Displacement noise-free interferometers for gravitational waves at ultra high frequencies

(Resonant speed meter)

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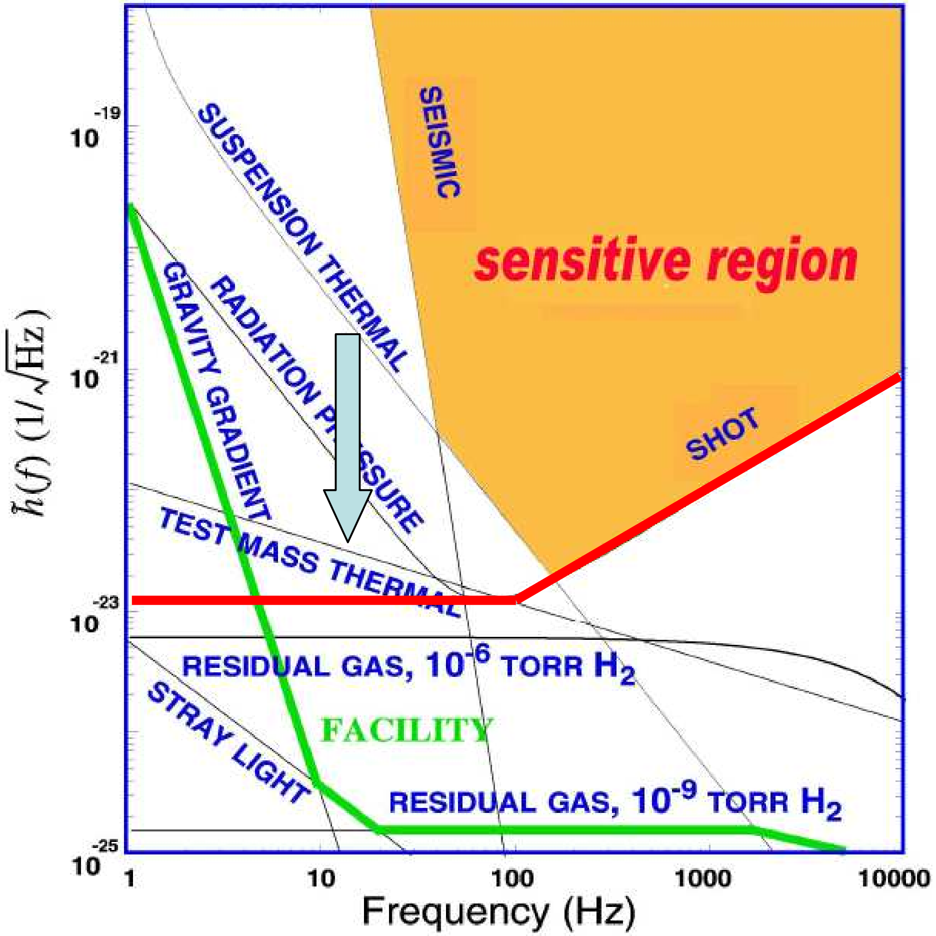
contents

1. **Displacement noise-Free gravitational-wave Interferometer (DFI)**
   - principles of DFI
   - undesirable features of DFI

2. **Resonant speed meter**
   (another approach to noise cancellation)
   - the principle
   - sensitivity

Displacement noise-Free gravitational-wave Interferometer (DFI)

Introduction



Displacement noise

seismic noise,
thermal noise,
radiation pressure noise,
etc…

↓

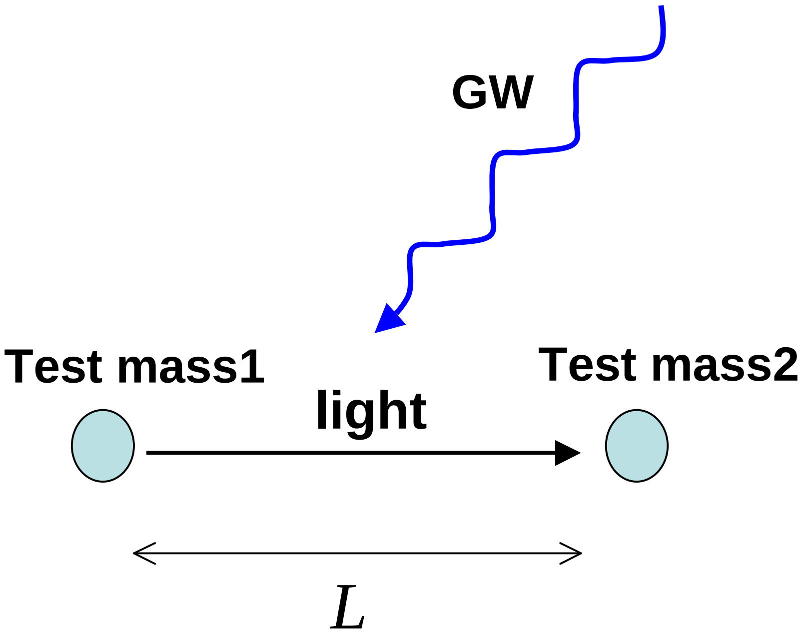
Almost all noises
at low frequencies

If we could calcel out
all displacement noises,
. . .

Priciple of DFI 1

S.Kawamura & Y.Chen, PRL 93, 2111103 (2004)
Y.Chen & S.Kawamura, PRL 96,231102 (2006)

Difference between GWs and displacement noise



$(L/\lambda)<1$

GWs act as tidal forces between two test masses. → indistinguishable

$(L/\lambda)>1$

Test masses behaves differently for GWs and displacement noises.

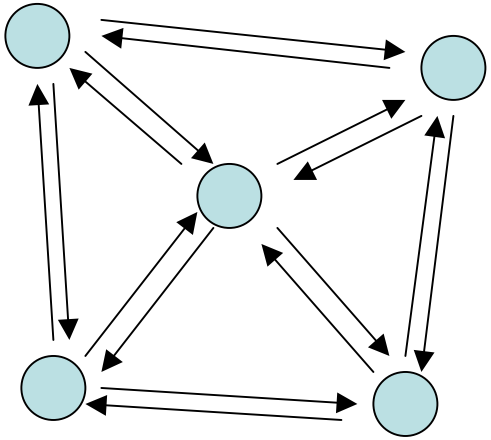
GW signal is the integral during light trip. Displacement noises act when the time of the emission and reception of light.

→ distinguishable

Priciple of DFI 2

Signal combination

Monitor mirror displacement redundantly at the same time.



N detectors in D-dimension

# signal	N (N-1)
# diplacement noise	N × D
# timing noise **(laser frequency noise)**	N

For the cancellation of these noises,

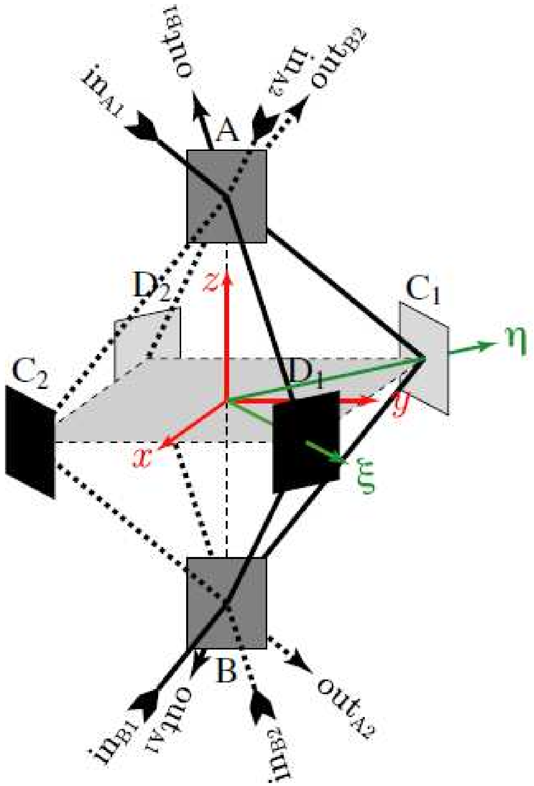
 # signal > # noise ⇒ $N(N-1) > N \times D + N$

⇒ $N > D + 2$

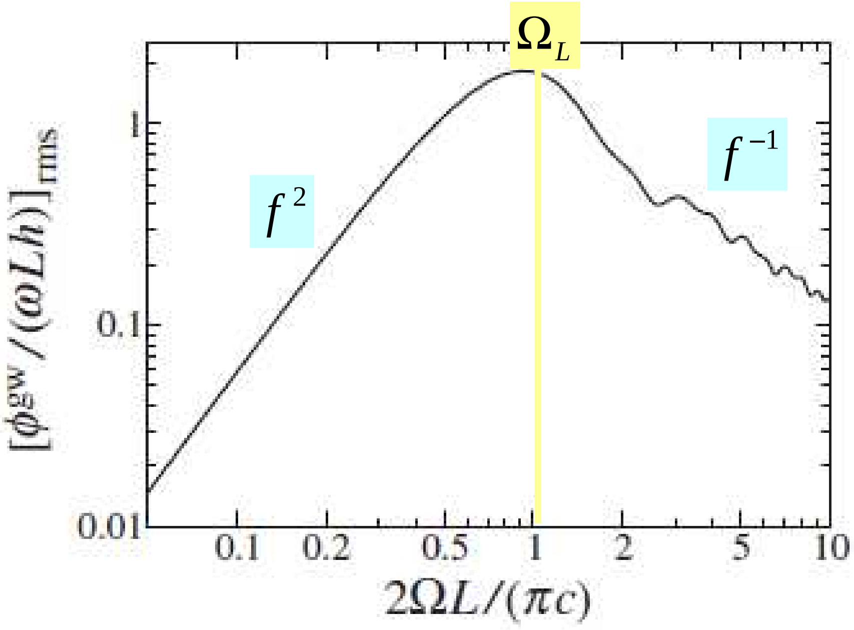
Displacement noises can be canceled remaining GW signal.

Practical design (3D bidirectional MZI)

Y.Chen et al., PRL 97, 151103 (2006)



angular mean GW response



- **At low frequencies, GW and displacement noise are indistinguishable. GW signals are partially canceled. GW response function becomes worse.**
- **However, the sensitivity is limited only by shot noise.**

undesirable features of DFI

- GW response function becomes $\propto f^2$ in low frequency.
- Cutoff frequency is too high for an application to ground-based detectors.

$$L \sim 3km \longrightarrow f_{cutoff} \sim 100kHz$$

⇓

Using FP cavity to improve the GW response at low frequencies.
Several designs are considered so far.

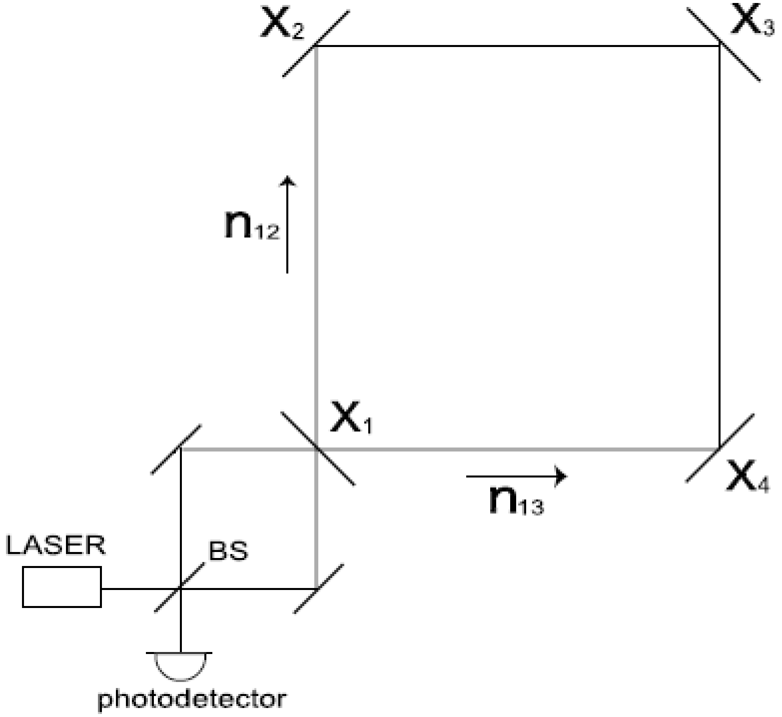
⇓

Those do not work well. The same response as the DFI without a cavity.
Not only GWs but displacement noises are amplified.
Then, the residual GW signal after cancellation is not improved.

Resonant Speed Meter

(another approach of noise cancellation)

Resonant speed meter



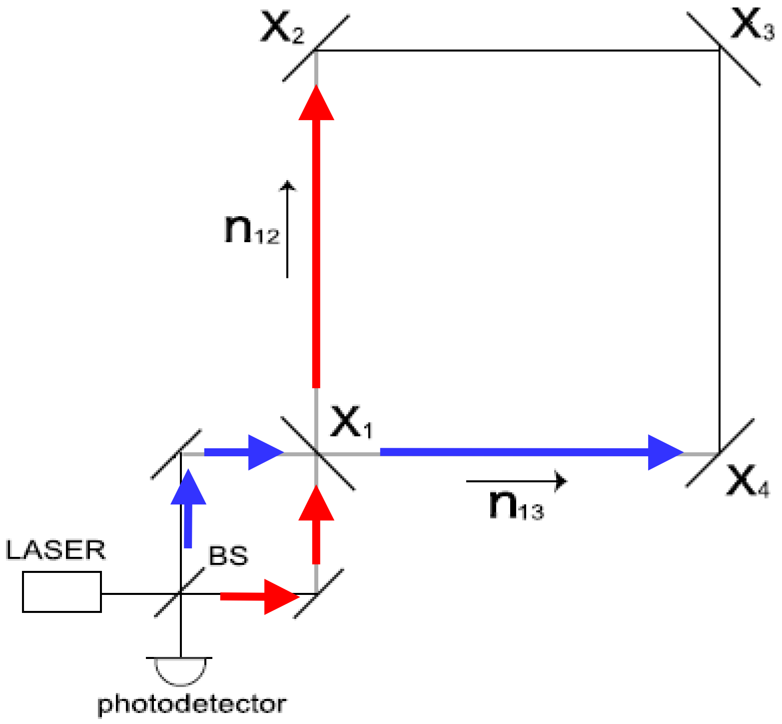
Amplify GW signals and **cancel displacement noises** **within narrowband.**

- X_3 **d. noise**
- X_1 **d. noise**
- X_2 **,** X_4 **d. noises**

- **GW signals**

Resonant speed meter

$$t = \frac{L}{c}$$



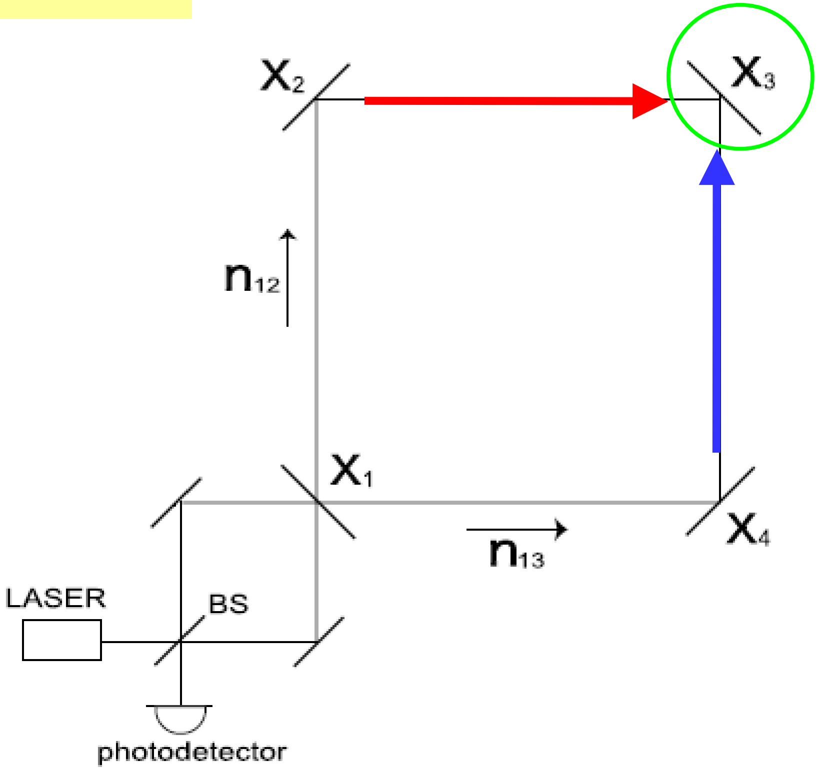
Amplify GW signals and cancel displacement noises within narrowband.

- X_3 **d. noise**
- X_1 **d. noise**
- X_2 **,** X_4 **d. noises**

- **GW signals**

Resonant speed meter

$$t = 2\frac{L}{c}$$

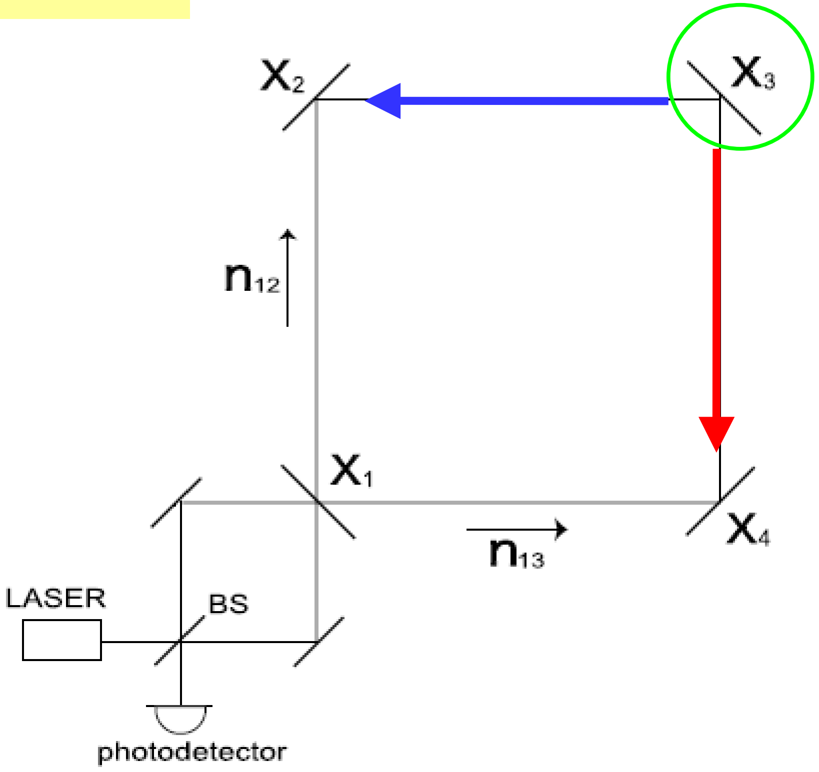


Amplify GW signals and **cancel displacement noises** **within narrowband.**

- X_3 **d. noise Canceled**
- X_1 **d. noise**
- X_2 **,** X_4 **d. noises**
- **GW signals**

Resonant speed meter

$$t = 3\frac{L}{c}$$



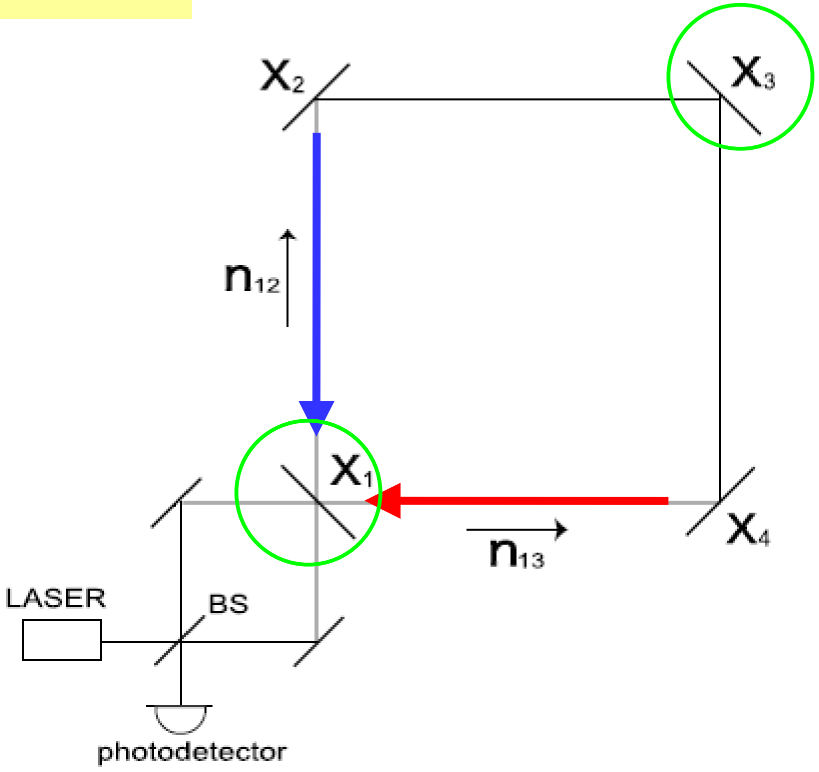
Amplify GW signals and cancel displacement noises within narrowband.

- X_3 **d. noise Canceled**
- X_1 **d. noise**
- X_2 , X_4 **d. noises**

- **GW signals**

Resonant speed meter

$$t = 4\frac{L}{c}$$

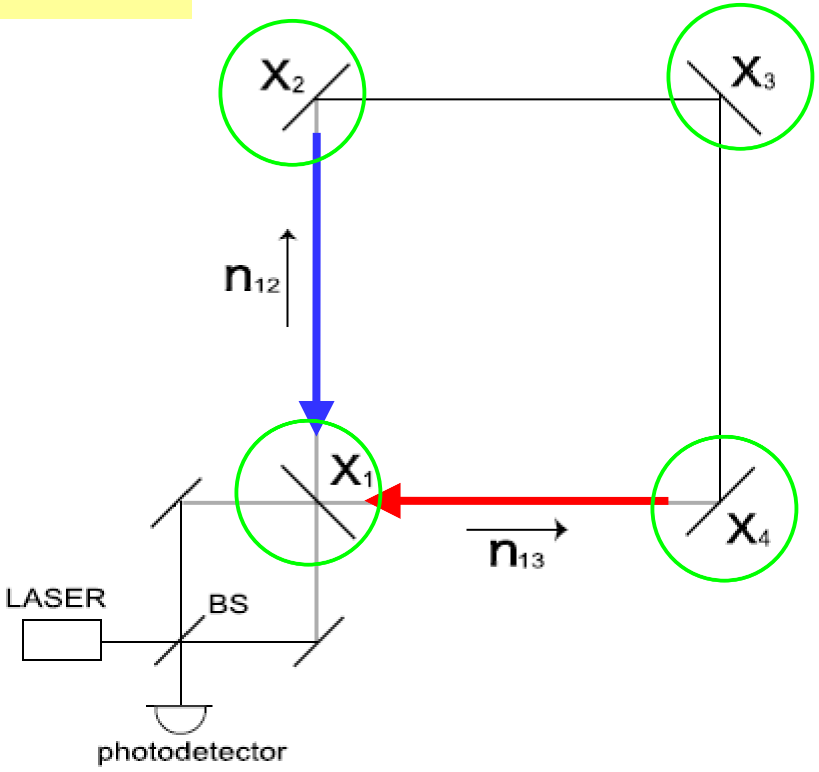


Amplify GW signals and cancel displacement noises within narrowband.

- X_3 **d. noise Canceled**
- X_1 **d. noise Canceled**
- X_2 **,** X_4 **d. noises**
- **GW signals**

Resonant speed meter

$$t = 4\frac{L}{c}$$



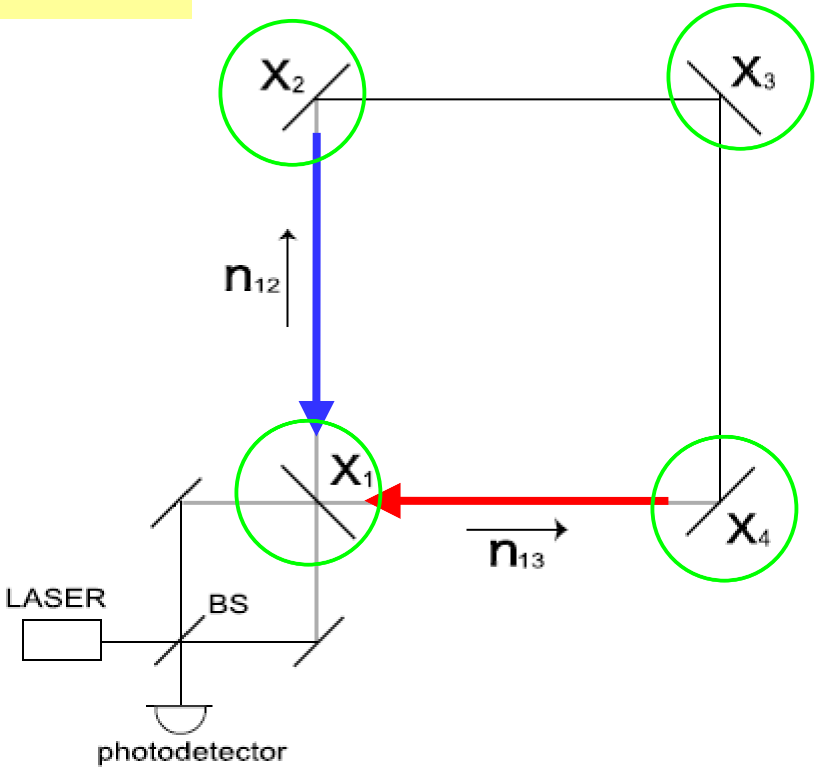
Amplify GW signals and cancel displacement noises within narrowband.

- X_3 **d. noise Canceled**
- X_1 **d. noise Canceled**
- X_2 **,** X_4 **d. noises**

  Canceled at $f_{cancel} = n\frac{c}{2L}$
- **GW signals**

Resonant speed meter

$$t = 4\frac{L}{c}$$



Amplify GW signals and cancel displacement noises within narrowband.

- X_3 **d. noise Canceled**
- X_1 **d. noise Canceled**
- X_2 , X_4 **d. noises**

Canceled at $f_{cancel} = n\frac{c}{2L}$

- **GW signals**

Resonate at $f_{gw} = (2m-1)\frac{c}{2L}$

The solution

$m = n = 1$ ($L = 1.5\ m \longrightarrow f_{cancel} = f_{gw} = 100MHz$)

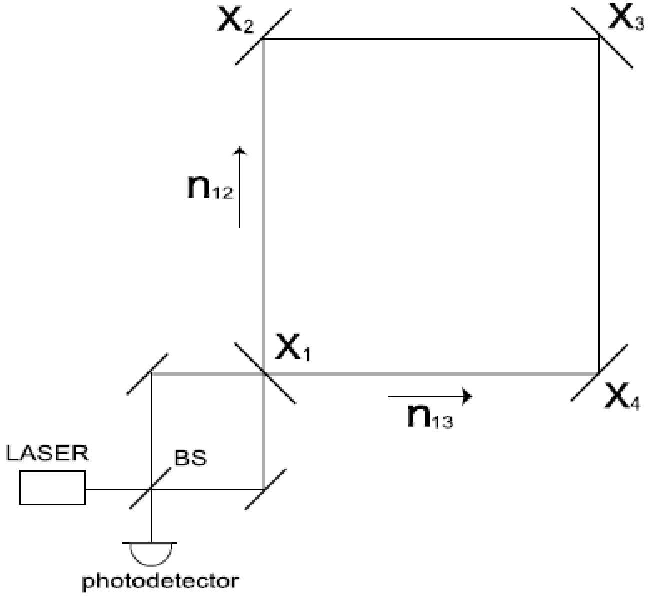
Why is it a resonant speed meter ?

Speed meter

— **CCW beam**
— **CW beam**

$$\phi_r^{(d)}(t) - \phi_\ell^{(d)}(t) = \sqrt{2}\omega/c\,[\underline{x_2(t-\tau)} - \underline{x_2(t-3\tau)} + \underline{x_4(t-\tau)} - \underline{x_4(t-3\tau)}]$$

$$\sim \sqrt{2}\omega/c\;2\tau\,[v_2(t-2\tau) + v_4(t-2\tau)]\,.$$



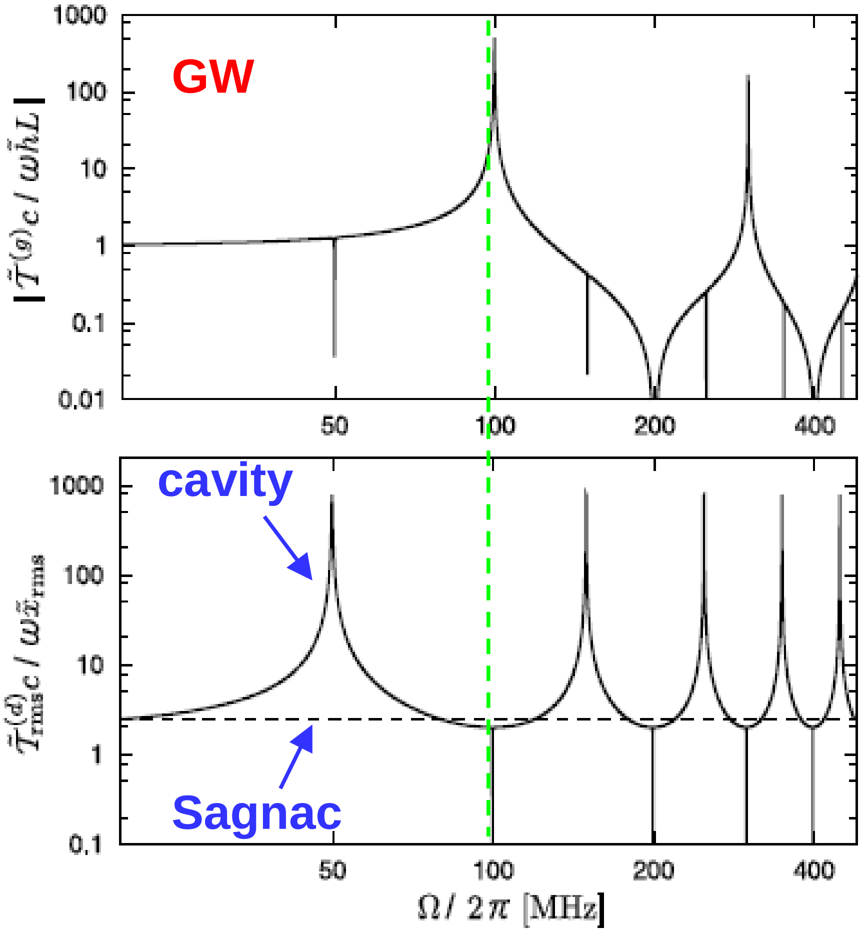
Monitoring the velocities of mirrors.

The same mechanism
as a conventional speed meter.

Resonant feature

In this design, GW signal is resonated by a cavity,
and no amplified displacement noise.

GW response and displacement noise



FSR ~ 50 MHz.

Amplification factor ~ 200.

GW response

Resonates at $f_{gw} = (2m-1)\frac{c}{2L}$

Displacement noise

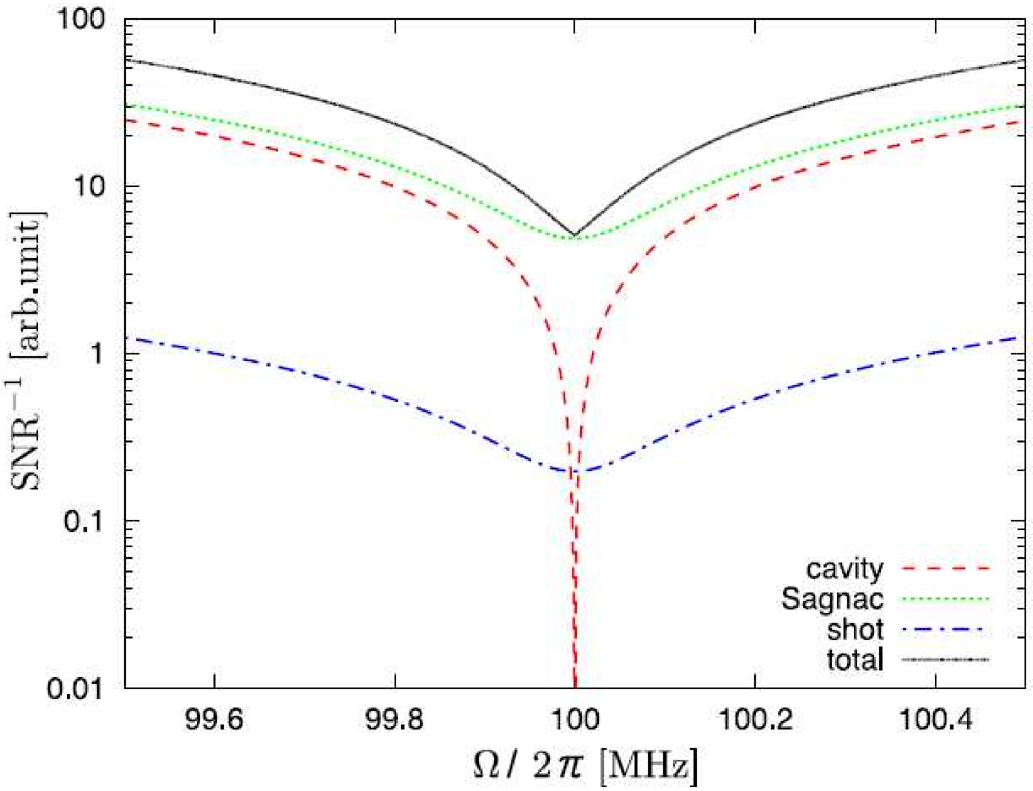
Cancels at $f_{cancel} = n\frac{c}{2L}$

(peaks vanish.)

Sensitivity - noise cancellation -

Amplification factor ~ 200. $$\tilde{x}_{\rm rms} = 10\,\tilde{x}_{\rm shot}$$

Cavity d. noise has a dip at 100 MHz.
The sensitivity is limited by the residual d. noise of Sagnac part.

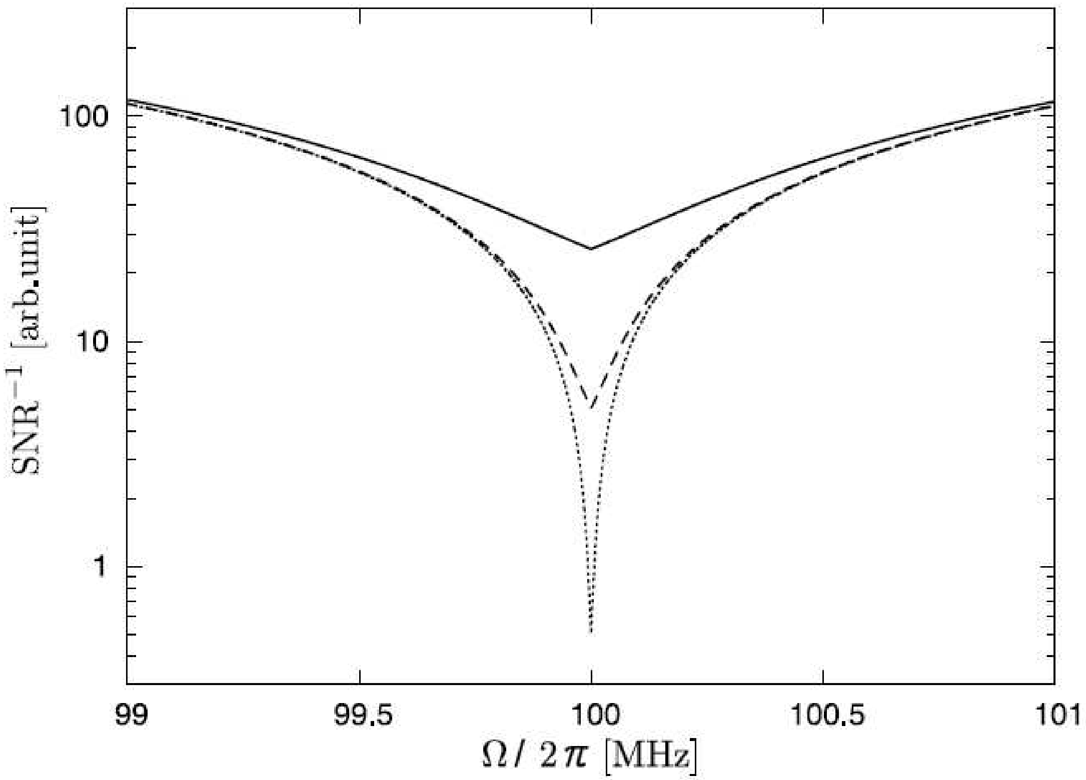


Sensitivity - amplification factor dependence -

The dependence of the sensitivity on the amplification factor.

Amplification factor ~ 40, 200, 2000.

Total sensitivity ~ $(amplification\ \ factor)^{-1}$



Summary

- **DFI : displacement noises are canceled,**
  then, the sensitivity is shot noise-limited.
  However, f^{-2} sensitivity at low frequencies.

- **FP cavity DFI: the same sensitivity as DFI without a cavity !**

- **Resonant speed meter: another approach to noise cancellation.**
  At certain frequencies, GW signals are amplified and displacement noises are suppressed.
  Then, high sensitivity with narrow bandwidth is realized, being proportional to circulating number of light in the cavity.

- **Applications: ultra high frequency GW search (~100 MHz).**

AN et al., PRD 77, 022002 (2008), AN et al., arXiv:0801.4149

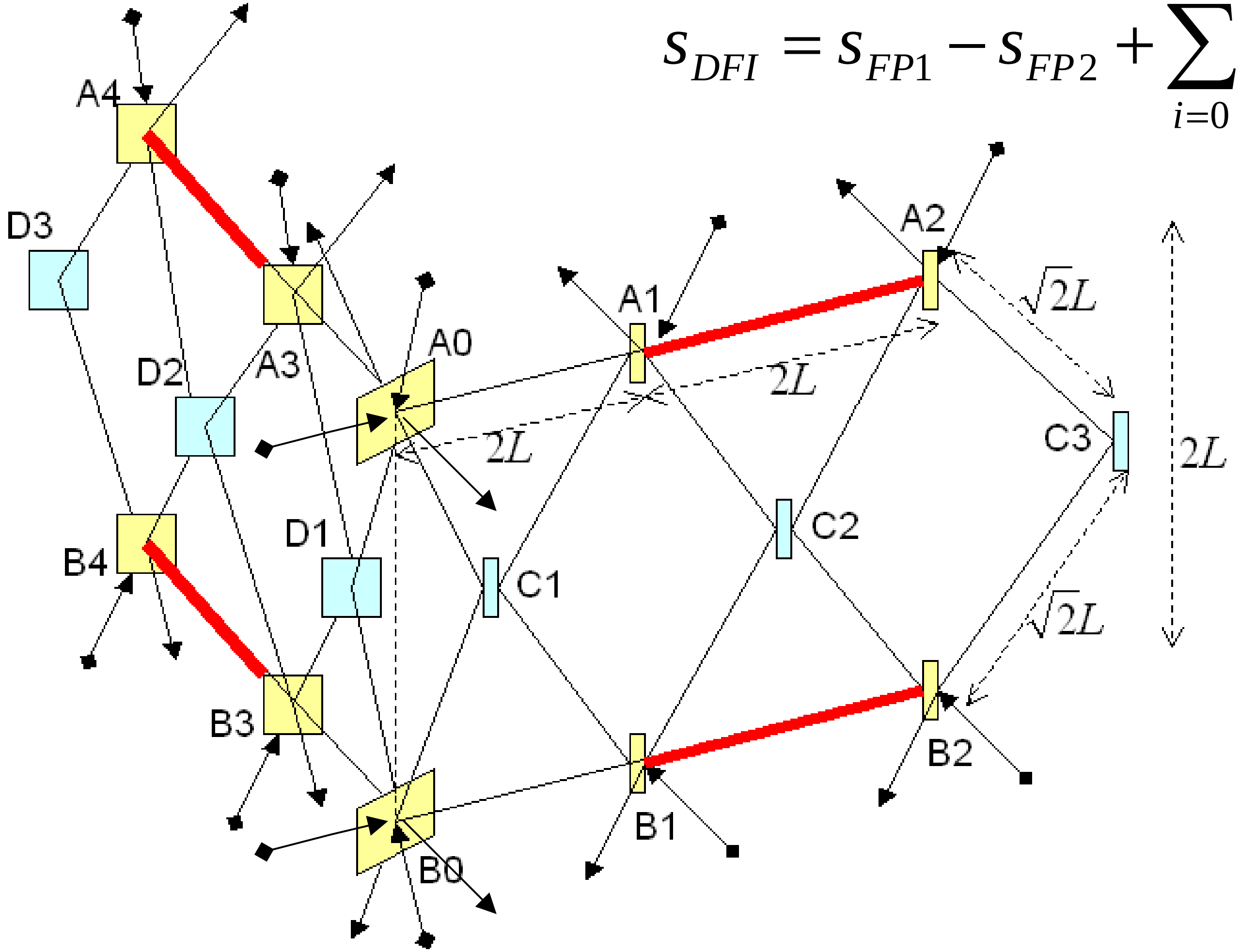
We are also investigating the application to ground-base detectors (LIGO and VIRGO etc.), and space-based detectors (LISA and DECIGO).

Appendices

DFI with FP-cavity

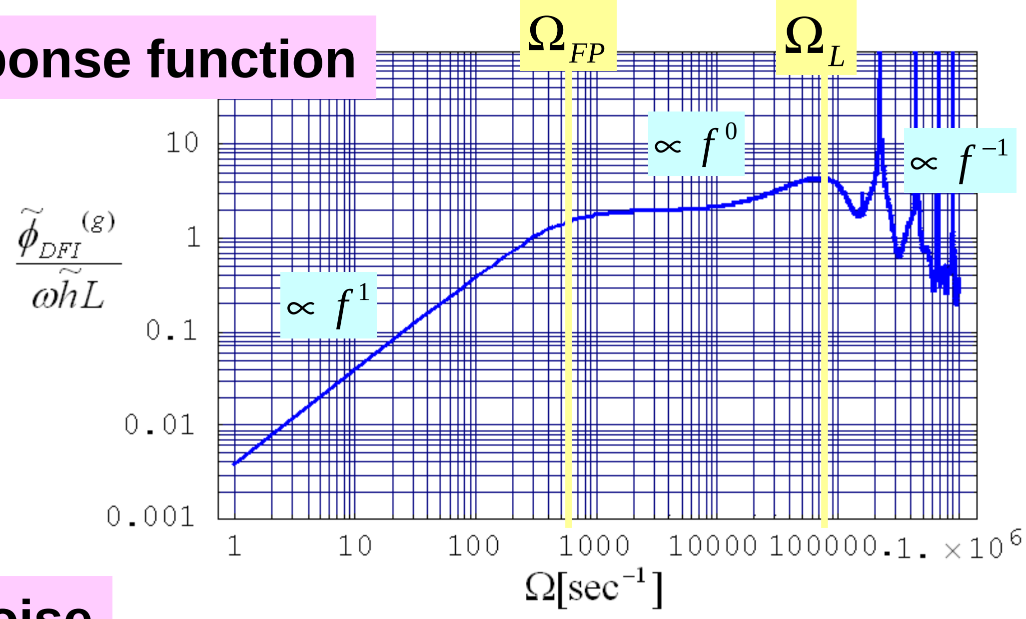
- 2 FPMI + 5 MZI
- All displacement noises are canceled.

$$s_{DFI} = s_{FP1} - s_{FP2} + \sum_{i=0}^{4} \gamma_i s_{MZi}$$

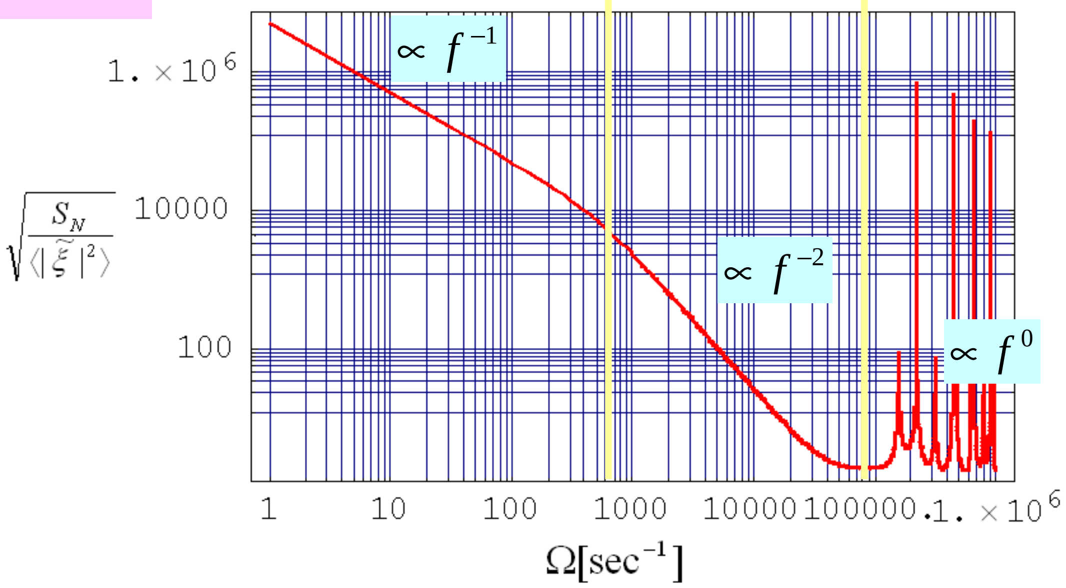


Results1

GW response function



Shot noise



Characteristic frequency

$$\Omega_{FP} \equiv \frac{T^2 c}{4L}$$

$$\Omega_L \equiv \frac{c}{L}$$

Parameters

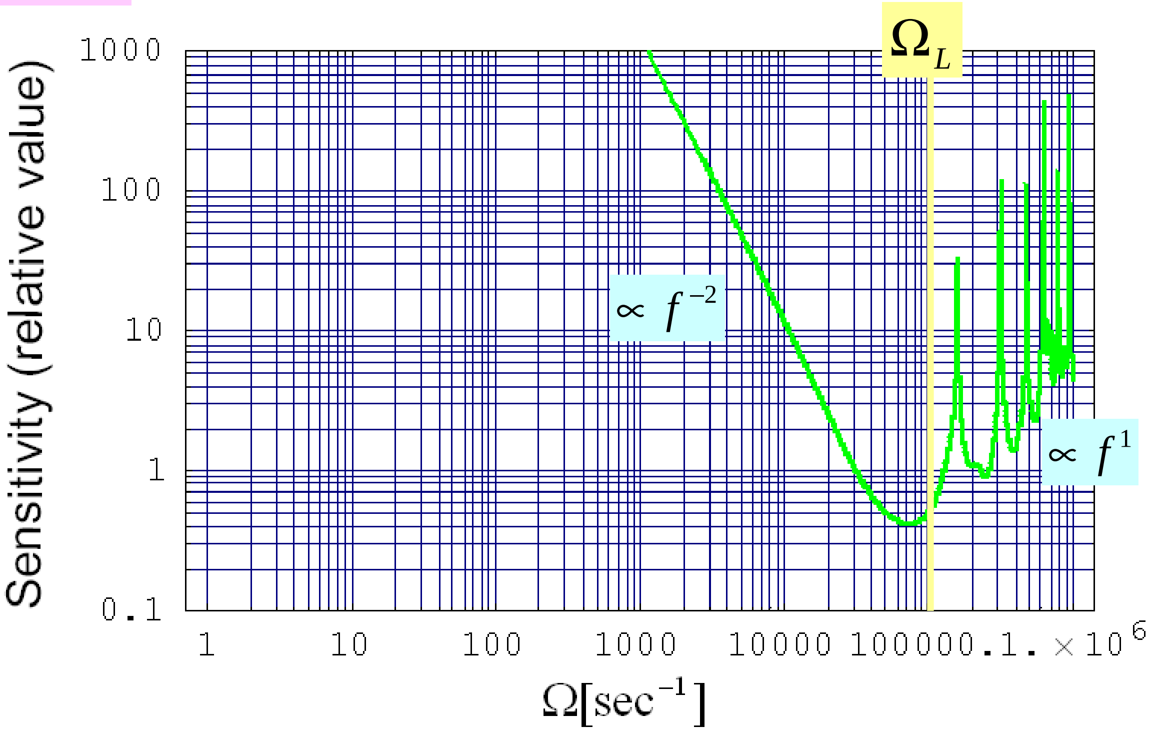
$$L = 3km$$

$$F \approx 157$$

Shot noise spectrum has frequency dependence due to DFI coefficients.

Results2

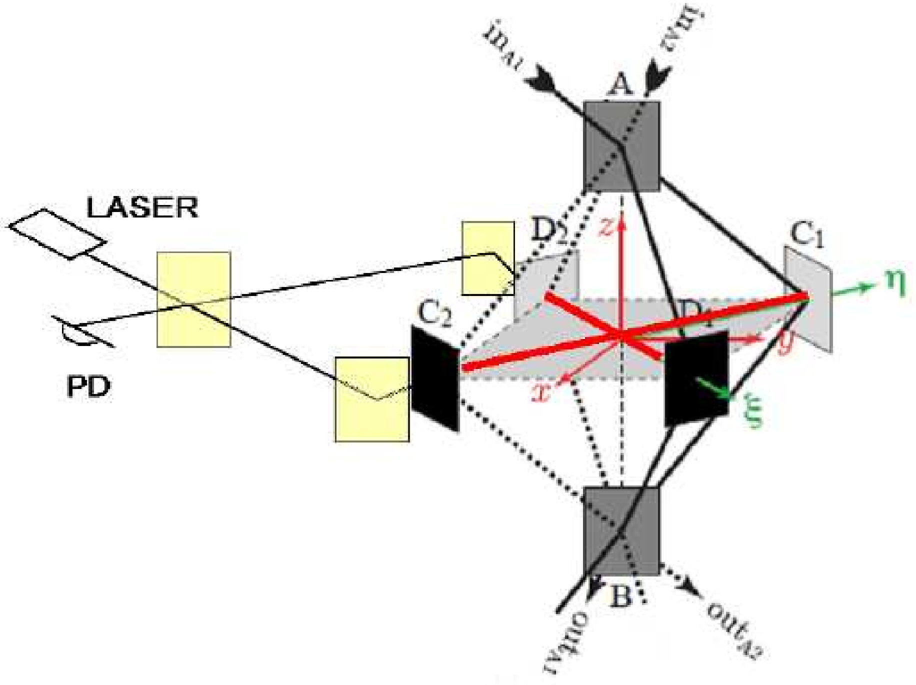
Sensitivity

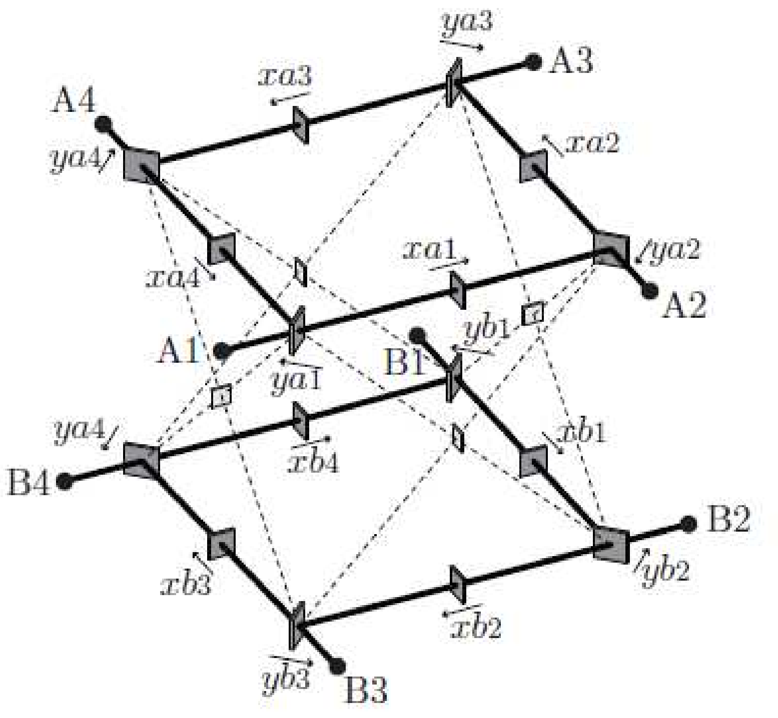


In total, the sensitivity becomes worse below Ω_L .
This is the same frequency dependence as DFI signal without FP cavity !

Unfortunately, we had negative results.

Other cavity DFI





Cavity DFI with two SRI