Three-mirror cavity for quantum noise reduction of future gravitational wave detectors

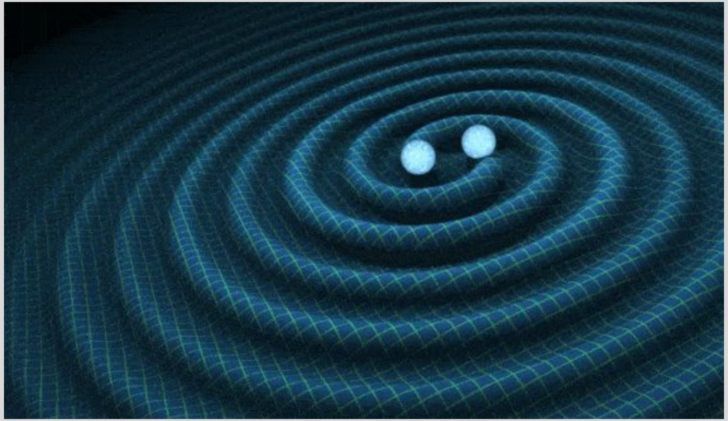
Outline

1. **Context**
2. **Three-mirror cavities optics**
3. **Conclusion**

Context

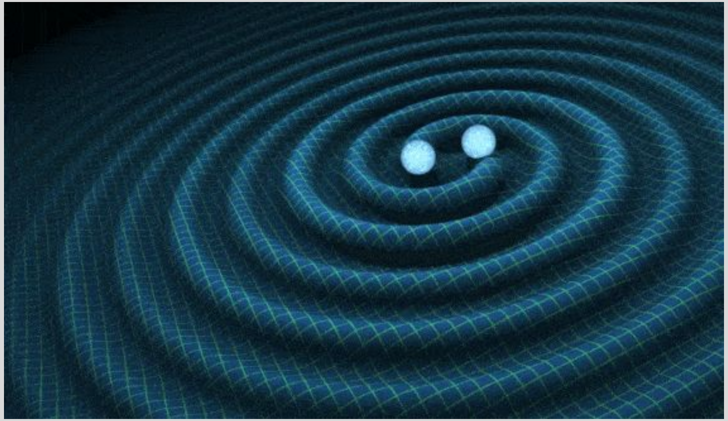
Gravitational waves

Context



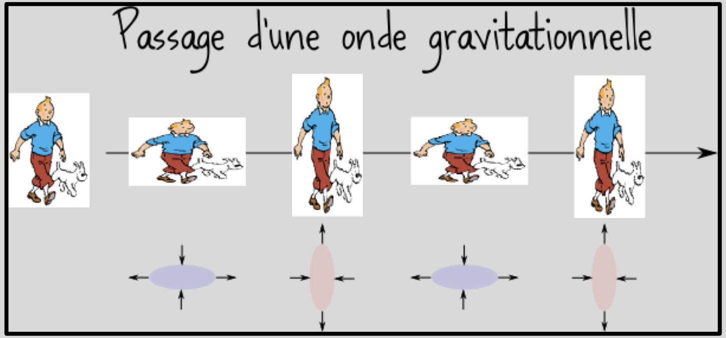
Accelerated masses &
propagation through
space-time

Gravitational waves



Accelerated masses & propagation through space-time

Stretch / compress orthogonal directions



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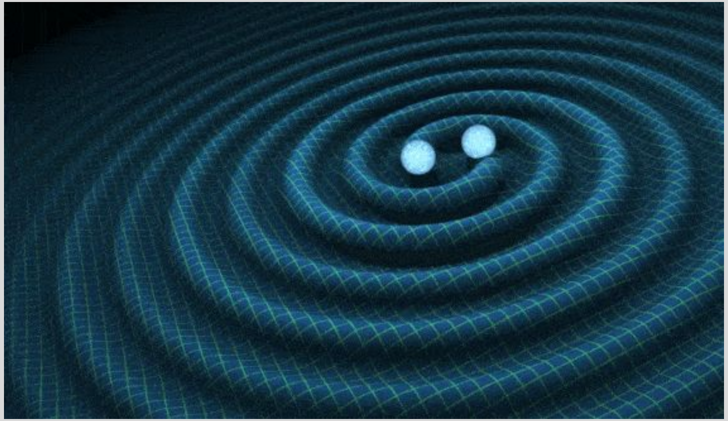

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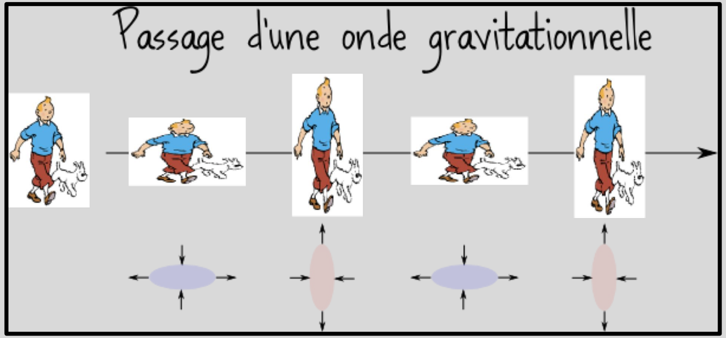
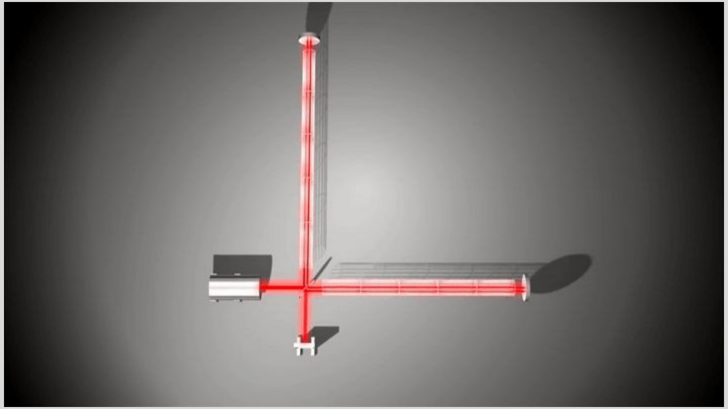


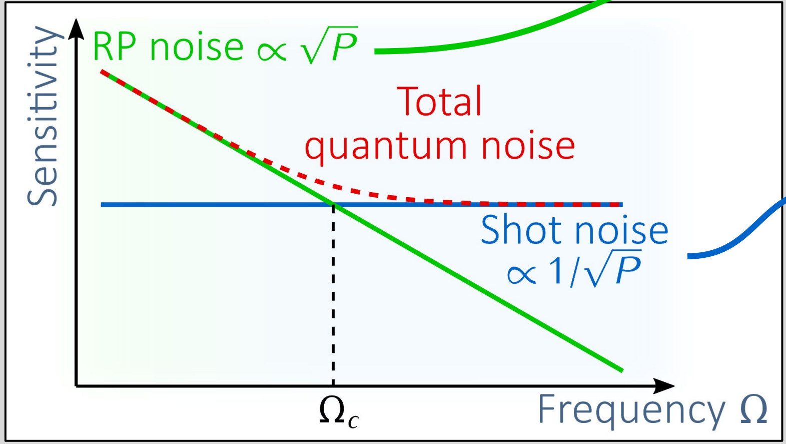


Detection via **Michelson interferometer**

Quantum noise

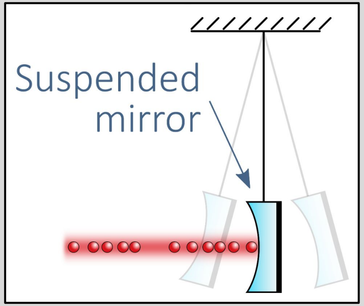
Total quantum noise : sum of two sources

- **Radiation pressure (RP) noise**
- **Shot noise**
- **Cross each other at frequency Ω_c**



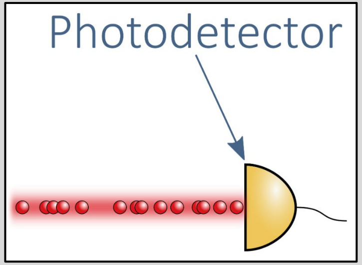
Radiation pressure noise
→ Is an amplitude noise

Arises from **impact of laser beam on mirrors**



Shot noise
→ Is a phase noise

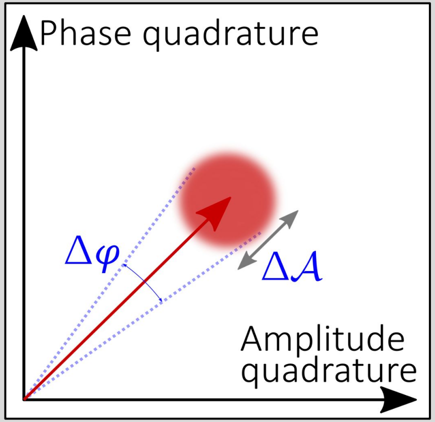
Arises from **variation of photon number in the beam** (Poisson statistic)



Context

Squeezed states of light

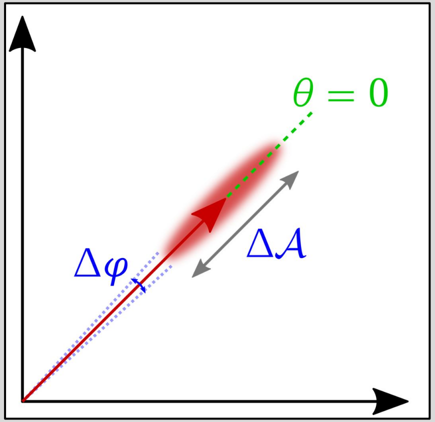
Coherent state



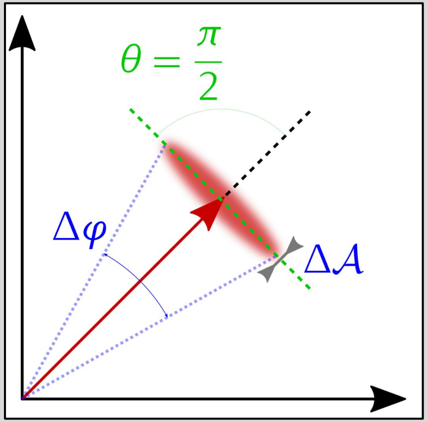
Uncertainty disk:
Heisenberg principle
$\Delta A \, \Delta \varphi \geq 1$

Optical Parametric Oscillator (OPO) "converts" input coherent beam to squeezed beam

Phase sq. state



Amplitude sq. state

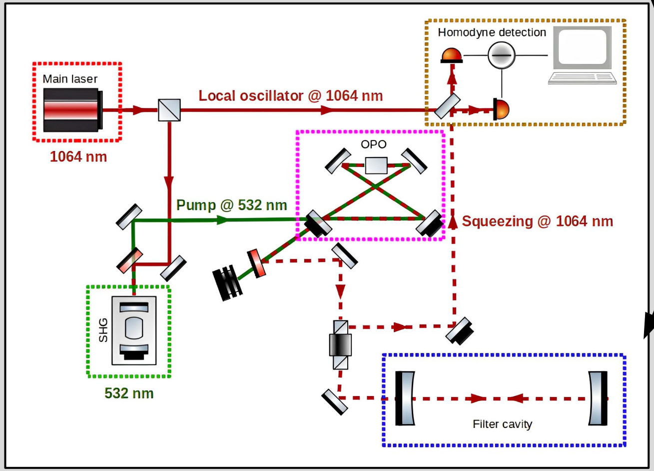


- For both cases, the area of uncertainty region is equal to the uncertainty of initial coherent state
- Choose either to reduce phase noise at the prize of increasing amplitude noise or the invert

Frequency dependent squeezing & filter cavity (1/2)

Context

The squeezed beam produced in the OPO enters into a **« filter cavity »**



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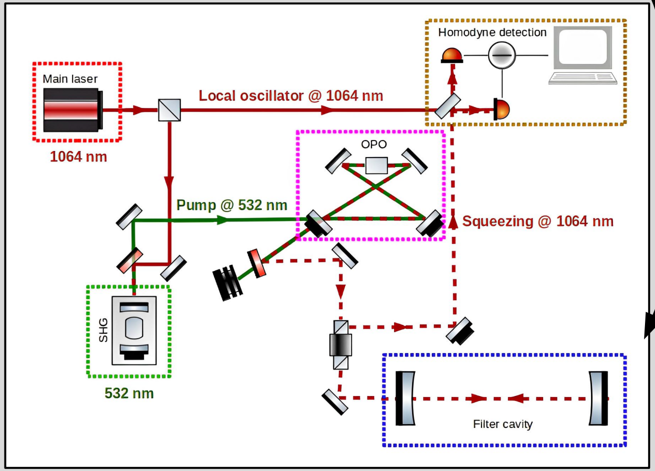

The configuration of the filter cavity define a **frequency Ω_t around which a transition of squeezing nature (amplitude / phase) occurs**

$$\Omega_t = \frac{\pi c}{\sqrt{2}LF(r_i)}$$

L: cavity length

F: finesse of the cavity (depends on mirrors reflectivities r_i)

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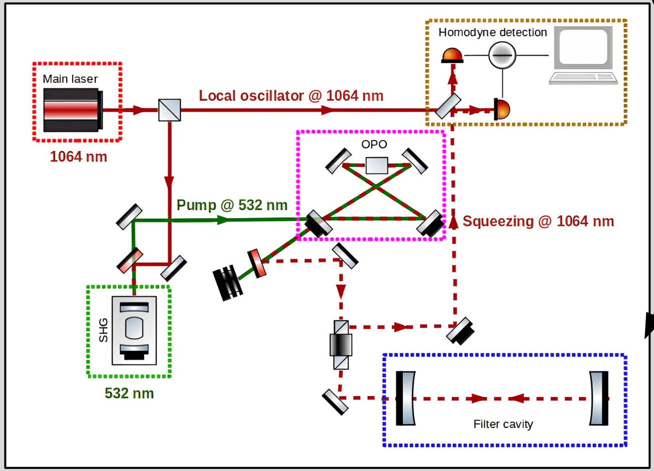

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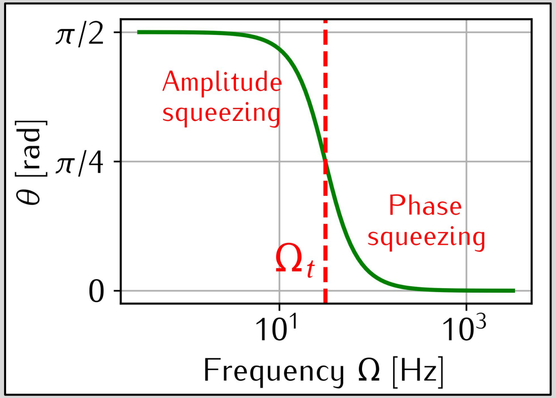

The squeezing ellipse rotation curve shape is a consequence of filter cavity optical behavior

Choose filter cavity setting so that $\Omega_t = \Omega_c$

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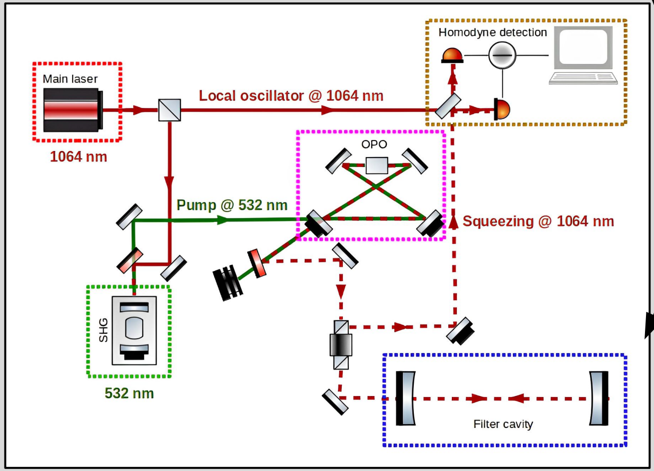

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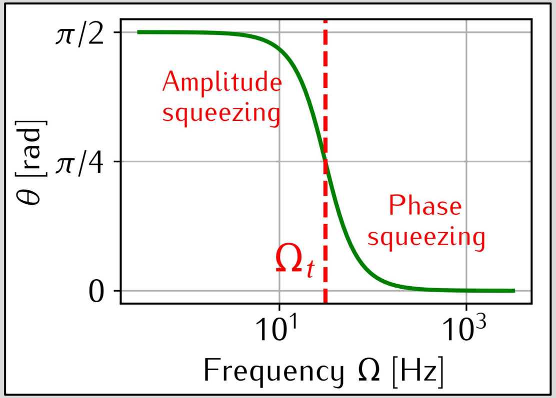

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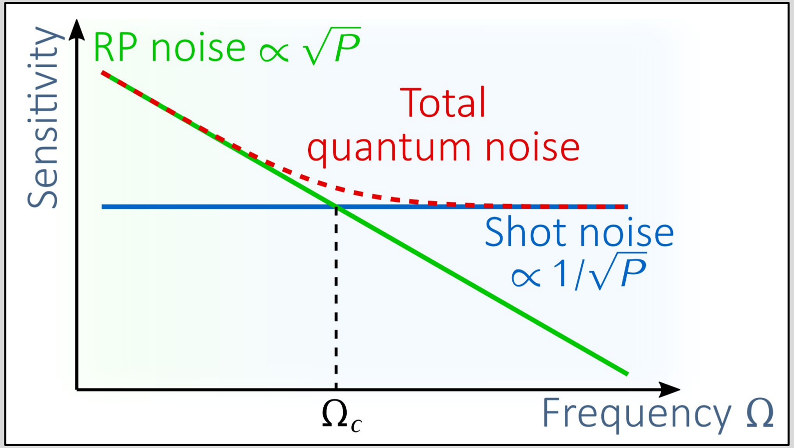

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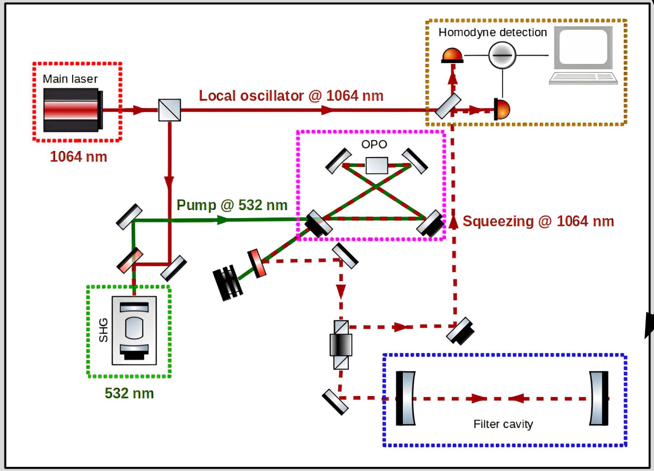

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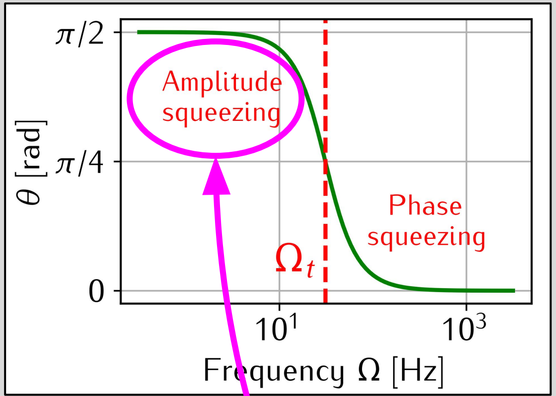

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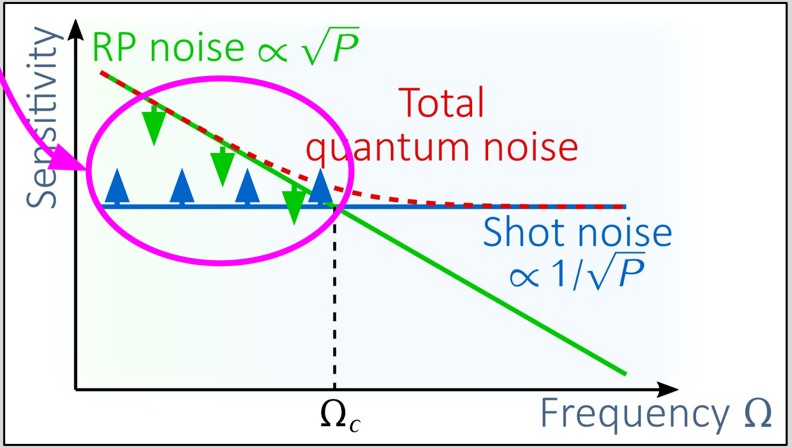
Resulting situation: below Ω_c the RP noise is decreased while the shot noise is increased



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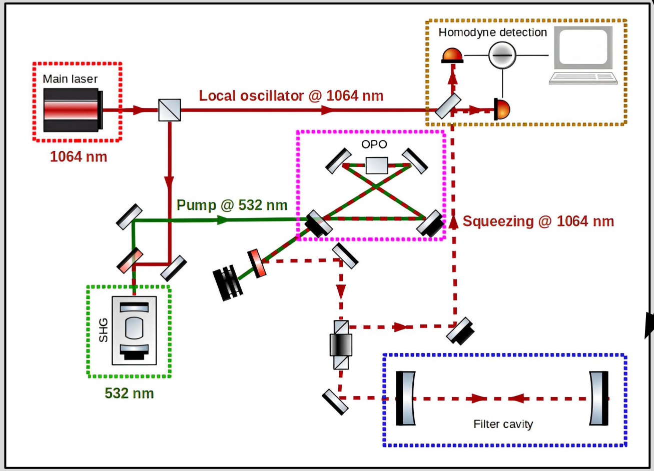

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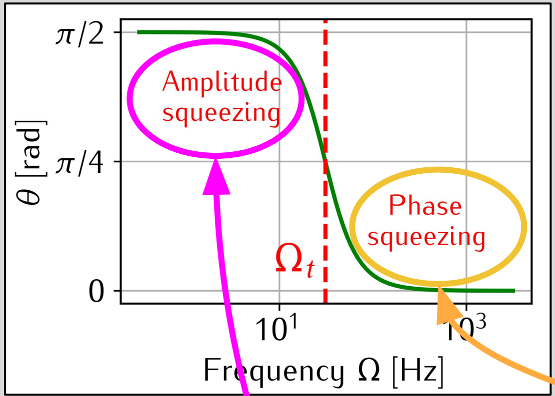
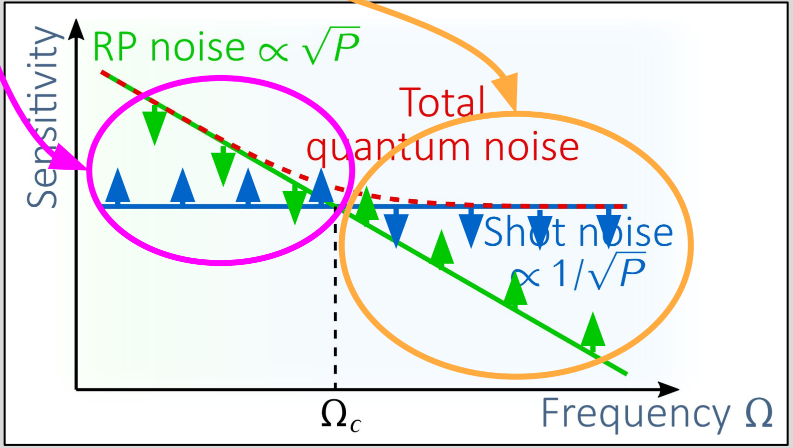


The squeezing ellipse rotation curve shape is a consequence of filter cavity optical behavior

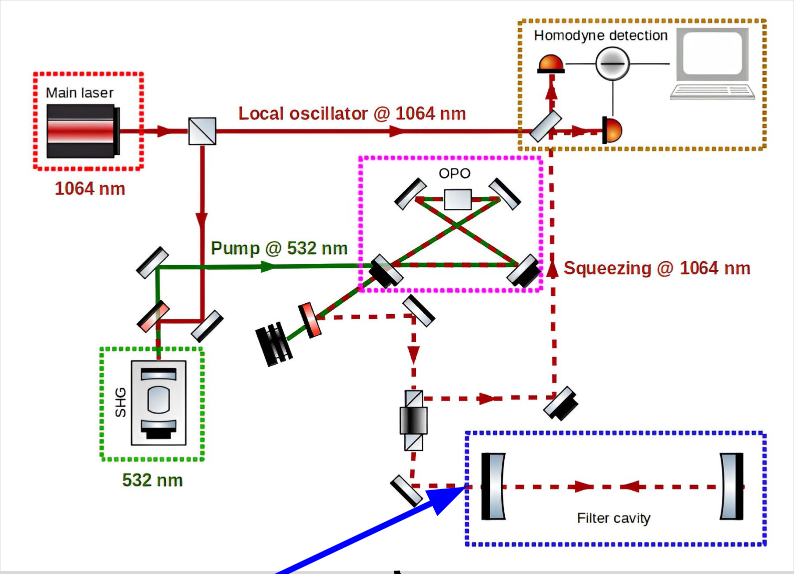
Choose filter cavity setting so that $\Omega_t = \Omega_c$

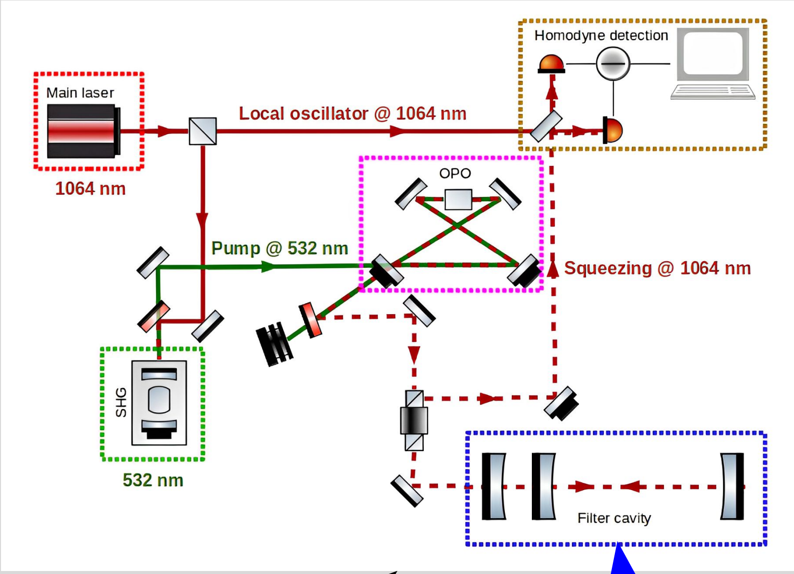
Resulting situation: below Ω_c the RP noise is decreased while the shot noise is increased, above Ω_c the situation is inverted

⇒ QN reduced at all frequencies



Frequency dependent squeezing & **three-mirror cavity**



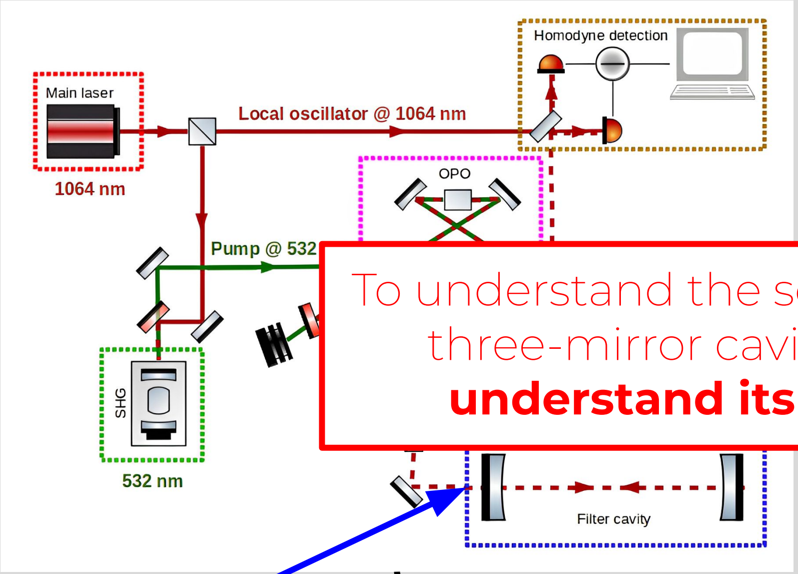


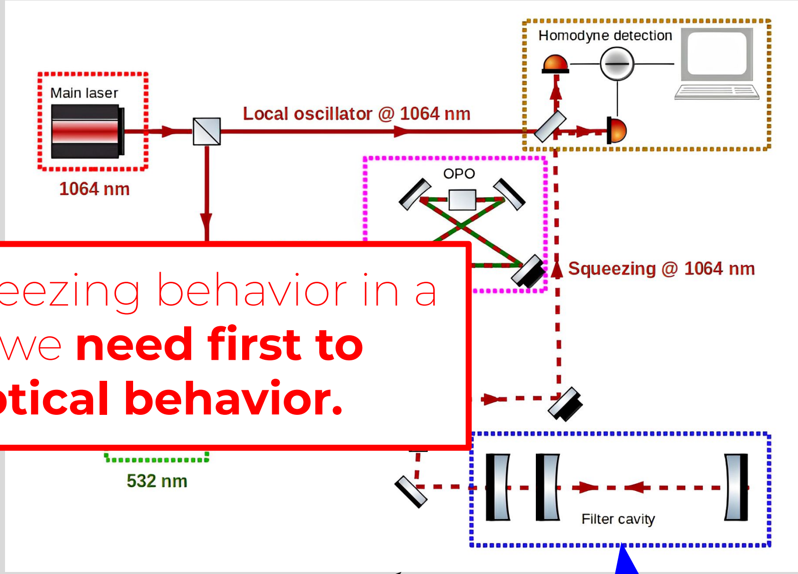
Fabry-Perot cavity

Impact on squeezing properties ?

Three-mirror cavity

Frequency dependent squeezing & **three-mirror cavity**





To understand the squeezing behavior in a three-mirror cavity, we **need first to understand its optical behavior.**

Fabry-Perot cavity

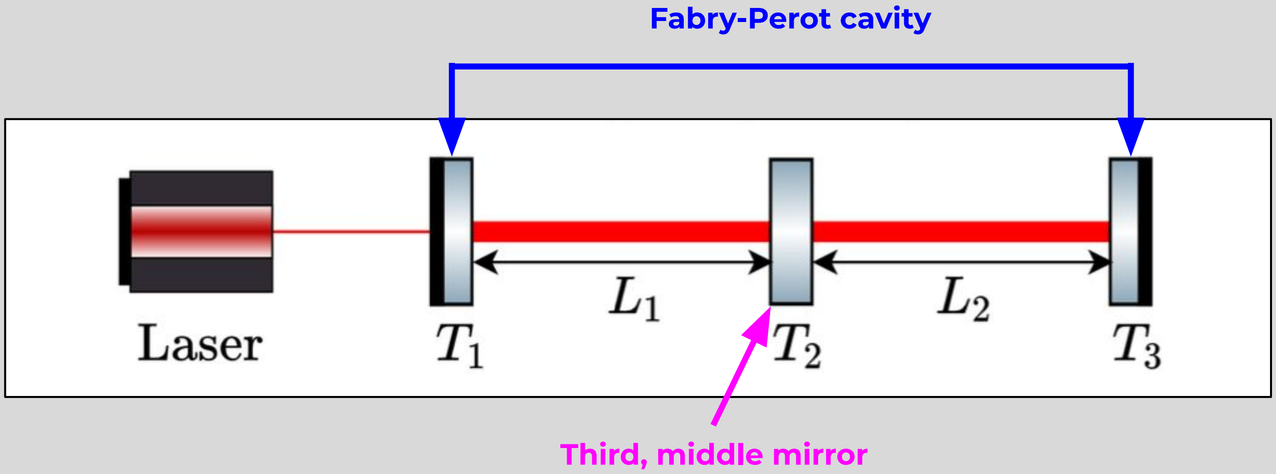
Impact on squeezing properties ?

Three-mirror cavity

Three-mirror cavities optics

Three-mirror cavity

- Simple Fabry-Perot cavity + third, “middle” mirror (two “sub” cavities)
- Three optical resonators
- Despite simple configuration, **non-trivial behavior**



Modelisation and simulation setup

To characterize the system: <u>how the global transmissivity and reflectivity of a three-mirror cavity change when we modify the configuration ?</u>

1 - Modelisation

2 - Simulations

Modelisation and simulation setup

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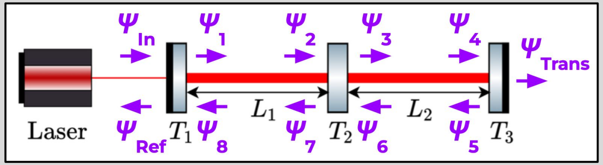

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k: wave-vector; r_i and t_i: reflection and transmission coefficients of mirror "i"

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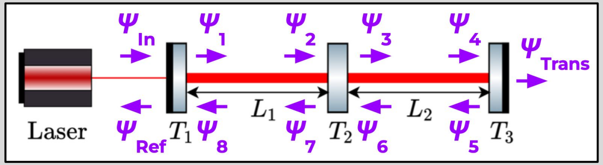

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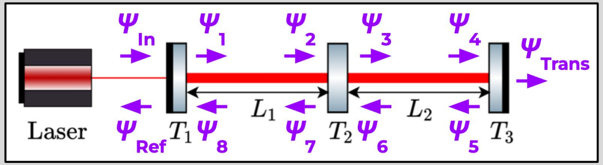

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C - Cavity behavior: complex combination of configuration parameters
➔ **simulations**

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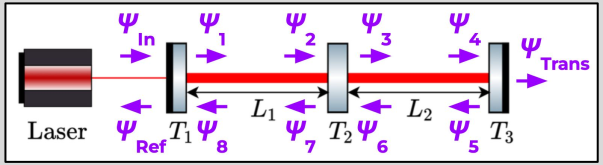

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→ **simulations**

2 - Simulations

- Implement global reflection and transmission coefficients in a code

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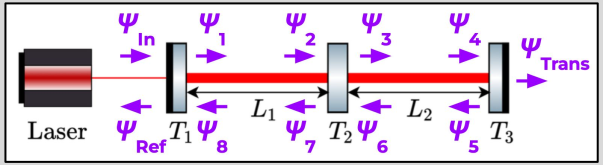

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C - Cavity behavior: complex combination of configuration parameters
→ **simulations**

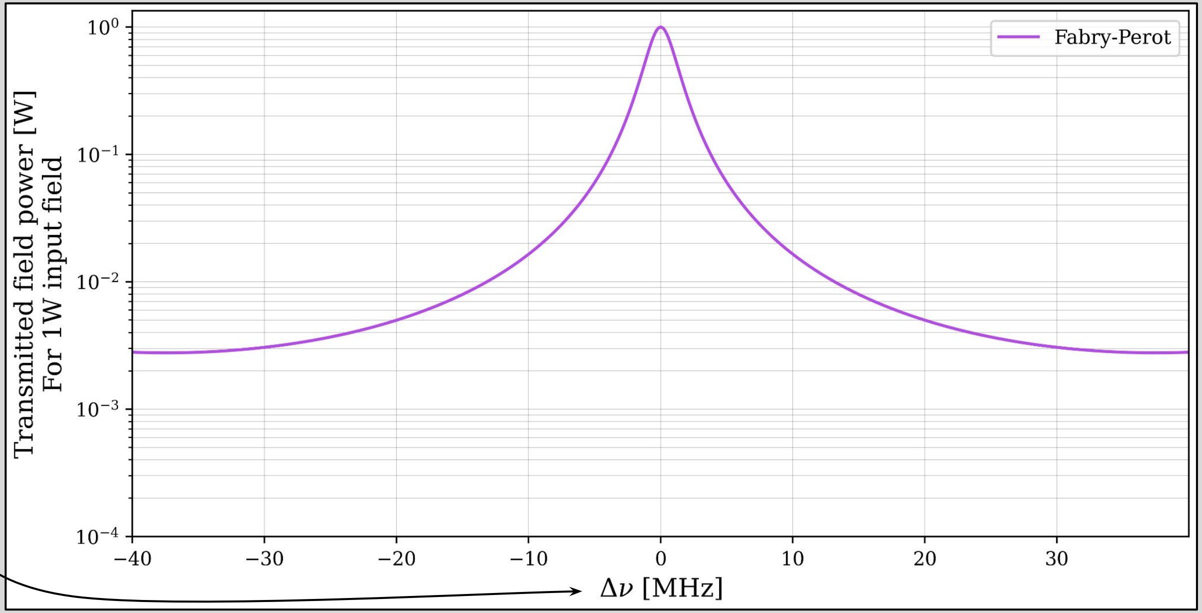
2 - Simulations

- Implement global reflection and transmission coefficients in a code
- Parameters to change:
  - **Laser wavelength (wave-vector)**
  - **First, second and third mirrors transmission coefficients**
  - **L_1 and L_2 distances**

The doubling of transmission peak

For Fabry-Perot cavity:
transmission peak for each resonance condition (cavity length = integer number of half-wavelength)

Scan the input field detuning



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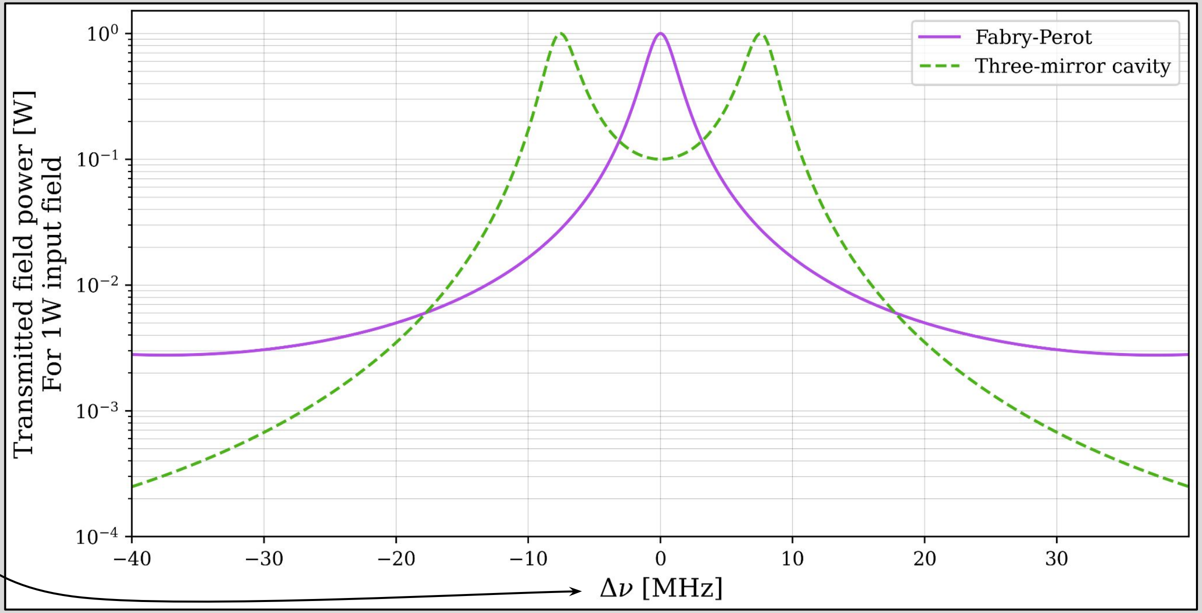

A <u>three-mirror cavity</u> can show off a <u>doubling of the transmission peak</u>

The doubling of transmission peak

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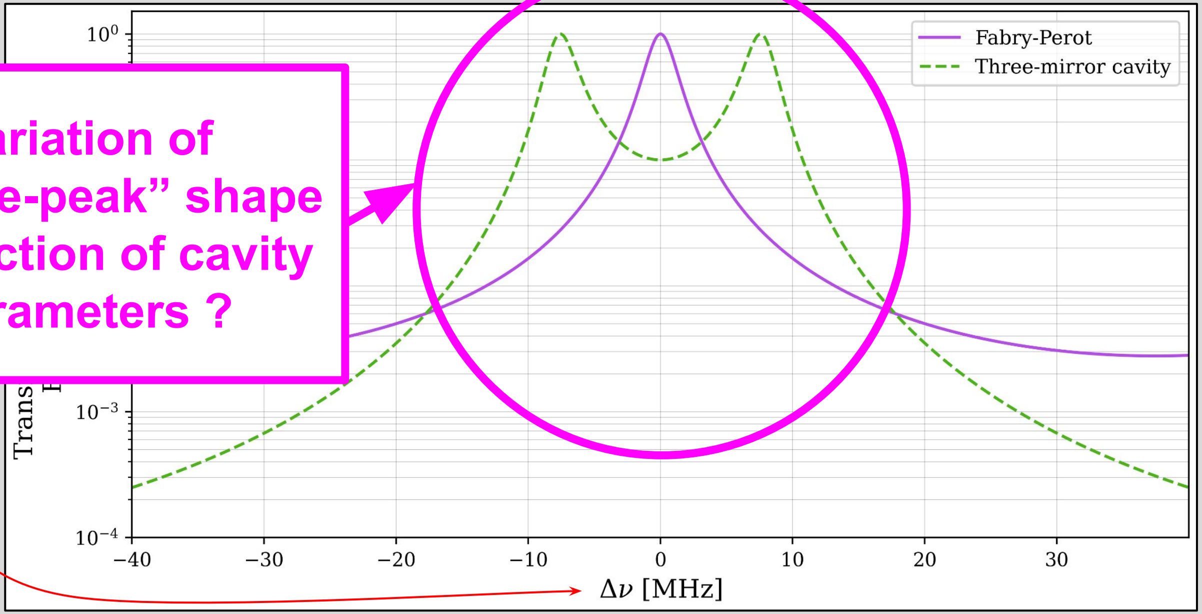
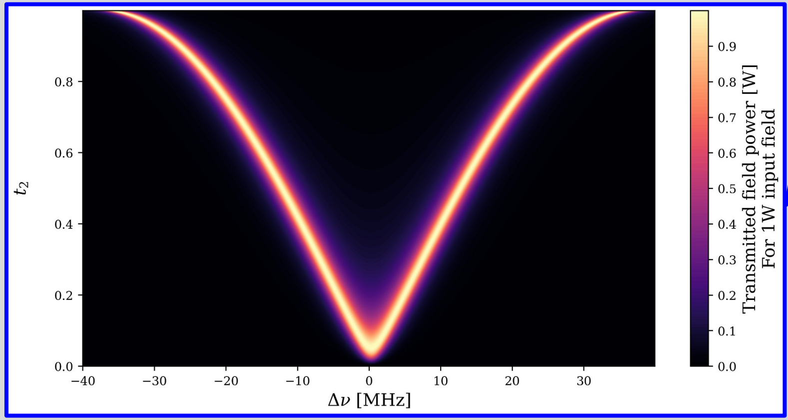
Variation of "double-peak" shape as function of cavity parameters ?

Scan the cavity length/input field detuning



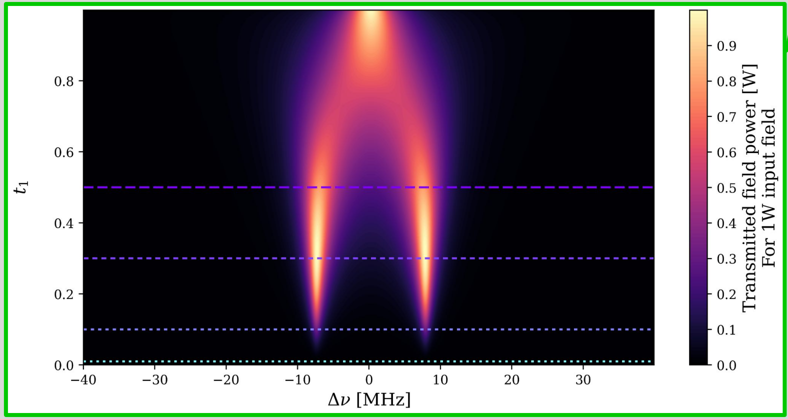
A <u>three-mirror cavity</u> can show off a <u>doubling of the transmission peak</u>

Mirrors transmissivity

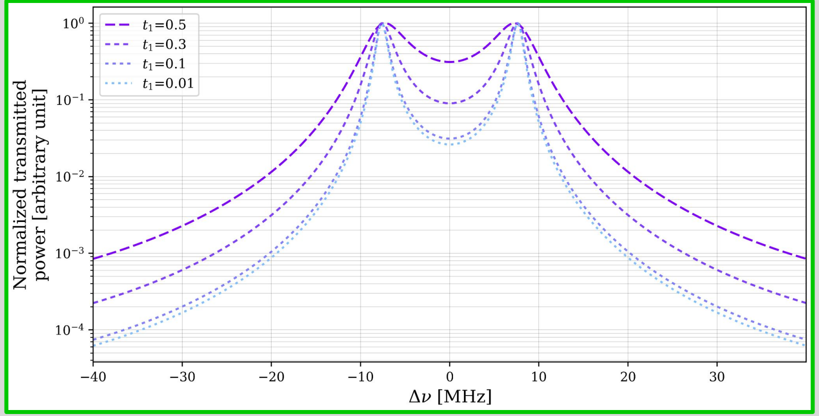


Second mirror transmissivity → **symmetrical variation of space** between maxima

First (or third) mirror transmissivity → **sharpen** each maxima

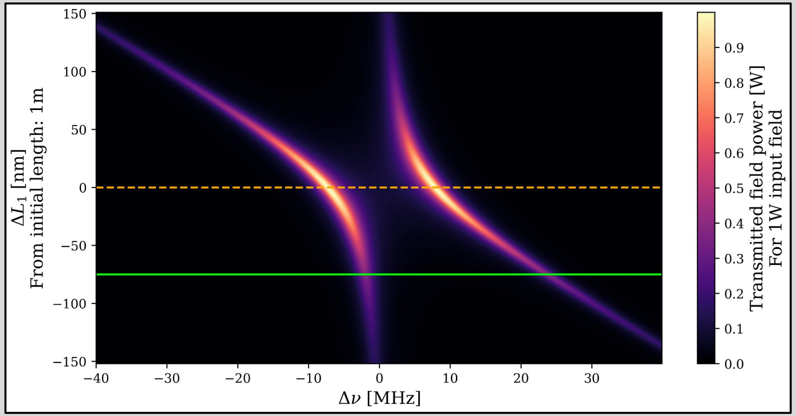


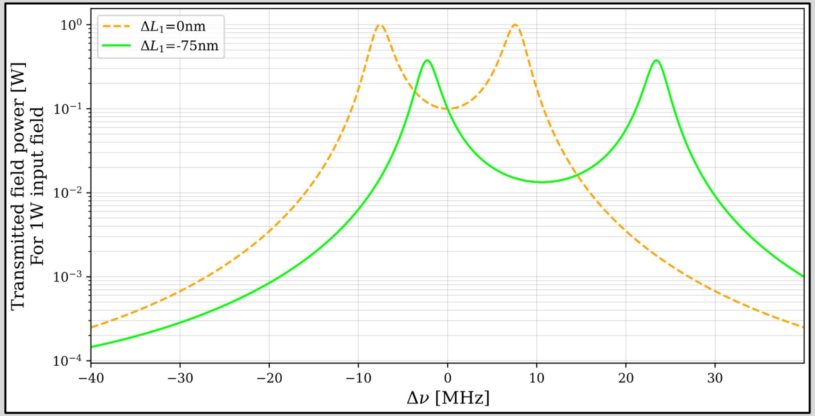
Fixed parameters: L_1 = L_2= 1m, R_2 = 0.9



Three-mirror cavities optics

Microscopic mirrors spacing

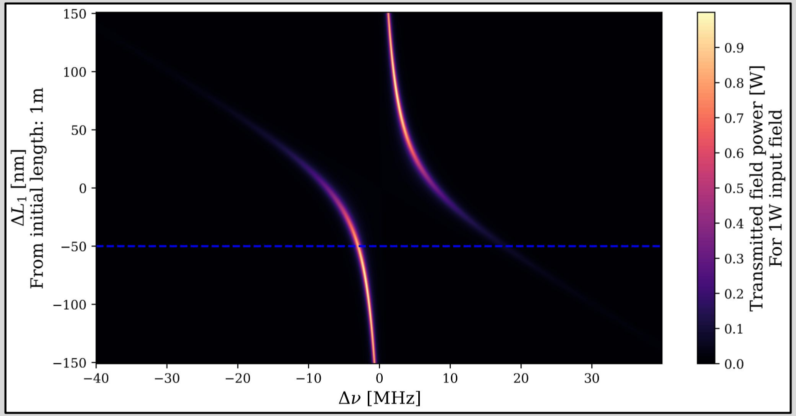


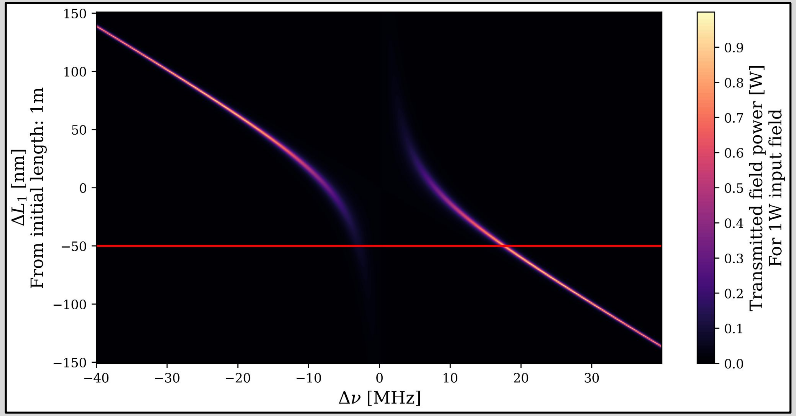


Asymmetrical variation of maxima spacing (same power in each maxima)

Fixed parameters: L_2 = 1m, R_1 = R_2= R_3 = 0.9

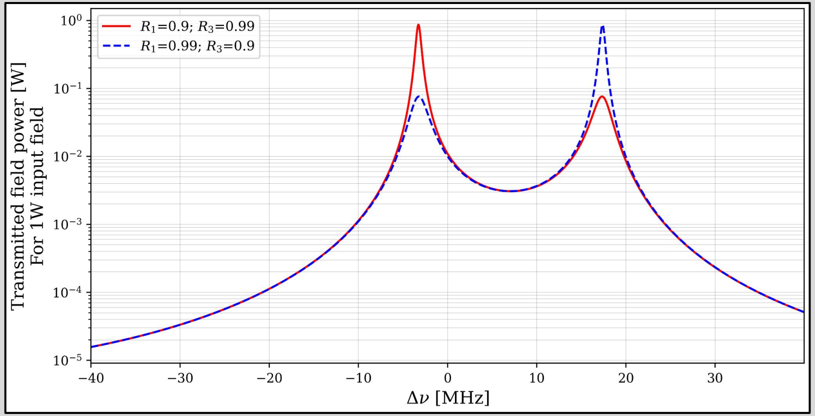
Mirrors transmissivity (again)





Variation of power along resonance lines

Fixed parameters: L_2 = 1m, R_2 = 0.9



Conclusion

Conclusion

- Simulations of three-mirror cavity optics: ✅
  - **Doubling of resonance peak**
  - **Position, height and sharpness of “double-peak” maxima almost completely modulable** by changing the cavity configuration
    ⇒ Quantum noise reduction for next GW detectors!
  - Need to pay attention to **cavity stability** (not presented here)
- Currently: implementation of a **meter-scale prototype on CALVA platform, IJCLab**
- Next step: **simulations of squeezing properties** in a three-mirror cavity

Thank you !

Backup slides

Frequency dependant squeezing for next generation of GW detectors

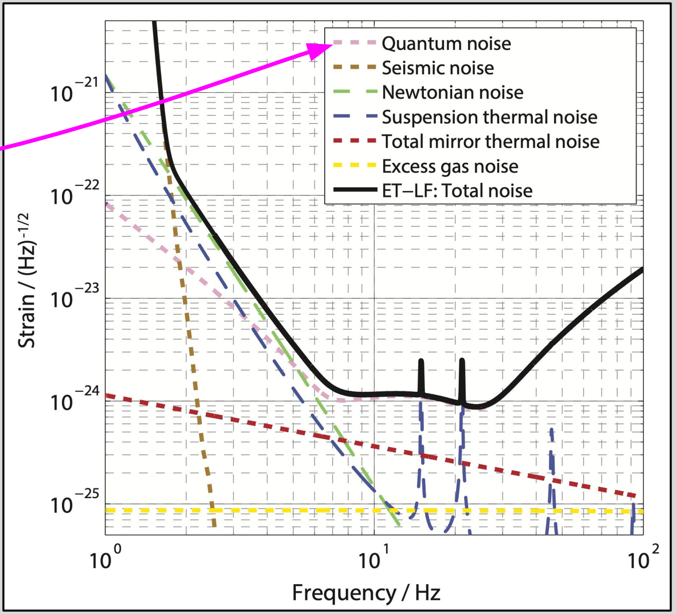
Context

Frequency dependant squeezing in current detectors:

⇒ Squeezed beam filtered with a “simple” Fabry-Perot cavity → allow to reduce QN at all frequencies

Future detectors:

⇒ Is it possible to develop a **system for more complex QN shape, Einstein Telescope - Low Frequency (ET-LF) ?**
⇒ Current proposition: two Fabry-Perot cavities in series



Problematic:

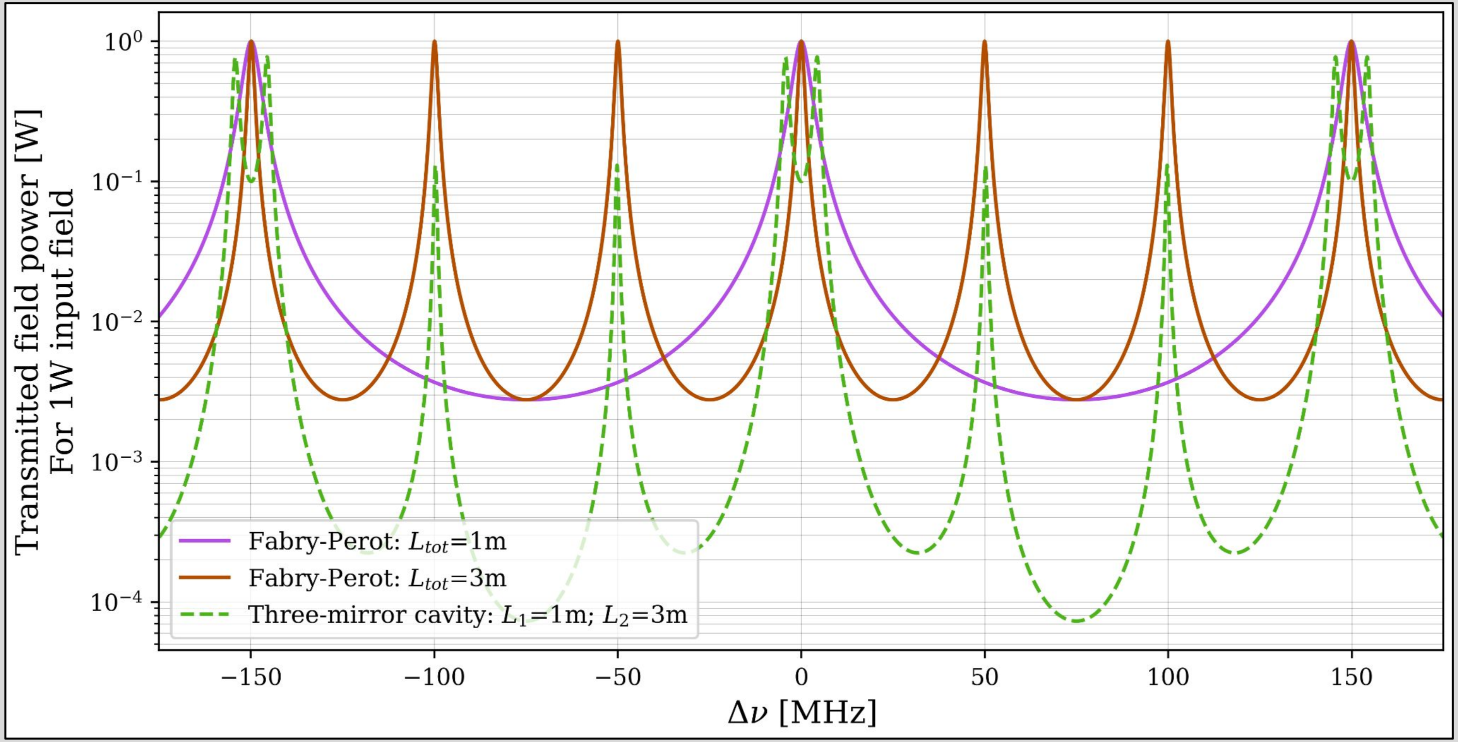
⇒ <u>Replace the two Fabry-Perot cavities with a three-mirror cavity ?</u>

To understand the squeezing behavior in a three-mirror cavity, we **need first to understand its optical behavior.**

Condition for doubling of transmission peak

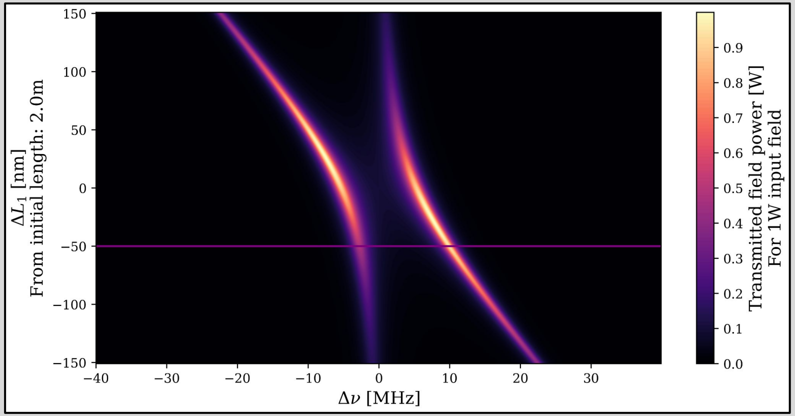
Three-mirror cavities optics

Each sub-cavity have to be resonant



Three-mirror cavities optics

Macroscopic mirrors spacing



Asymmetrical variation of maxima spacing and power ratio

Fixed parameters: L_2 = 1m, $R_1 = R_2 = R_3 = 0.9$