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Realistic Polarizing Sagnac Topology with DC Readout for the Einstein Telescope

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GWADW 2013, Elba

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M. Wang et. al. Phys. Rev. D 87, 096008 (2013)

Outline

- Motivation of a polarizing Sagnac topology for ET
- Quantum noise behavior by accounting for a finite extinction ratio of polarized beam splitter (PBS)
- How to realize DC readout
- Control of a polarizing Sagnac interferometer
- Summary

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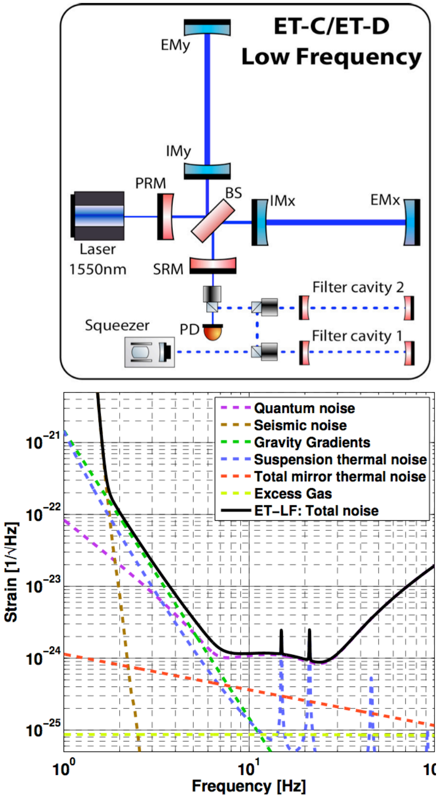
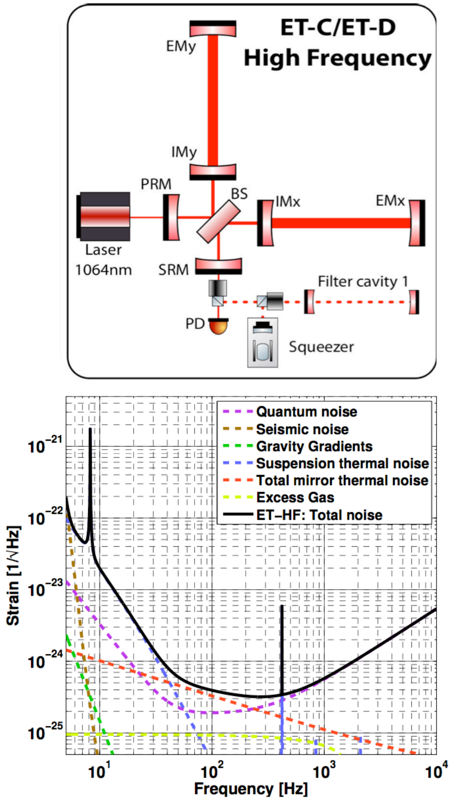
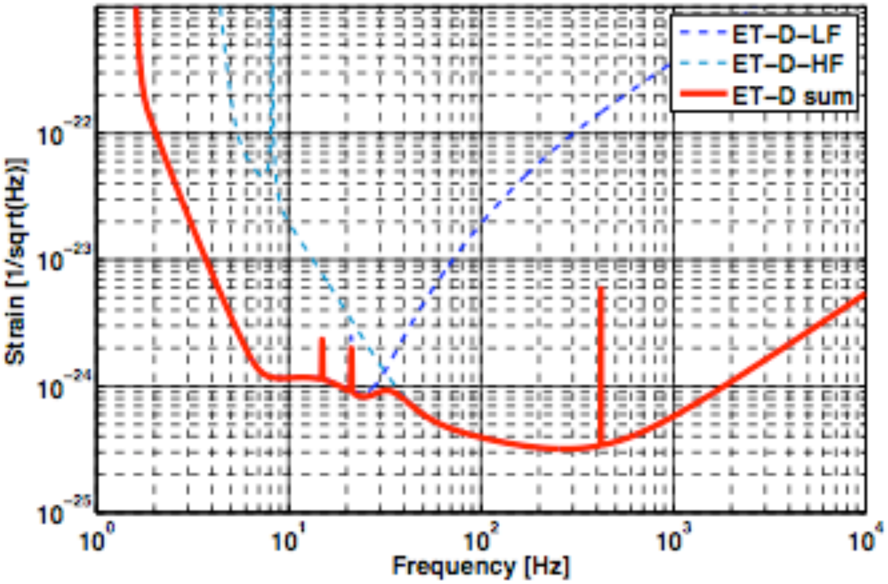
Current ET Design

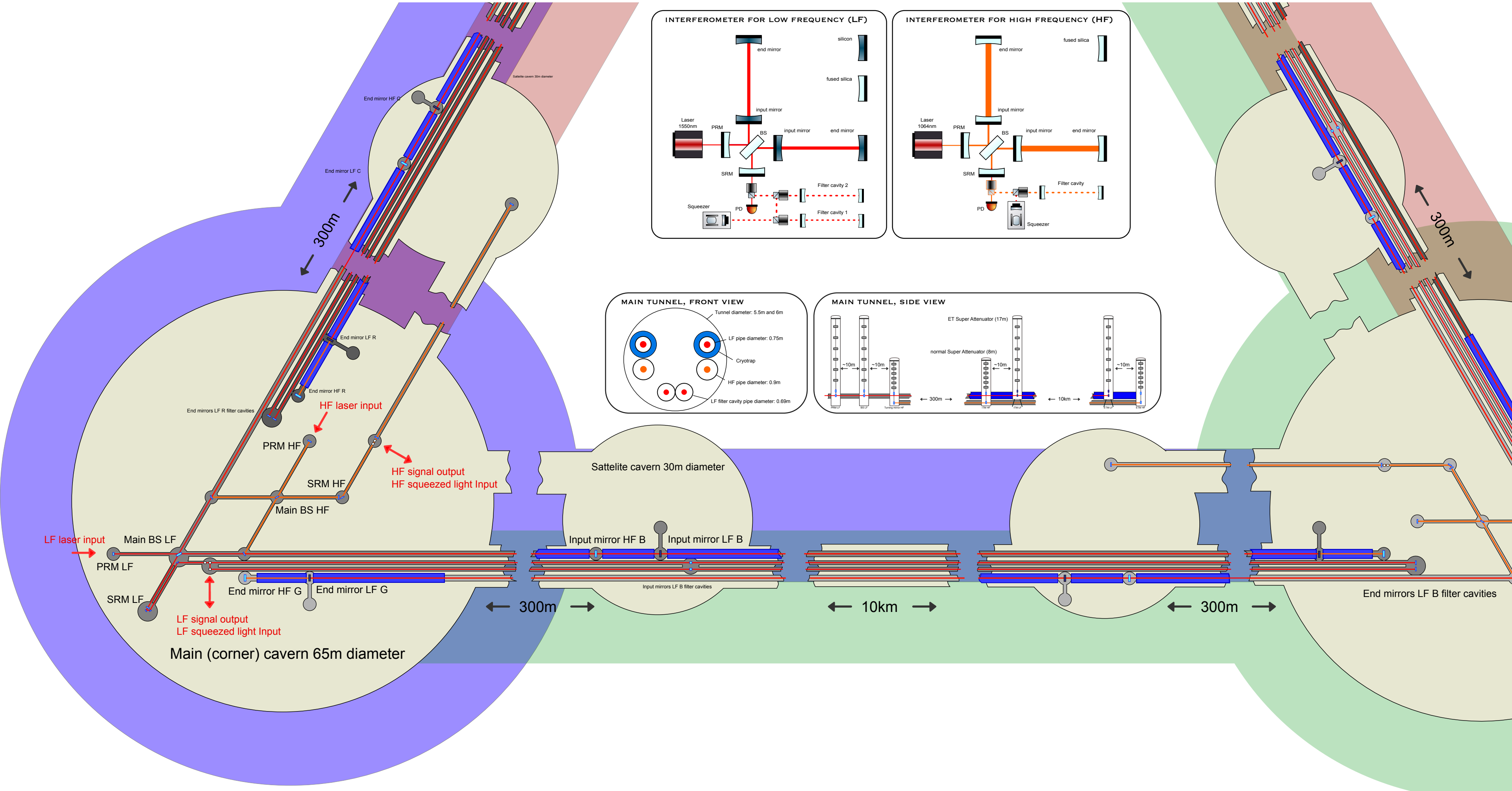
- 3 triangle-nested detectors, each being composed of two Michelson-type interferometers with xylophone design located underground
- Dual-recycled configuration with 10km arm cavities
- Frequency-dependent squeezing input to reduce quantum noise





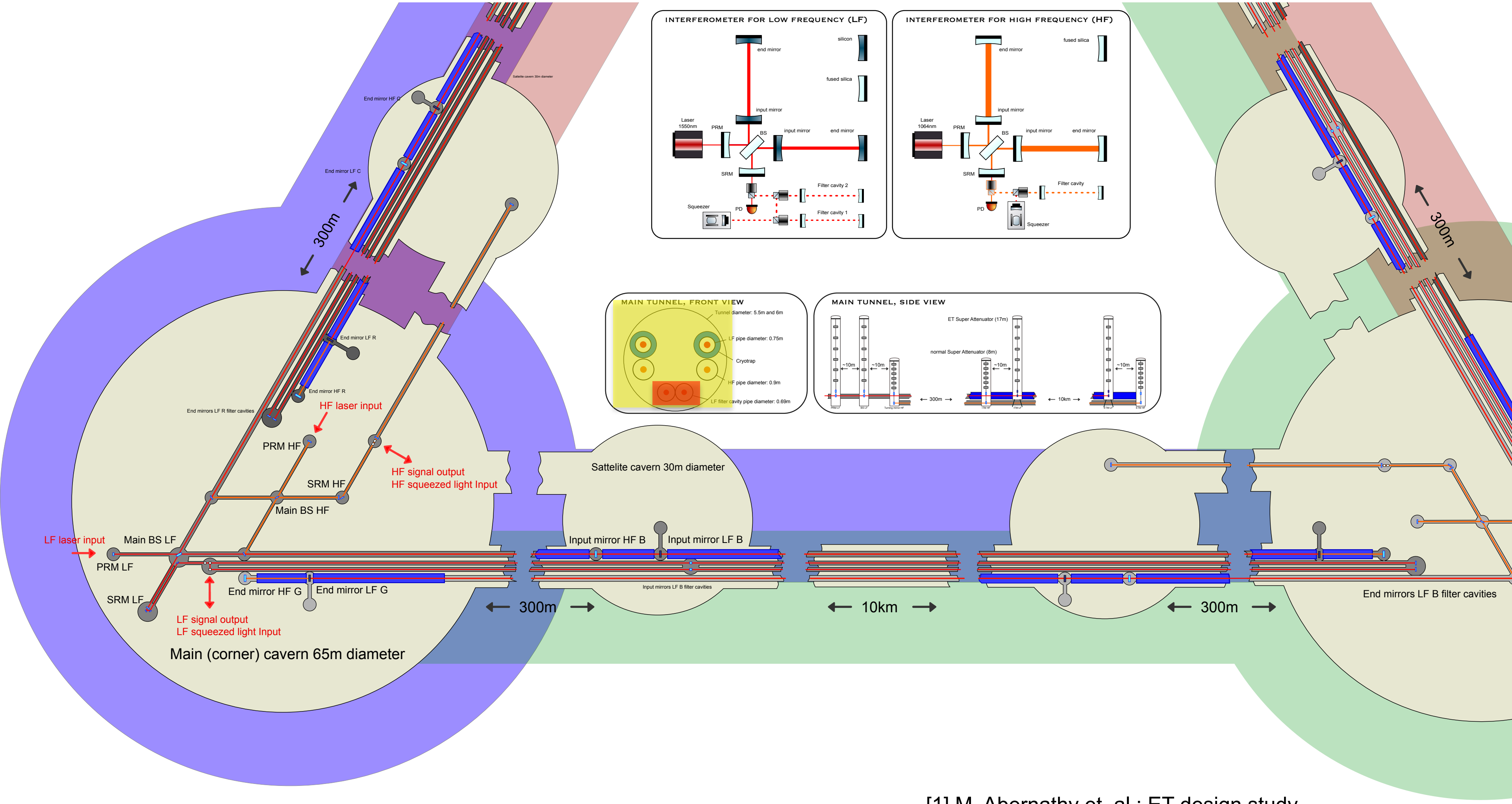


Current ET Design



[1] M. Abernathy et. al.: ET design study

Current ET Design



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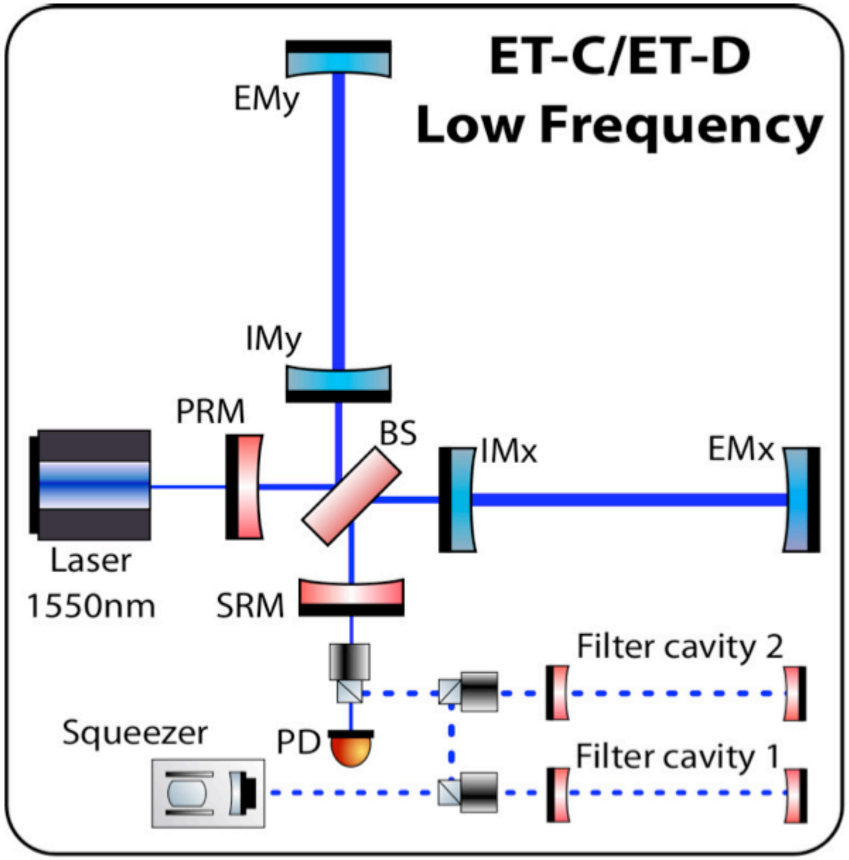
ET-Low Frequency (LF) Interferometer

Aim: to minimize radiation pressure noise

Michelson-type:

- Dual-recycled configuration with 10km arm cavities
- Two 10km input filter cavities (for frequency-dependent squeezing) to reduce quantum noise



ET-Low Frequency (LF) Interferometer

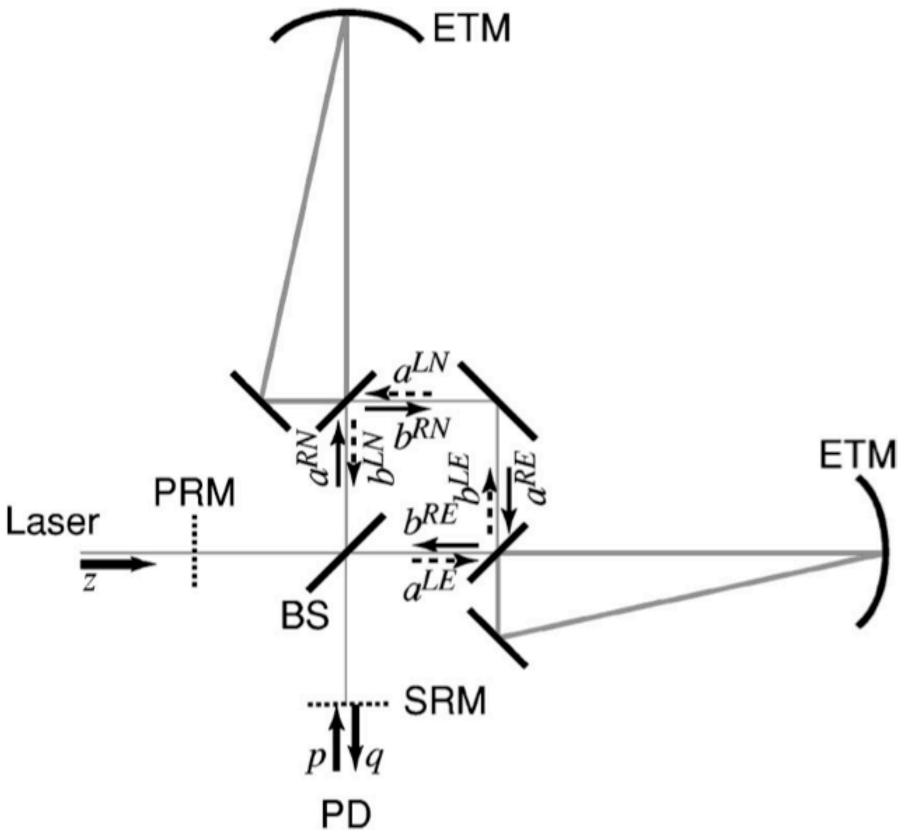
Aim: to minimize radiation pressure noise

Michelson-type:

- Dual-recycled configuration with 10km arm cavities
- Two 10km input filter cavities (for frequency-dependent squeezing) to reduce quantum noise

Sagnac-type:

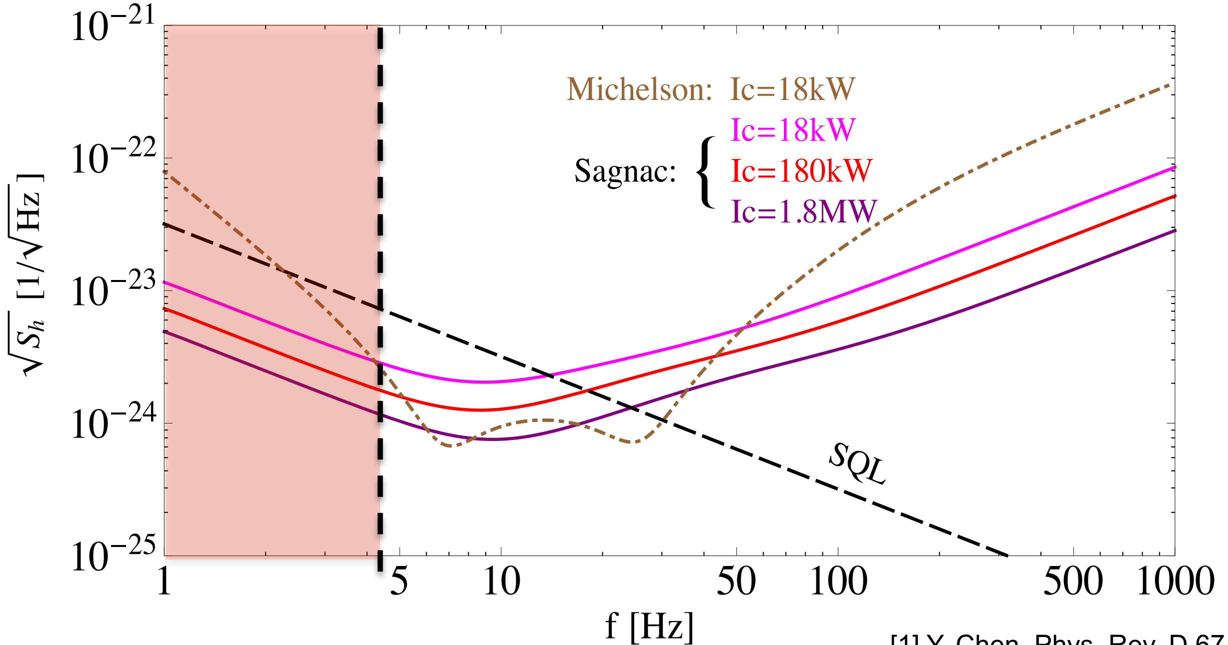
- A speed meter having low radiation pressure noise [1]
- No input filter cavities needed
- No signal recycling mirror needed



[1] Y. Chen, Phys. Rev. D 67, 122004 (2003)

Sagnac vs. Michelson

- A potential low noise at low frequencies, but a worse peak sensitivity at same level of power [1, 2]
- A better quantum noise can be achieved by increasing the cavity circulating power [2]
- A 10 times higher power may be possible [3]



[1] Y. Chen, Phys. Rev. D 67, 122004 (2003)
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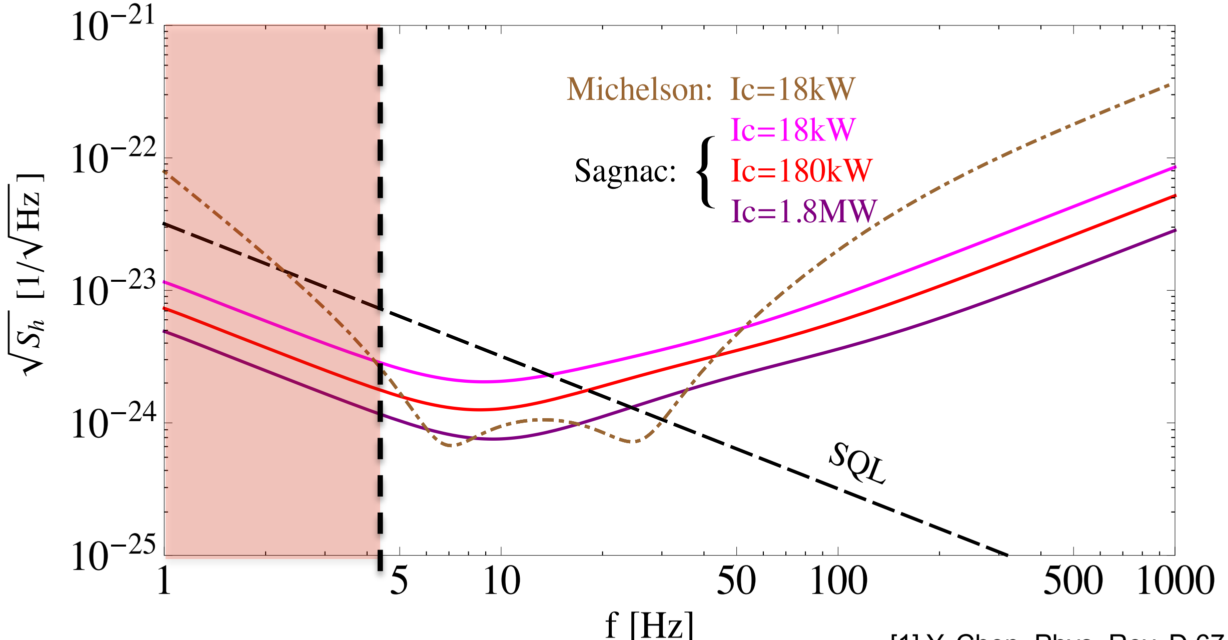
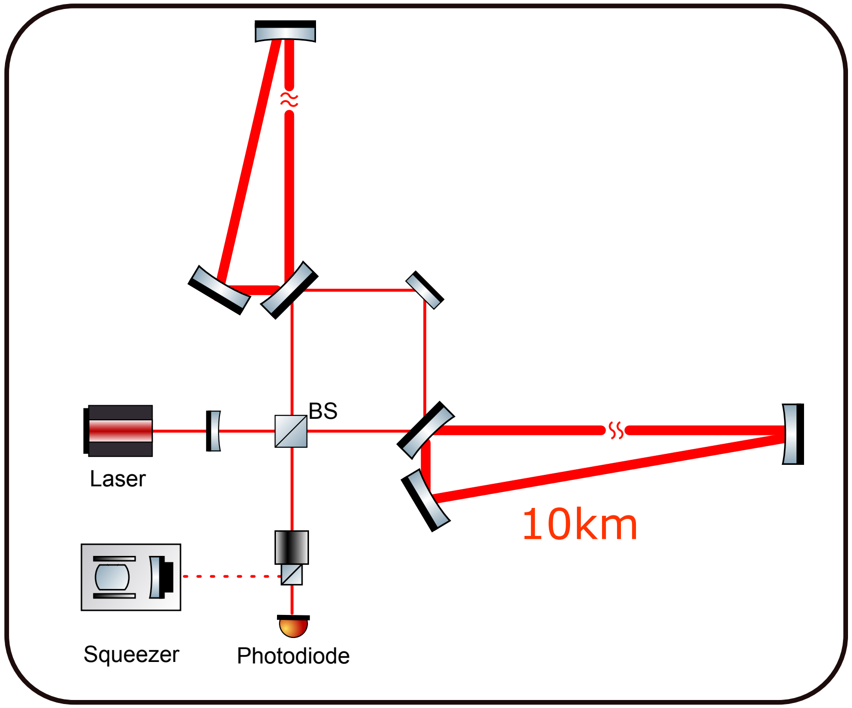


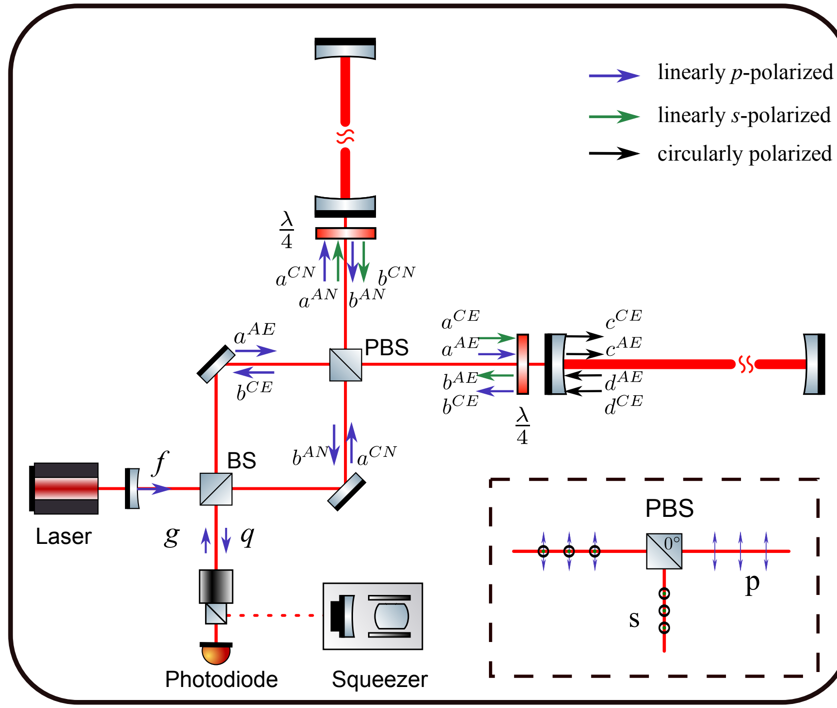
Practical Sagnac?

[1] Y. Chen, Phys. Rev. D 67, 122004 (2003)
[2] M. Wang et. al. Phys. Rev. D 87, 096008 (2013)
[3] D. Shoemaker. "Future Limits to Sensitivity," at the Aspen Workshop, 2001

Polarizing Sagnac Topology

- Requires minimum changes to the current Michelson interferometer [1]
- Has no small angle scattering and elliptical beam spot issues
- However, includes polarizing optics, i.e., polarizing beam splitter (PBS), quarter wave plate (QWP)

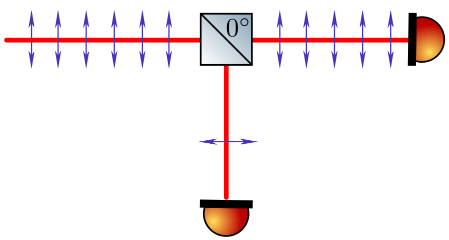




[1] S. L. Danilishin, Phys. Rev. D 69, 102003 (2004)

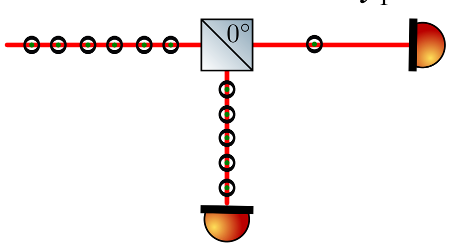
Polarizing Beam Splitter

- Finite extinction ratio
  - p-polarization

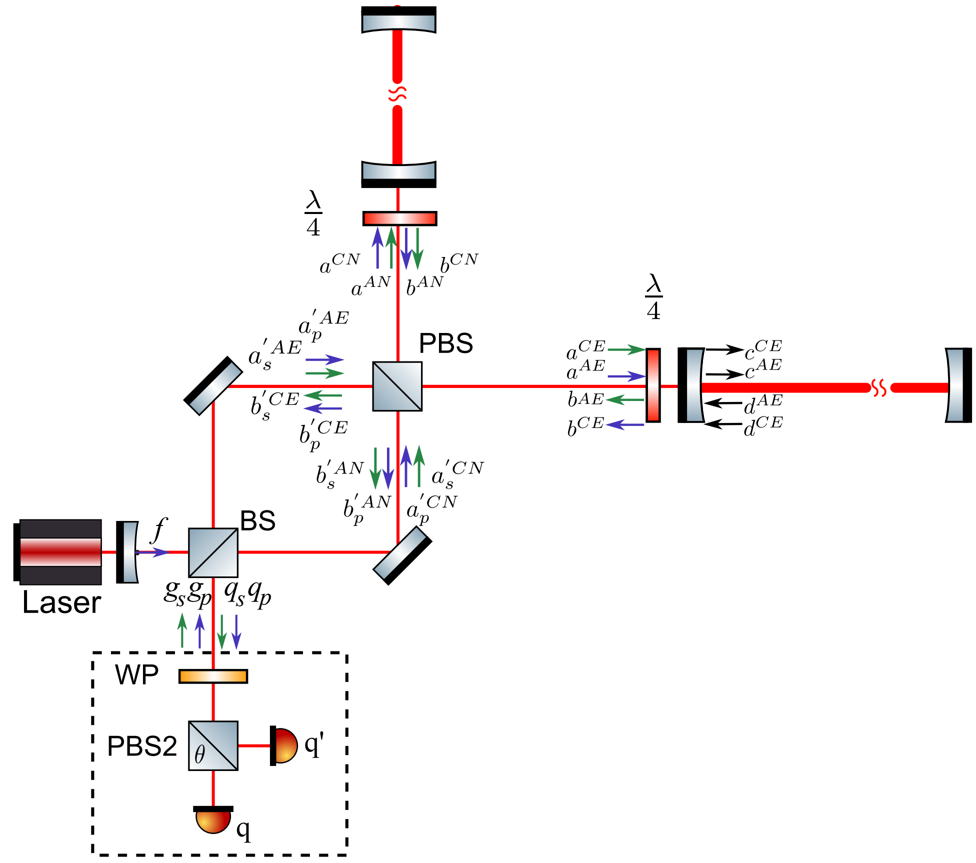


$$\eta_p = \frac{x_1}{x_2}$$

  - s-polarization



$$\eta_s = \frac{y_1}{y_2}$$



$$\eta_{p,s} << 1 \quad \text{i.e.,} \quad \eta_{p,s} = \frac{1}{1000}$$

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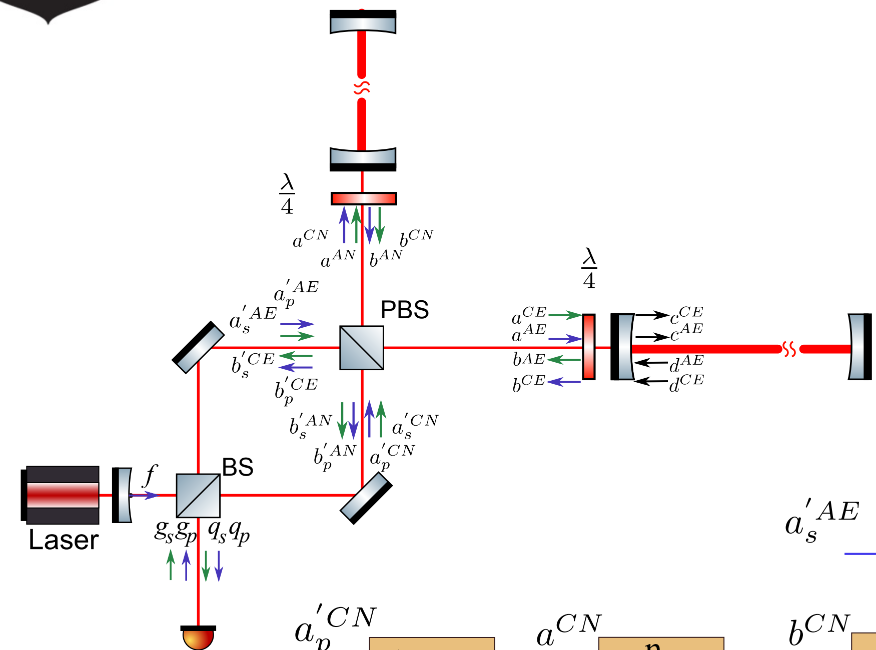
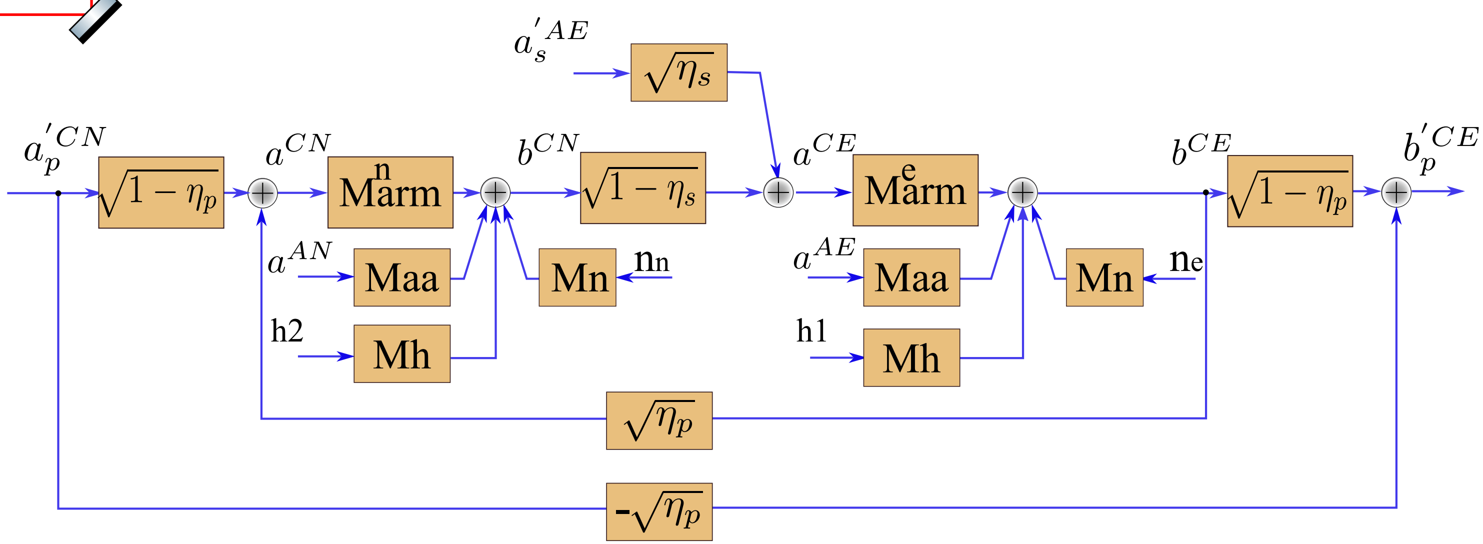
Input-output Relation of a Sagnac

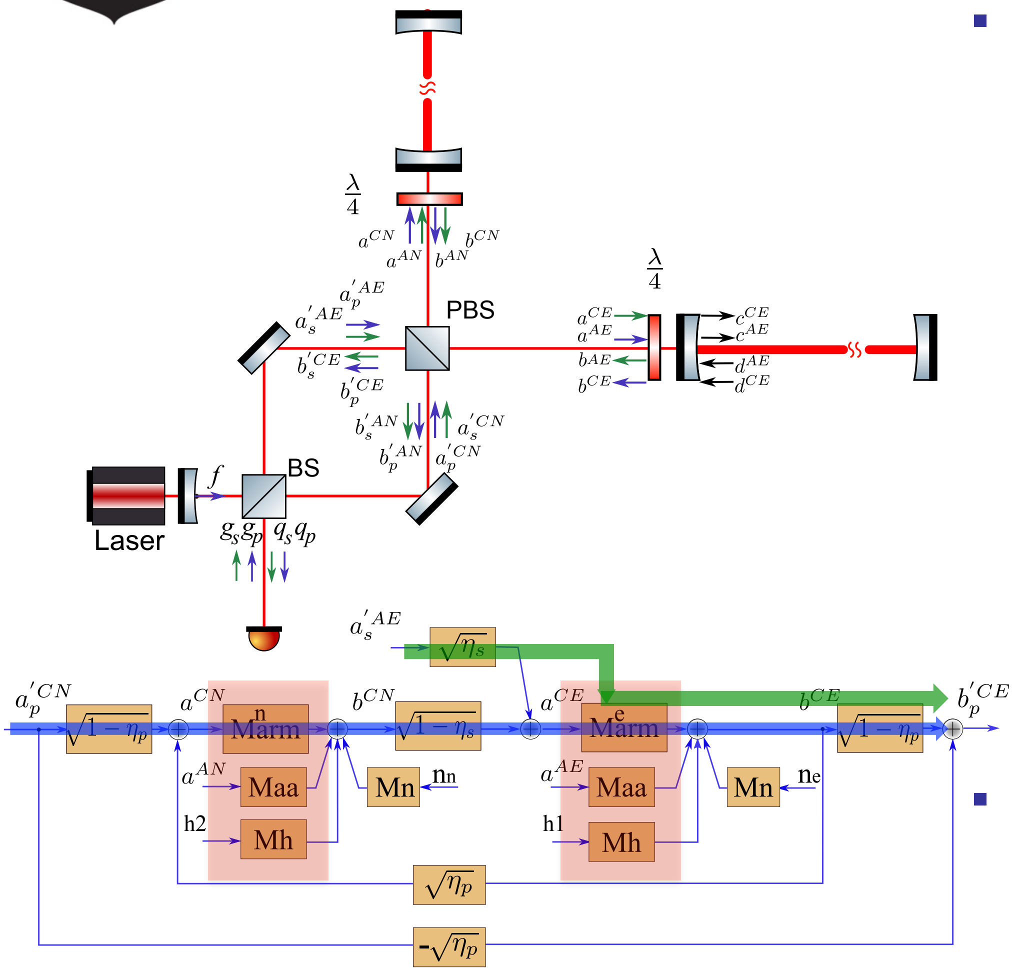


- Finite extinction ratios $\eta_{p,s}$ are considered
- Input-output relation is illustrated by the following block diagram
- Marm is the arm cavity response, Mh is the test mass response to gravitation wave, and Mn is the response due to optical loss



Details in the appendices, M. Wang . Phys. Rev. D 87, 096008 (2013)

Input-output Relation of a Sagnac



- P-polarized output q_p contains not only a p-polarized vacuum fluctuation g_p but also a s-polarized vacuum g_s, and the s-polarized vacuum induces a radiation pressure noise which has the same frequency dependence as the one in a typical Michelson interferometer

$$q_p \approx \underbrace{M_{sag} g_p}_{\text{Sagnac noise}} + \underbrace{\sqrt{\eta_s} M_{arm} g_s}_{\text{Michelson noise}} + H_{sag} h$$

- S-polarized output q_s gains a Michelson response

$$q_s \approx -g_s + \sqrt{\eta_s} M_{arm} g_p + \sqrt{\eta_s} H_{arm} h$$

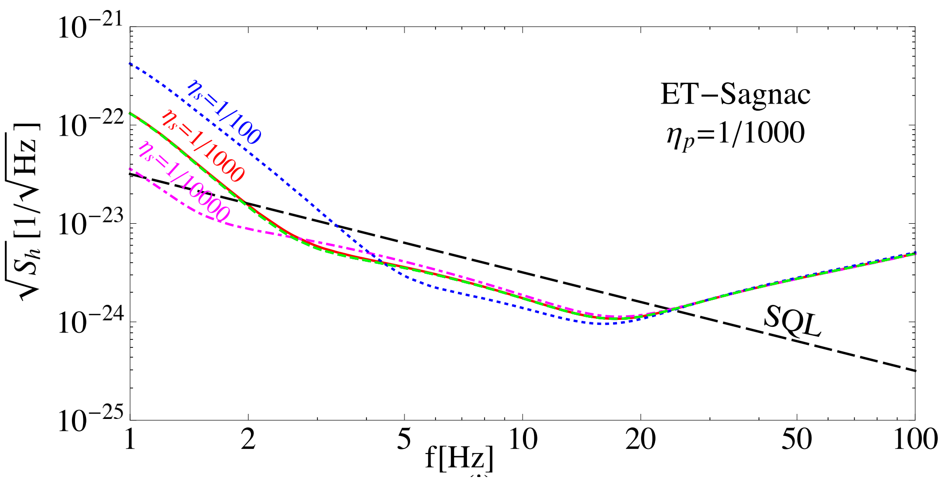
Quantum Noise of a Polarizing Sagnac

- Quantum noise spectrum including finite extinction ratio of PBS

$$S_h = \underbrace{\frac{e^{2r_p}\left(\cot\zeta - \kappa_{sag}\right)^2 + e^{-2r_p}}{2\kappa_{sag}} h_{SQL}^2}_{\text{Sagnac type noise}} + \underbrace{\frac{e^{2r_s}\left(\sqrt{\eta_s}\cot\zeta - \sqrt{\eta_s}\kappa_{arm}\right)^2 + \eta_s e^{-2r_s}}{2\kappa_{sag}} h_{SQL}^2}_{\text{Michelson type noise}}$$

r is the squeezing factor, ζ is the homodyne detection angle, and κ is the optomechanical coupling strength

- We found
  - ➢ the quantum noise arises from a combined response of Sagnac and Michelson
  - ➢ the degradation is more sensitive to s-polarized extinction ratio than to optical loss



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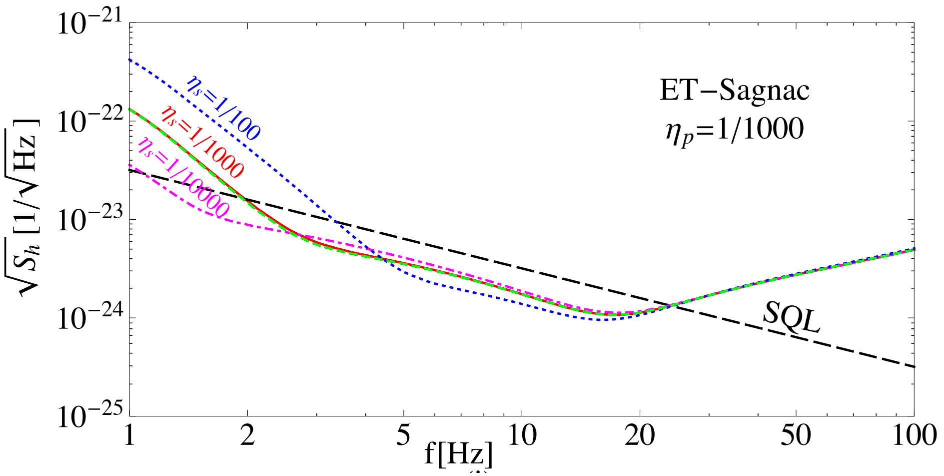

Readout scheme?

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Local Oscillator (LO) for DC readout

Can we do the DC readout for the Sagnac?

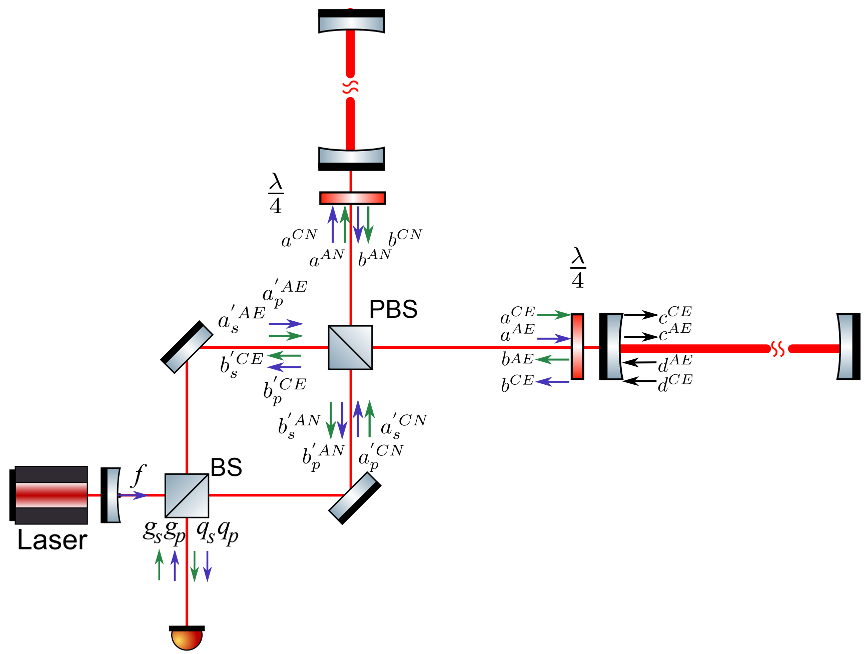
- Required ratio (ratio between the LO power to central BS power)

$$\gamma = 1.75 \times 10^{-5}$$

- Sagnac has null response to static mirror displacement

- LO can be created by
  - Non-zero Sagnac Area
    → a very large area required ✖
  - Non-50:50 central BS
    → not in the right quadrature ✖
  - Leaked s-polarized field
    → an intended arm length offset ?

$$q_{LO} = \sqrt{\eta_s} H_{arm} \frac{\Delta L}{L}$$



Local Oscillator Created by PBS leakage

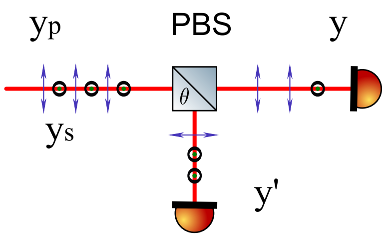
- Mixing outputs via polarization axes rotated PBS

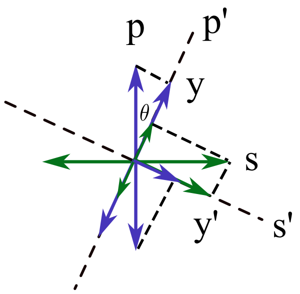
$$q_s \approx -g_s + \sqrt{\eta_s} M_{arm} g_p + \underline{\boxed{\sqrt{\eta_s} H_{arm} \frac{\Delta L}{L}}}$$

LO s-polarization

$$q_p \approx M_{sag} g_p + \sqrt{\eta_s} M_{arm} g_s + \underline{\boxed{H_{sag} h}}$$

GW signal p-polarization





$$q^\theta = \underbrace{\boxed{q_p \cos\theta}}_{\text{signal}} + \underbrace{\boxed{q_s \sin\theta}}_{\text{LO}}$$

- Parameter requirements for DC readout

$$\gamma = \eta_s \sin^2\theta = 1.75 \times 10^{-5} \left(\frac{\eta_s}{0.001}\right)\left(\frac{\sin\theta}{0.13}\right)^2$$

$$\Rightarrow \boxed{\theta = \frac{\pi}{24} \qquad \eta_s = \frac{1}{1000}}$$

Local Oscillator Created by PBS leakage

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$$q_s \approx -g_s + \sqrt{\eta_s} M_{arm} g_p + \boxed{\sqrt{\eta_s} H_{arm} \frac{\Delta L}{L}}$$

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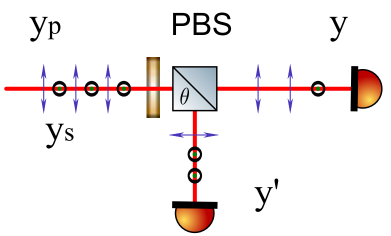

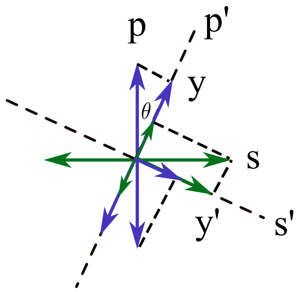

$$q^{\theta} = \underbrace{q_p \cos\theta}_{\text{signal}} + \underbrace{q_s \sin\theta}_{\text{LO}}$$

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$$\theta = \frac{\pi}{24} \qquad \eta_s = \frac{1}{1000}$$

✔ A wave plate can be used to select the homodyne detection angle

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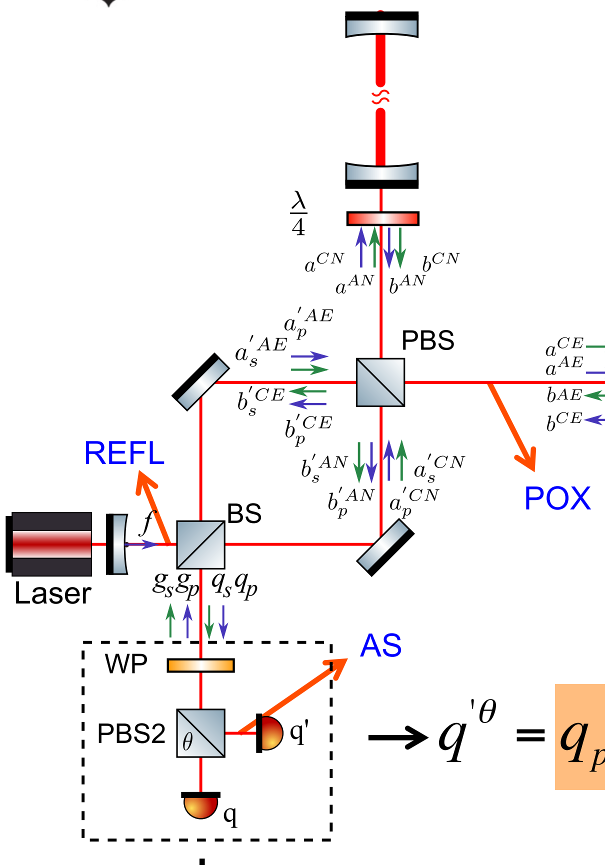
Potential mirror position control

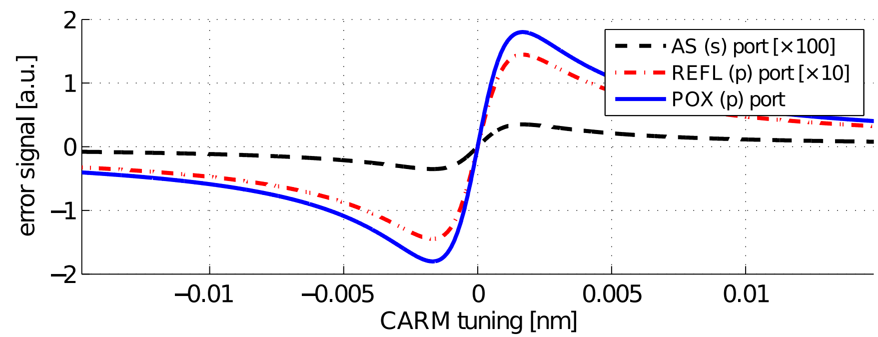


Detection

$$\rightarrow q'^{\theta} = \boxed{q_p \sin\theta} + \boxed{q_s \cos\theta}$$

small signal   large LO

- We need to control 4 different degrees of freedom (DoFs) in this 'Sagnac'
- Preliminary results have shown that error signals can be extracted at this port (AS) as well as other ports, i.e., REFL, Pickoff (POX/POY)
- Full control scheme needs further investigation



[Simulated by C. Bond using FINESSE]

A polarizing Sagnac interferometer

Advantages

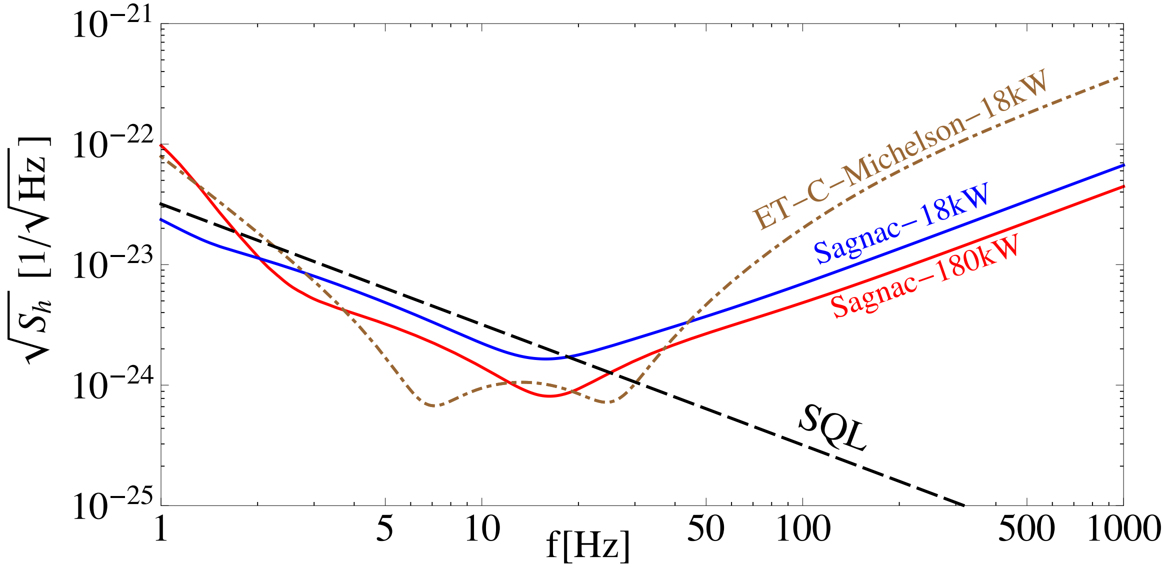
- Using linear arm cavities
- No need for filter cavities to reduce low-frequency quantum noise
- No need for signal recycling in ET-LF
- Less susceptible to optical losses
- Realization of DC readout scheme

Challenges

- The performance greatly relies on the quality of polarizing optics
- The birefringence of cryogenic optics not yet considered
- The position control of polarizing optics, including the polarization axes control

Conclusion

- We show a potential implementation of a polarizing Sagnac interferometer for ET-LF detectors
- It presents a comparable sensitivity curve whilst having a reduced complexity of the system that does not require filter cavities nor a signal recycling mirror
- A realization of DC readout is achieved by detecting the mixed polarized outputs due to the PBS's finite extinction ratio



Thank you !

Appendix: ET-LF: Sagnac V.S. Michelson

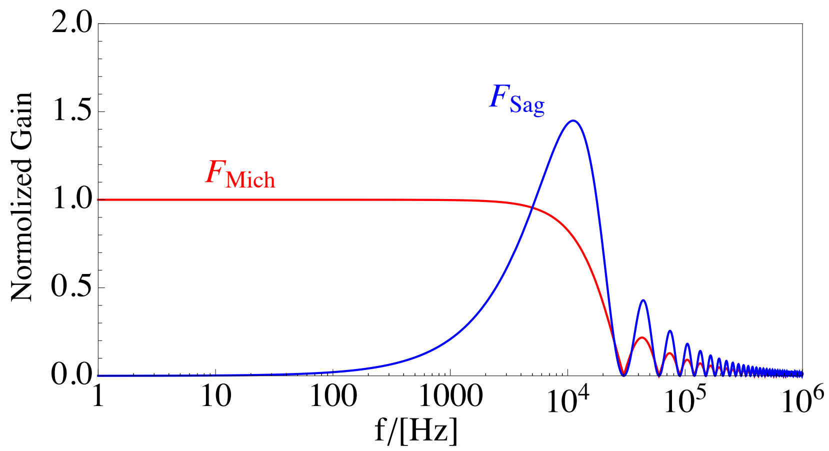
- A higher power use is still possible, though resulted in a higher mirror thermal and suspension noise [1]
- Based on the ET model: temperature increased to 20K and the noise increases by a factor of $\sqrt{2}$
- The power increased curves also include a bandwidth adjustments, broader bandwidth are required to satisfy the lowest peaks sitting around 10Hz. Parameters are

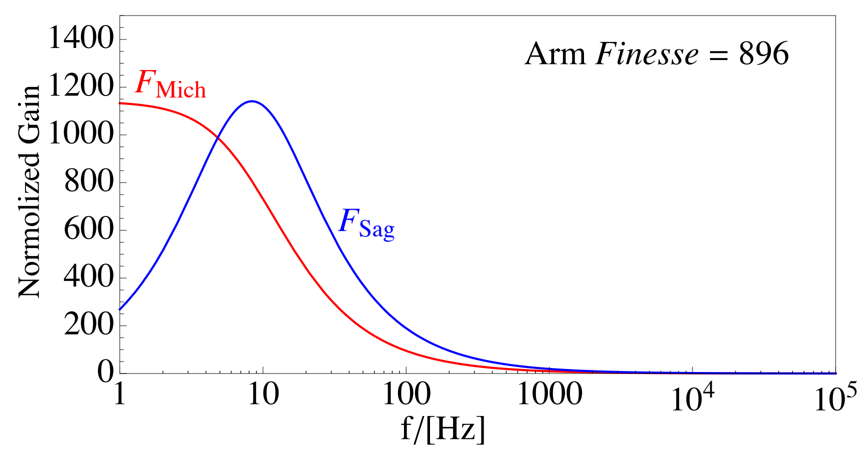
Input mirror reflectivity	0.981	0.971	0.953
Input power	45.8W	665W	10.86kW
Cavity power	18KW	180KW	1.8MW
Homodyne angle	1.263	0.77	0.402

[1] D. Shoemaker, “Future Limits to Sensitivity,” at the Aspen Workshop, 2001

Appendix: response issue

- Sagnac has null response to static mirror displacement
- The Sagnac interferometer transfer function can be improved via having longer arm length and high finesse arm cavities





Appendix: Cryogenic mirror

- Two origins of the heat inputs into the cold mirror:
  - thermal radiation from the warm surface of the vacuum tube
  - absorption of a small fraction of the laser light
    i.e.,1ppm absorption 18kW power→ 18mW absorbed power

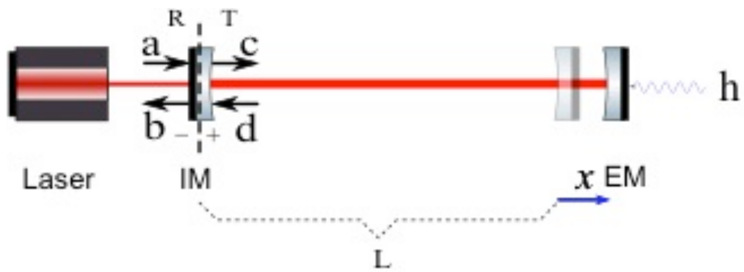
- The equilibrium temperature is achieved when the power extracted by the cooling system is equal to the power absorbed by the mirror, where $\langle k_{si} \rangle$ is the thermal conductivity of silicon (maximum at 30K)

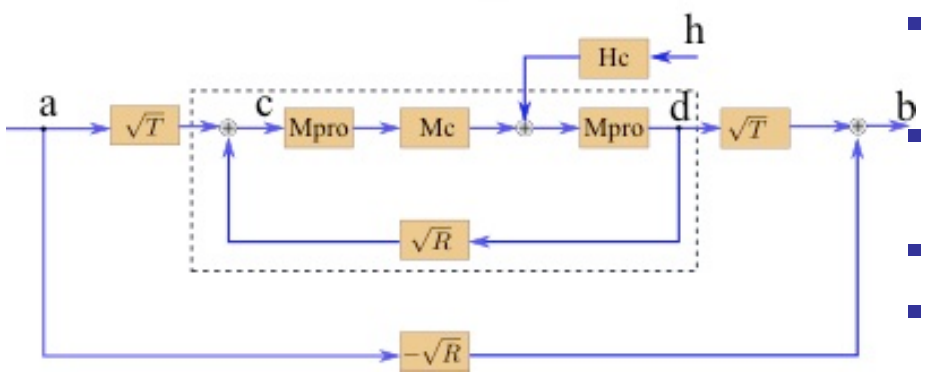
$$Q_{abs} = \frac{4S}{L}\langle k_{si}\rangle\left(T_{mir} - T_{fix}\right)$$

- We still have room

Input-output Relation of a Cavity

- Lossless cavity

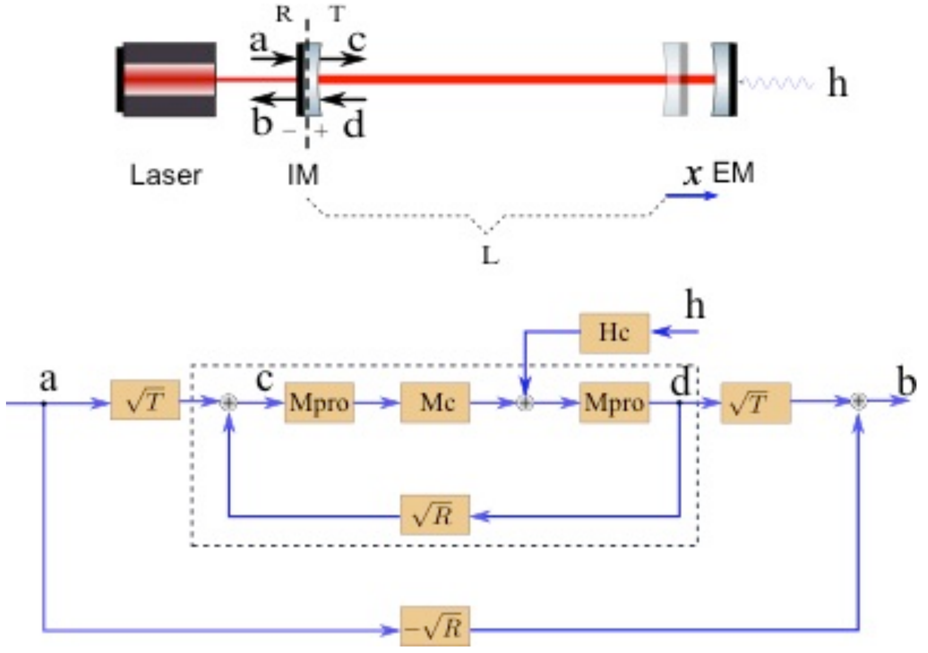




- $a, b, c,$ and d : light fields
- h :gravitational wave signal
- x : Radiation pressure induced mirror displacement
- Mpro: transfer function of a light field propagating a distance L
- Mc : transfer function of end mirror including mechanical response
- T : input mirror reflectivity
- R : input mirror transmissivity

Input-output Relation of a Cavity

- Lossless cavity



$$c = \sqrt{T}a + \sqrt{R} \cdot d$$

$$d = M_{pro} \cdot M_c \cdot M_{pro} \cdot c + H_c \cdot h$$

$$b = -\sqrt{R}a + \sqrt{T}d$$

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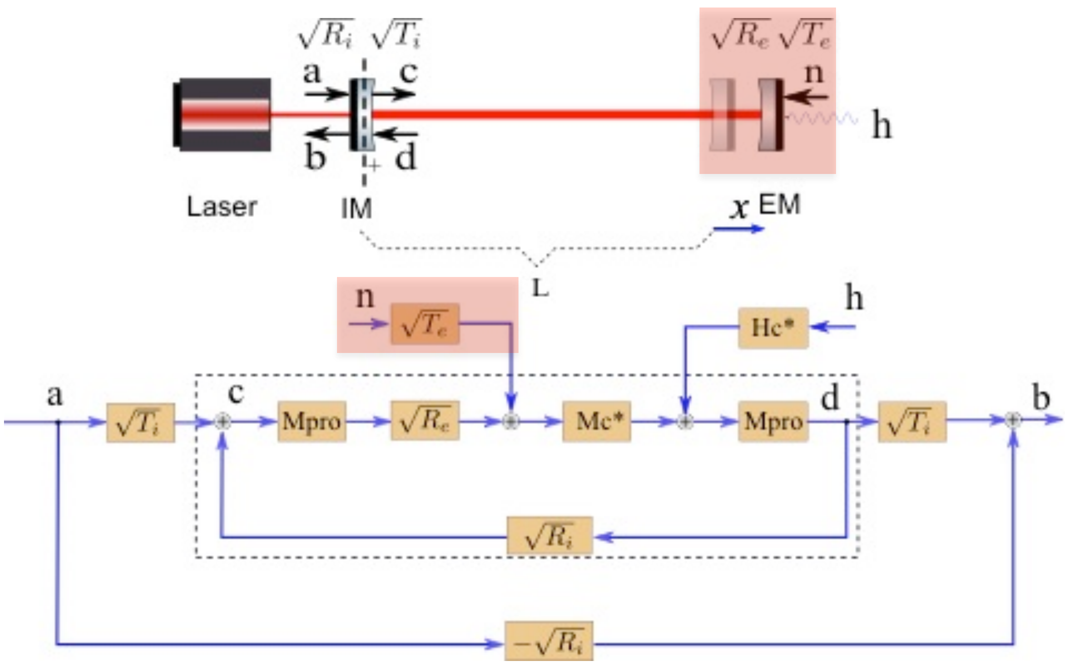
Input-output Relation of a Cavity

- Adding optical losses



$$c = \sqrt{T_i}\,a + \sqrt{R_i} \cdot d$$

$$d = M_{pro} \cdot M_c^* \cdot M_{pro} \cdot c + H_c^* \cdot h + \sqrt{T_e}\,M_c^* \cdot M_{pro} \cdot n$$

$$b = -\sqrt{R_i}\,a + \sqrt{T_i}\,d$$

- New blocks for a lossy cavity

$$b = M_{arm}\,a + M_h\,h + M_n\,n$$

Details in the appendices, M. Wang . Phys. Rev. D 87, 096008 (2013)