\sqrt{\bar{n}_{nocav}}}{1-r} = \frac{2t}{t^2+l^2}\sqrt{\bar{n}_{nocav}}$$

Optimal signal build-up requires impedance matching $|t| = |l|$

But then: $r_{cav} = 0$ **and the squeezed vacuum is lost inside the cavity and replaced by ordinary vacuum in reflection**

No squeezing left for that optimum case ...

Summary II

Can we improve sensitivity with squeezing?

<u>Preliminary:</u>

- **Not if we optimize cavity finesse** $|t| = |l|$
- **But impedance matched cavities might be impractical for very low loss mirrors and then squeezing could help**

To be continued ... and I hope I am wrong ...