CALVA: Experimental platform for GW detectors

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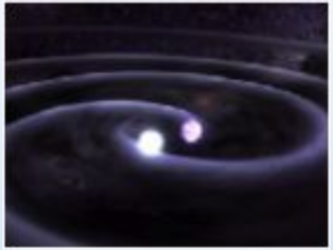
A2C Seminar

What are Gravitational waves ?

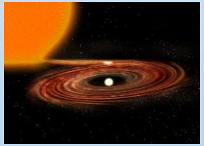


- Solution from General Relativity derived by A. Einstein in 1916, first experiments in the 60s
- Gravitation is a curvature of the space-time metric
- Any massive object will introduce a deformation of the metric
- Gravitational waves are a perturbation of space-time propagating at the speed of light

<u>Some sources:</u>

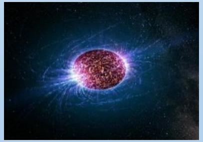
<u>Supernova</u>

Assymetric core collapse



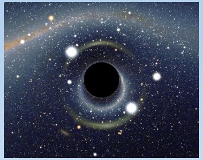
<u>White dwarf</u>

- 1.4 solar masses
- Density : 1.10^{9} kg/m^{3}



<u>Neutron star</u>

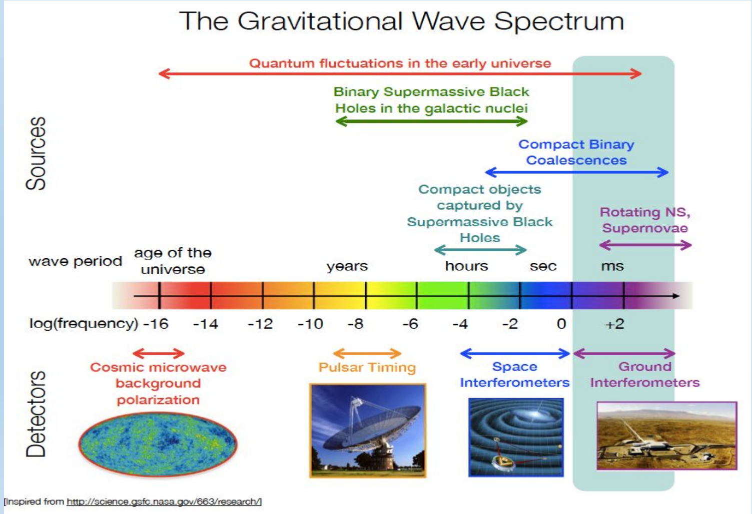
- up to 3 solar masses
- Density : up to 6.10^{17} kg/m^{3}



<u>Black hole</u>

- No mass limit
- Biggest known: TON618 66 billion solar masses

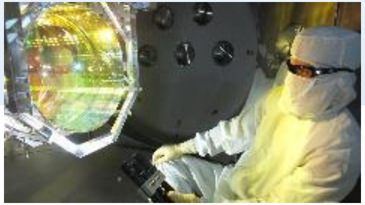
+ other sources: primordial GW, cosmic strings …



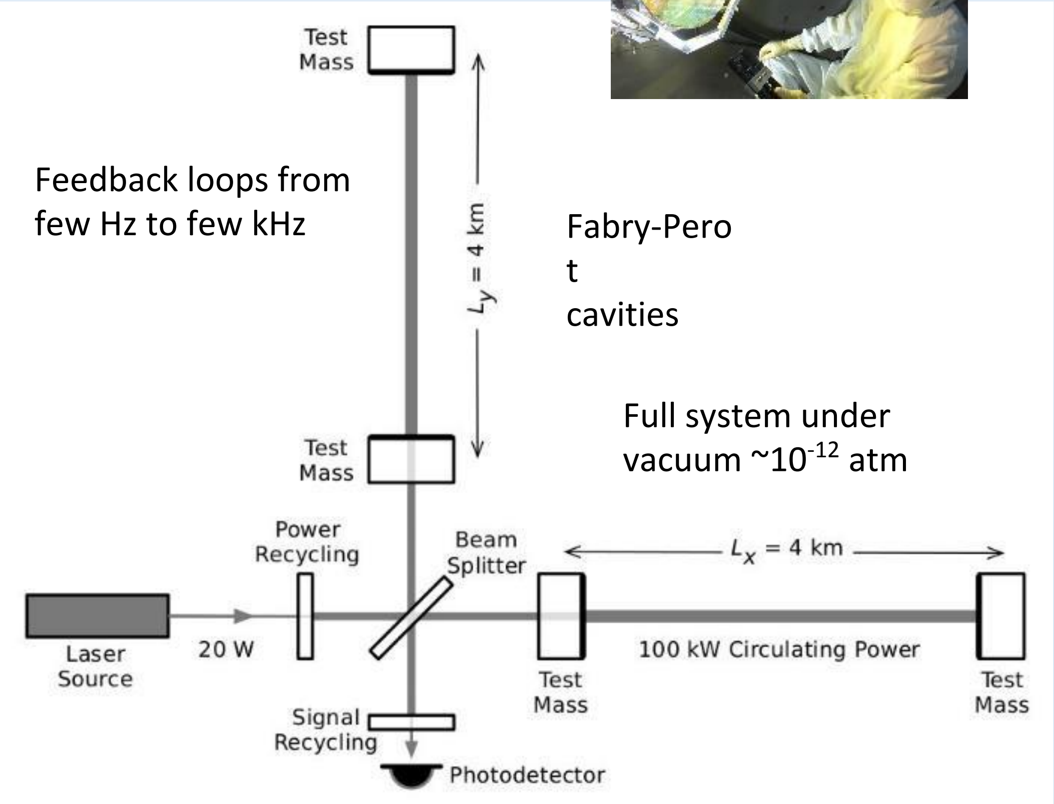
Advanced generation detectors

Michelson interferometer

Goal : $(L_x - L_y)/L_x = 10^{-23}$



High quality optics – 40 kg

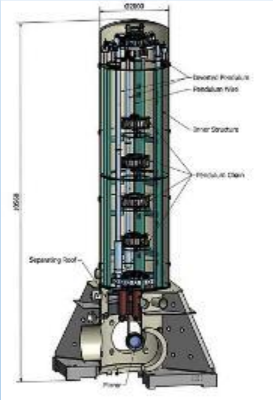


Feedback loops from few Hz to few kHz

Fabry-Perot cavities

Full system under vacuum ~10^{-12} atm

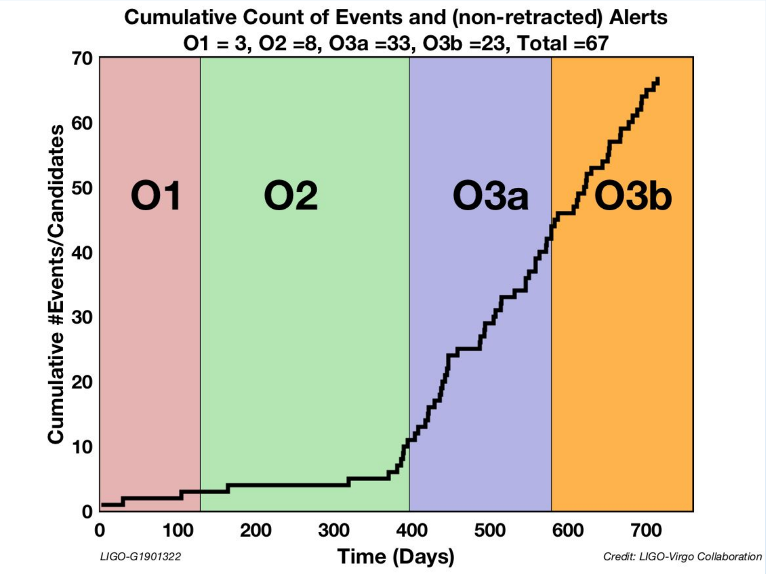
High power laser

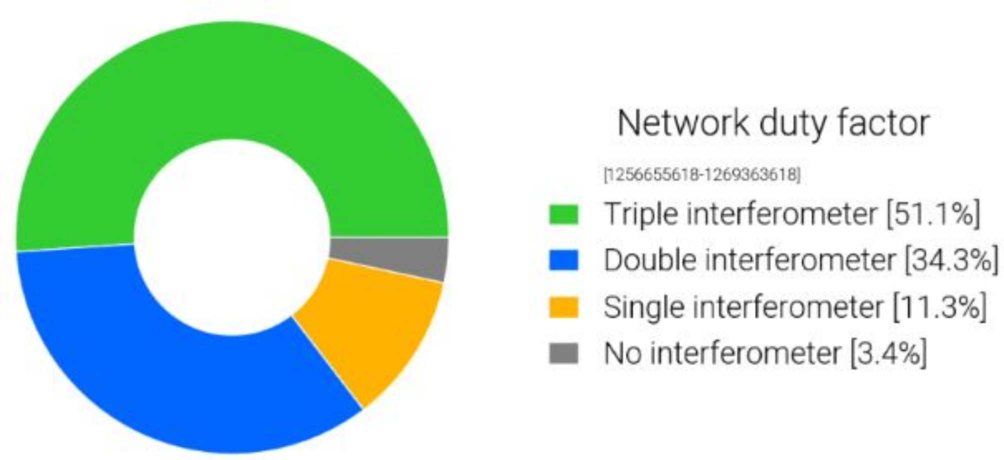


Suspended Optics

Attenuation 10^{14} @ 10 Hz

Current situation

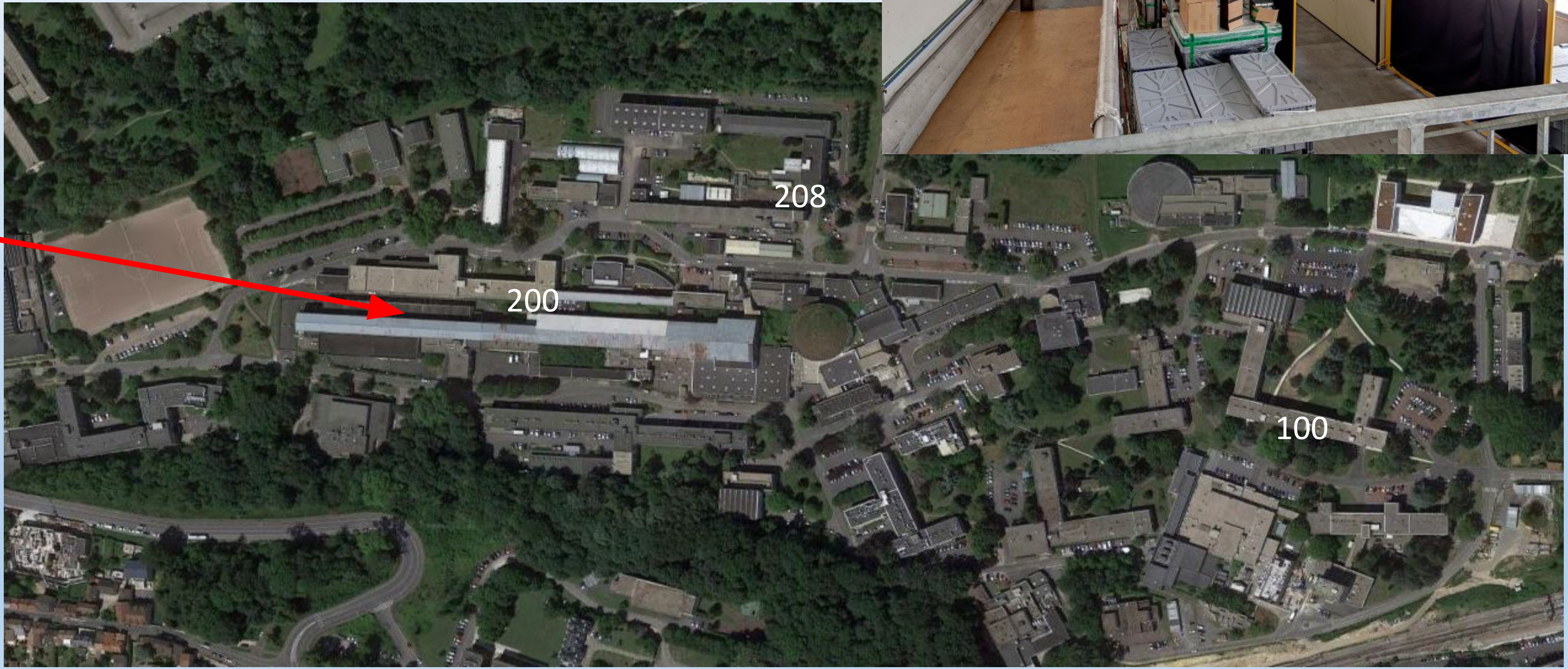




Many Binary Black Holes, a few Binary Neutron Stars and 1 or 2 Neutron star-Black Hole Binary

CALVA : CAvités pour le Lock de Virgo Avancé

you are here



situation en 2014 : http://www.visites-virtuelles.universite-paris-saclay.fr/?s=pano21744&h=23&v=0&f=90

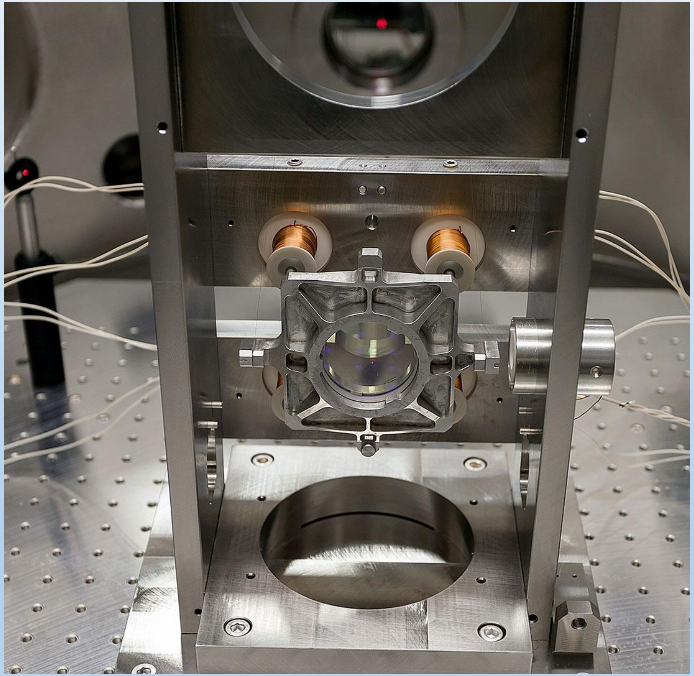
CALVA : CAvités pour le Lock de Virgo Avancé

The initial goal was to build a prototype to test a new technique for locking GW interferometers

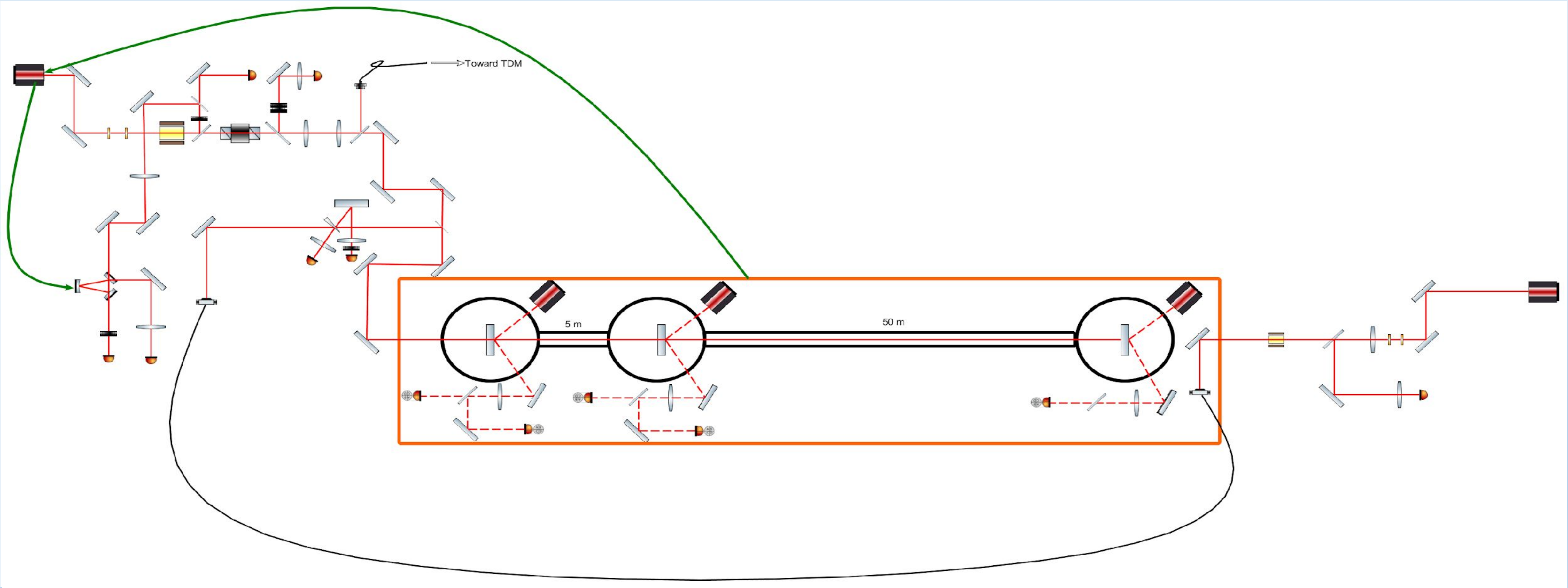
- using suspended optical coupled cavities (ie 2 cavities with 3 mirrors)
- similar Power/Mirror mass than real GW interferometer
- use at maximum similar electronics and software from Virgo to ease integration
- different wavelengths to control the cavities

Some history

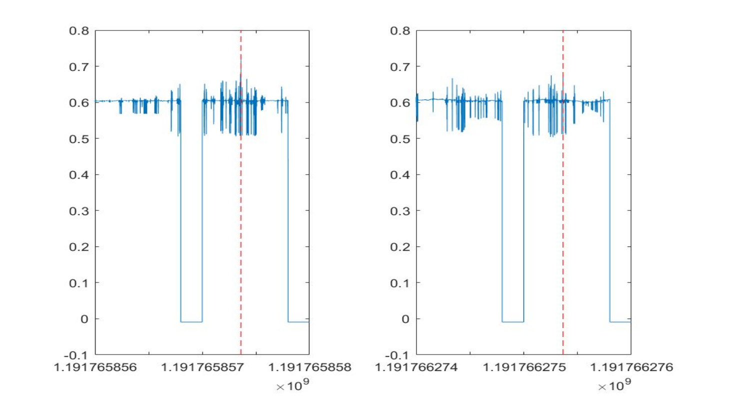
- Start to work on the project in 2009-2010
- Lot of problems during installation : asbestos, ground, vacuum tanks, …
- Have the possibility to control mirror positions in angles and length
- Perform control on the small cavity in 2010
- Control of the 50m long cavity was more problematic due to limit of our system, take time to solve them
- So far : 3 thesis used the facility and 16 internships (L3 to M2) + 8 L2 students from Physics department

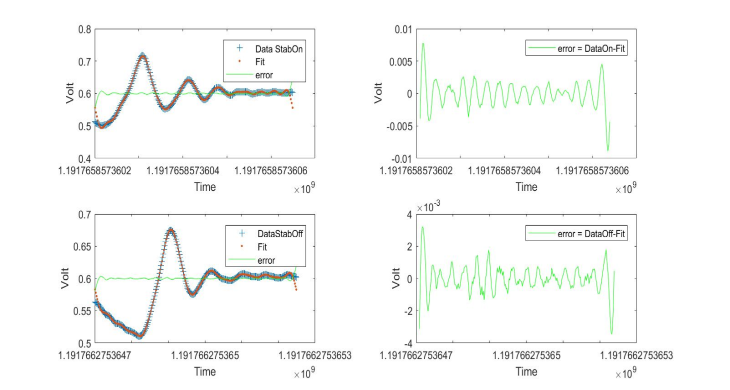


Calva : Cavity for the Lock of Advanced Virgo Lock on 1064 nm laser



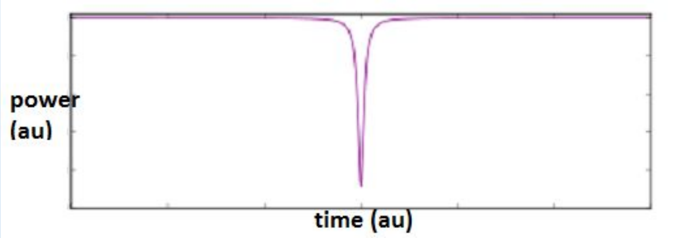
Calva : Cavity for the Lock of Advanced Virgo
Lock on 1064 nm laser



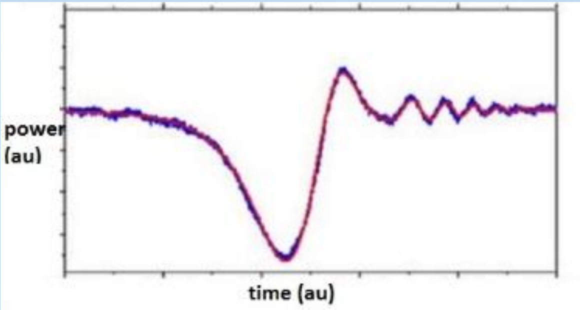


We've investigated the locking problem by looking at the ringing:

In theory :

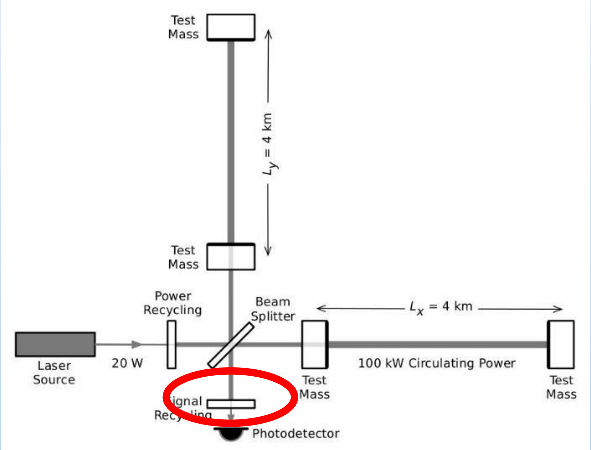


In practice :

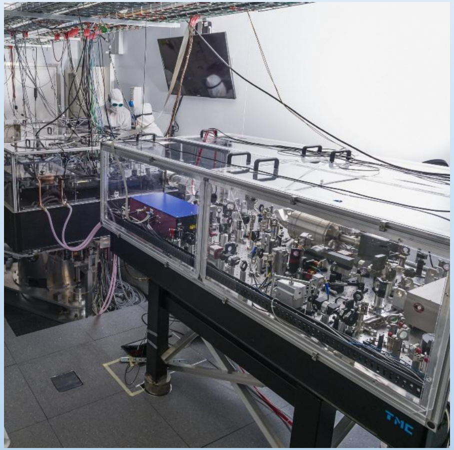


(illustrations)

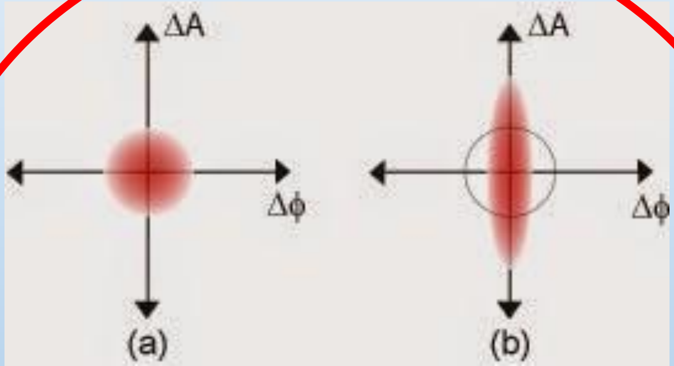
Improvements on the current detectors between O3 and O4



Signal recycling



Increase of laser power
From 60W to 120W



Frequency dependent squeezed states of light

ANR ExSqueez Laboratoire Kastler Brossel Physique quantique et applications

iP2i LES 2 INFINIS LYON

LAPP

Exsqueez

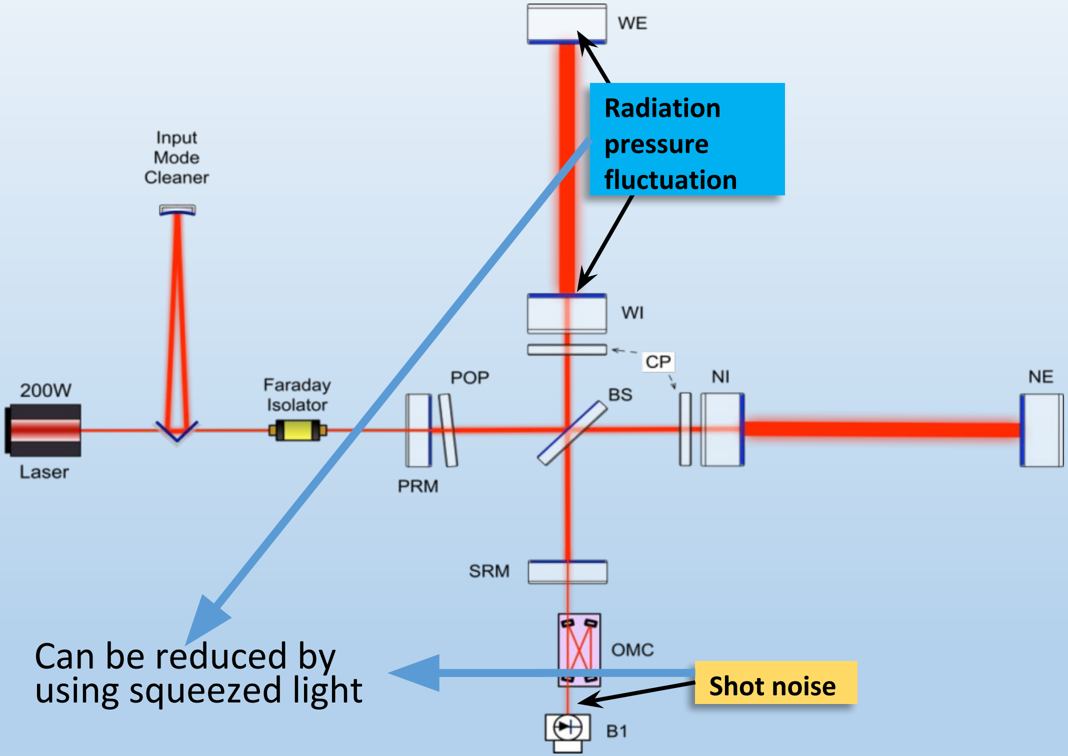
We were able to find an easier solution for Virgo and then we seeked other possibilities for CALVA

Idea is to use our facility to test squeezing techniques to improve the GW interferometer sensitivity, prepare O5 run (≥2024) with source under vacuum

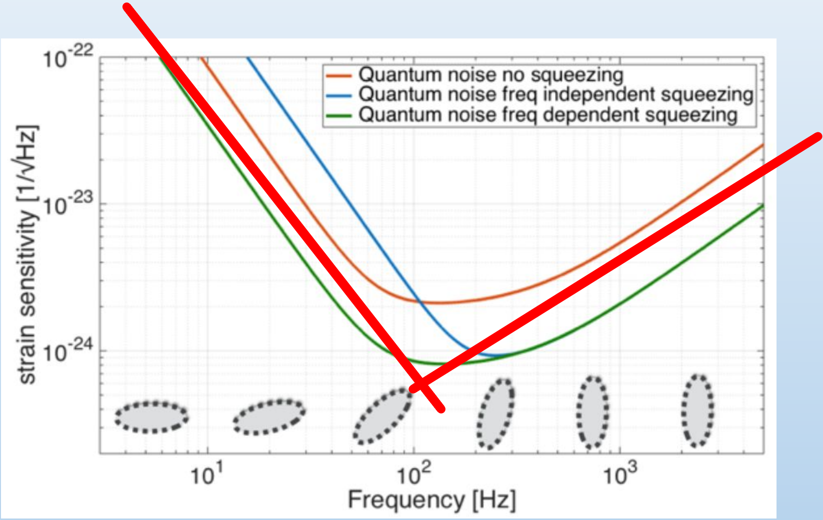
Need one long cavity and optics under vacuum

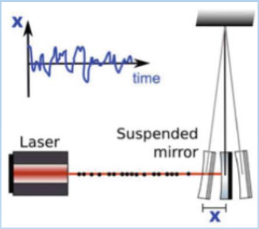
Reuse our infrastructure to work on this

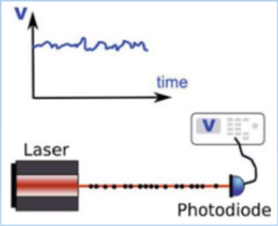
Beat the standard quantum limit using squeezed light



Can be reduced by using squeezed light

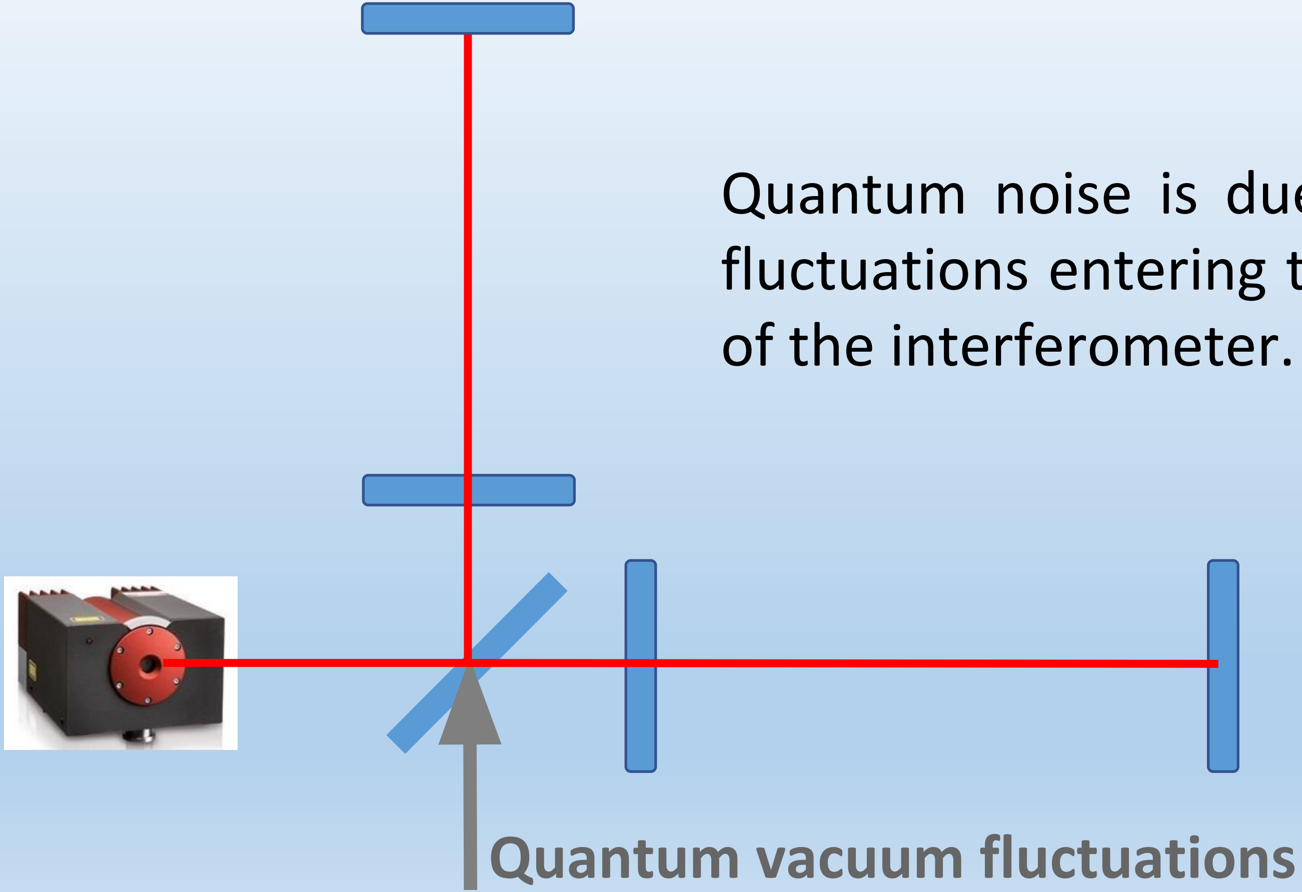






Beat the standard quantum limit using squeezed light

Quantum noise is due to vacuum fluctuations entering the dark port of the interferometer.

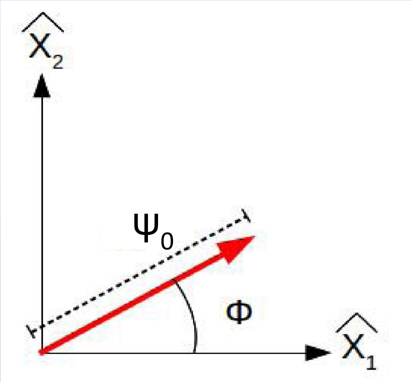


Laser quantum description

Boson creation and annihilation operators: $\hat{a}^\dagger = \sqrt{\frac{m\omega}{2\hbar}}\left(x - \frac{ip}{m\omega}\right)$ $\hat{a} = \sqrt{\frac{m\omega}{2\hbar}}\left(x + \frac{ip}{m\omega}\right)$

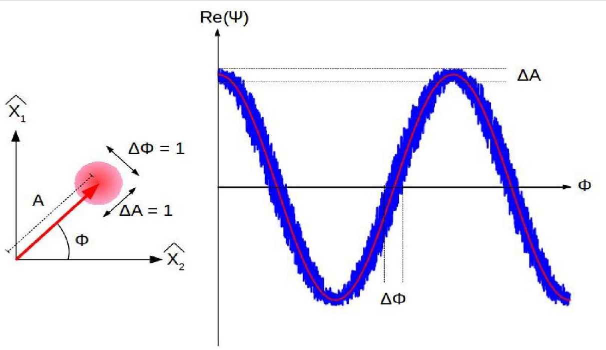
Construct observable operators (amplitude and phase quadrature): $\hat{X}_1 = \hat{a} + \hat{a}^\dagger$ $\hat{X}_2 = i(\hat{a}^\dagger - \hat{a})$

Also: $[\hat{X}_1, \hat{X}_2] \neq 0$ Thus they are complementary observables and can't be measured both with infinite precision at the same time -> **quantum noise**



Consider classical electric field: $\Psi = \Psi_0 e^{i\phi}$

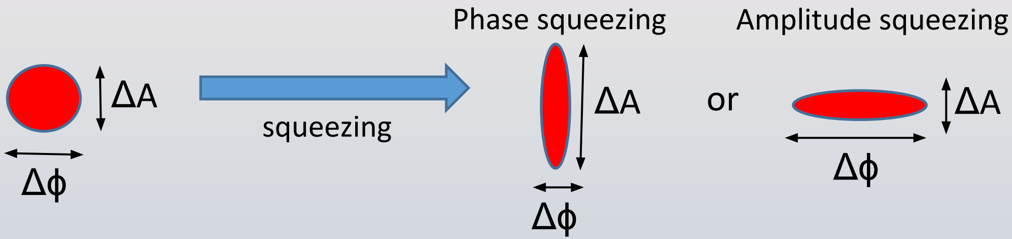
Also written as: $\Psi = \Psi_0(cos(\phi)\hat{X}_1 + isin(\phi)\hat{X}_2)$

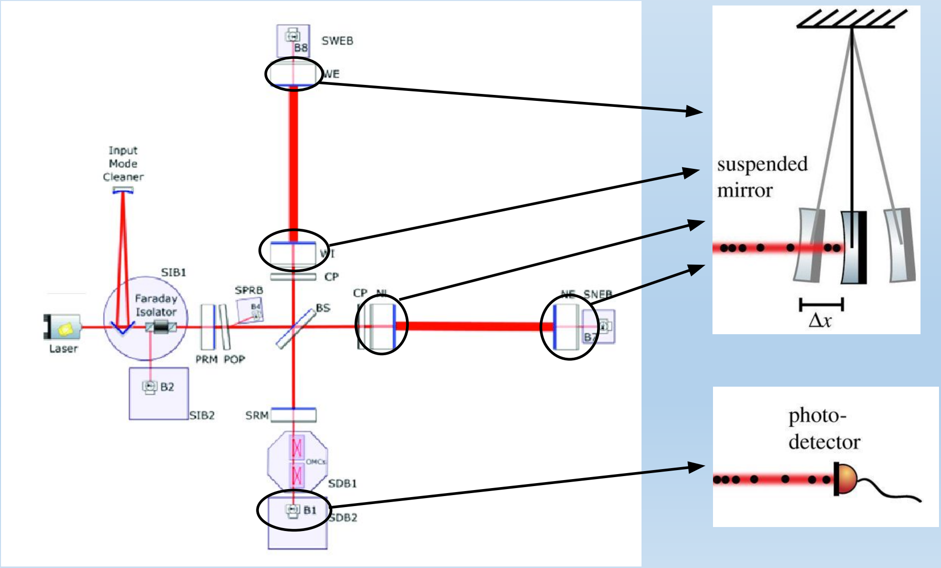


For coherent light the best case regarding the Heisenberg uncertainty principle is: $\Delta\hat{X}_1 = \Delta\hat{X}_2 = 1$

Squeezed light

Photons are not perfect:
Uncertainty in phase (Δϕ) and amplitude (ΔA)





Heisenberg uncertainty principle:

$$\Delta A \times \Delta\phi \geq 1$$

Squeezed light in theory

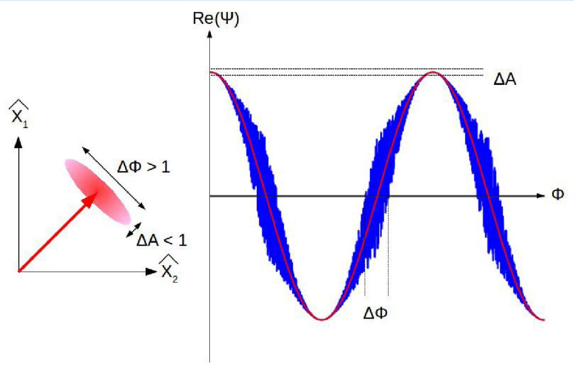
In Dirac notation coherent states are noted as $|\alpha\rangle$ where α is the coherent amplitude of the state.

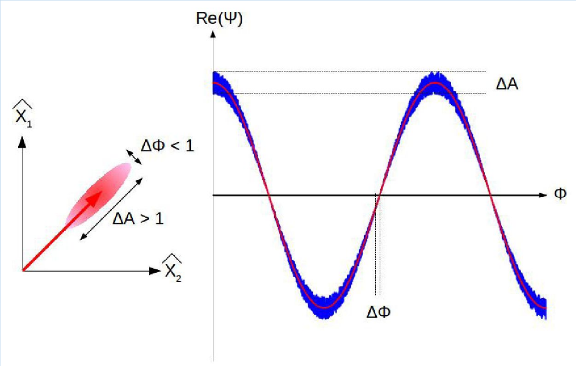
They are generated from vacuum states $|0\rangle$ using the unitary displacement operator D(α):

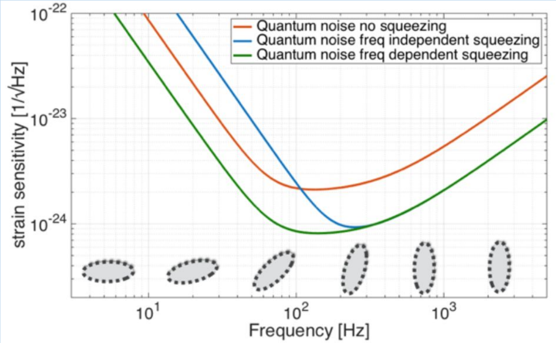
$|\alpha\rangle = \hat{D}(\alpha)\,|0\rangle$ where $\hat{D}(\alpha) = exp(\alpha\hat{a}^\dagger - \alpha^\star\hat{a})$ and α is a complex number.

Whereas squeezed state are noted as: $|\alpha, \epsilon\rangle$ ε being the squeezing parameter: $\epsilon = re^{2i\theta}$

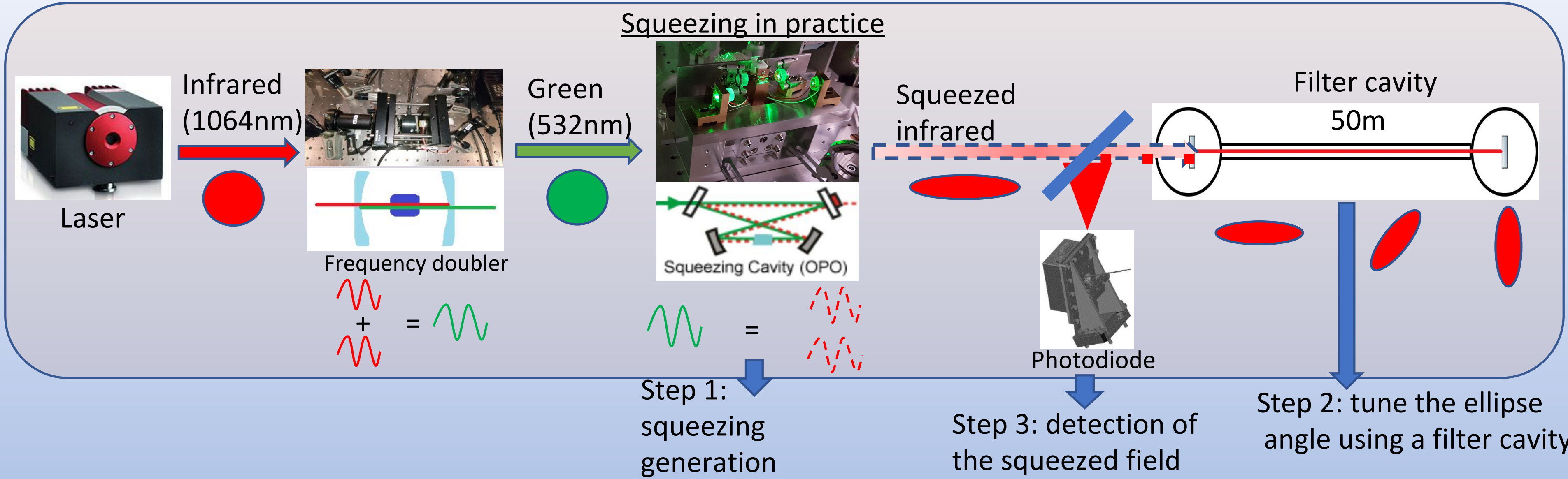
$|\alpha, \epsilon\rangle = \hat{D}(\alpha)\hat{S}(\epsilon)\,|0\rangle$ where $\hat{S}(\epsilon) = exp\left(\frac{1}{2}\left[\epsilon^\star\hat{a}^2 - \epsilon\hat{a}^{\dagger 2}\right]\right)$







Squeezed light at CALVA: global scheme



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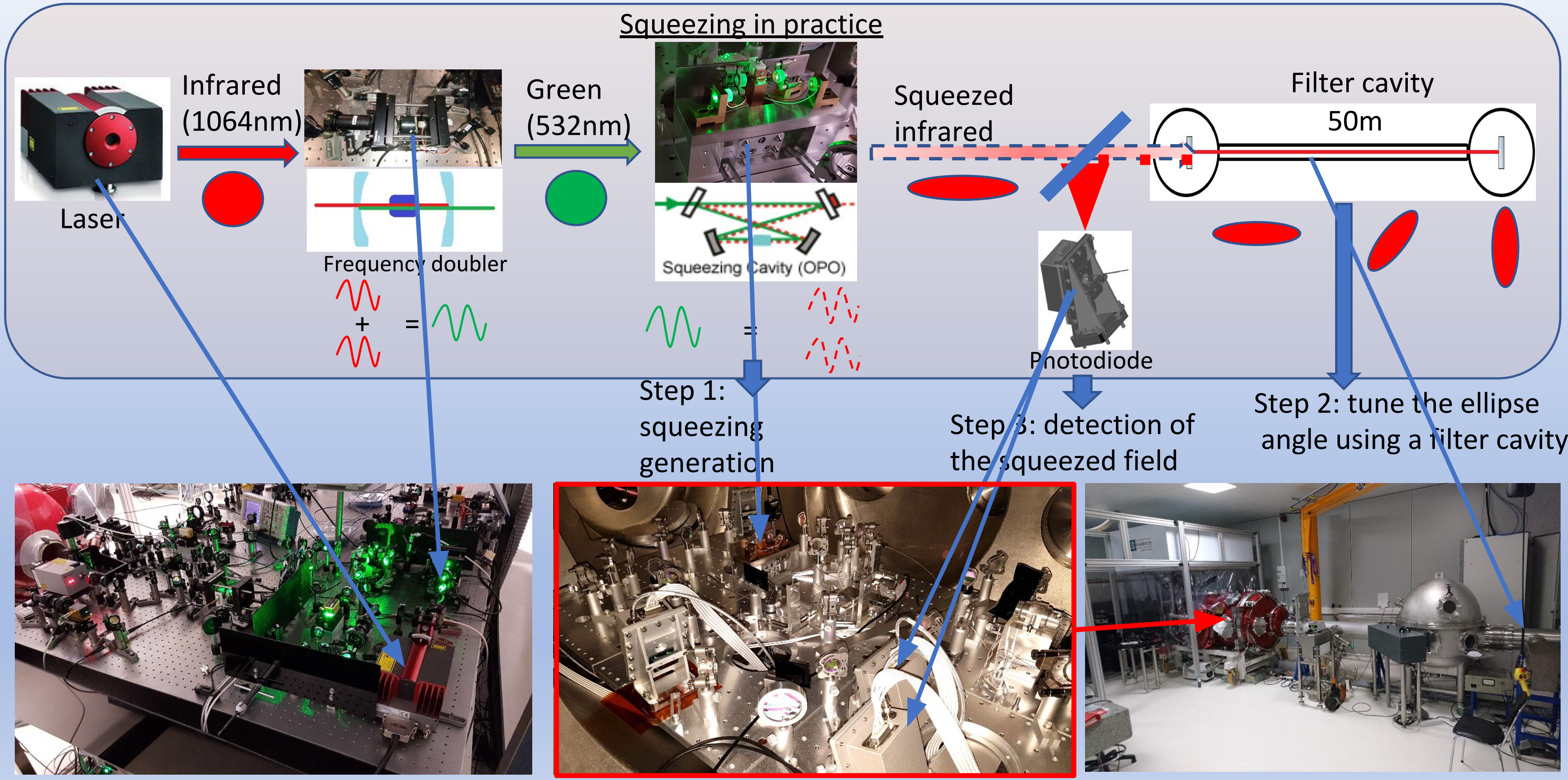
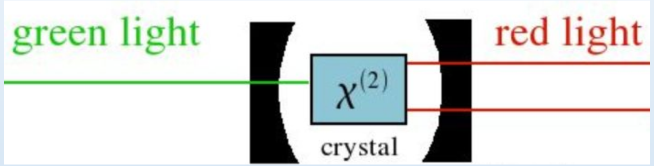


Squeezed light in practice: step 1, producing squeezing



1 photon of green light (532 nm) produces 2 correlated photons of infrared light (1064 nm)

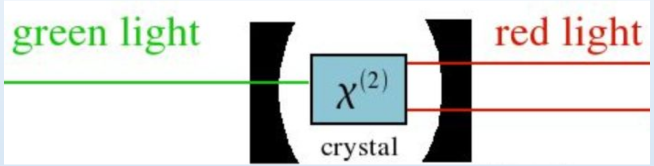
Electric displacement of the excited electrons due to incoming laser field: $\vec{D} = \epsilon_0 \vec{E} + \vec{P}$

For low power the electric polarization is: $\vec{P} = \epsilon_0 \chi_e \vec{E}$

$\chi^{(i)}$ being a tensor

$$P = \epsilon_0 \left[\chi^{(1)} E + \chi^{(2)} E^2 + \chi^{(3)} E^3 + \ldots \right]$$

Squeezed light in practice: step 1, producing squeezing



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$\chi^{(i)}$ being a tensor

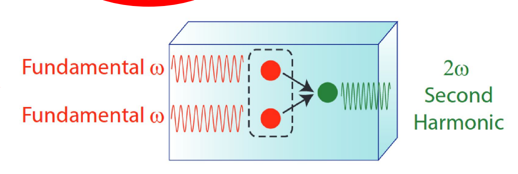
$$P = \epsilon_0 \left[\chi^{(1)} E + \chi^{(2)} E^2 + \chi^{(3)} E^3 + \ldots \right]$$

Considering 2nd order interaction:

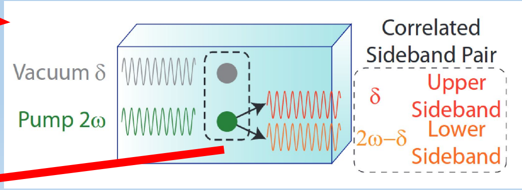
$$P^{(2)}(t) = \epsilon_0 \chi^{(2)} [E_1 cos(\omega_1 t) + E_2 cos(\omega_2 t)]^2$$

$$= \epsilon_0 \chi^{(2)} \{E_1^2 + E_2^2 + \frac{1}{2}[E_1^2 cos(2\omega_1 t) + E_2^2 cos(2\omega_2 t)$$

$$+ E_1 E_2 cos((\omega_1 + \omega_2)t) + E_1 E_2 cos((\omega_1 - \omega_2)t)]\}$$



ω1=ω2



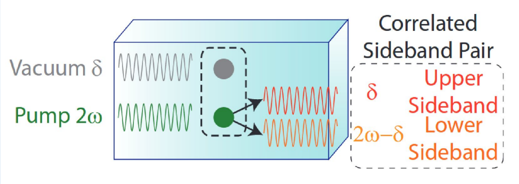
ω1=δ

ω2=2ω

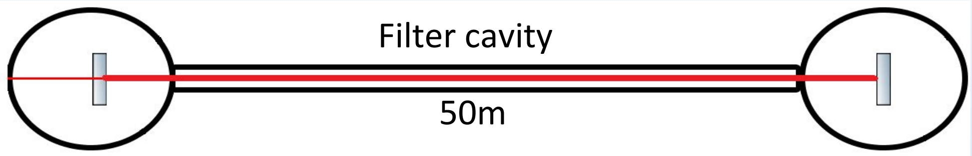
<u>Squeezing</u>

δ is the angular frequency of the photons produced by vacuum fluctuations

Squeezed light in practice: step 2, controlling ellipse angle



$\delta=\omega-\Omega$
$2\omega-\delta=\omega+\Omega$

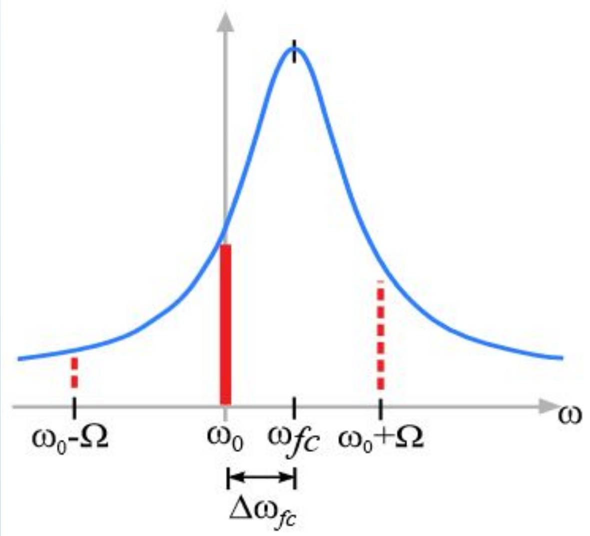


$$r_{fc}(\Omega) = r_1 - \frac{t_1^2 r_{rt} e^{-i\Phi(\Omega)}}{r_1(1 - r_{rt} e^{-i\Phi(\Omega)})}$$

$r_{rt}=r_1 r_2$ is the roundtrip reflectivity and $\Phi(\Omega)$ the roundtrip phase:

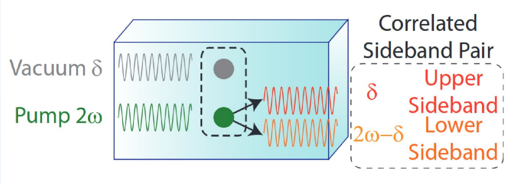
$$\Phi(\Omega) = (\Omega - \Delta\omega_{fc})\frac{2L_{fc}}{c}$$

L_{fc} = 50m and $\Delta\omega_{fc}$ is the cavity detuning



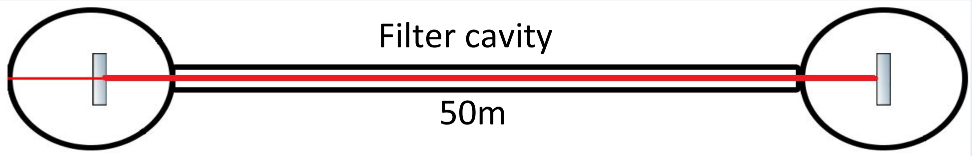
For the coherent sidebands produced by the OPO r_{fc} becomes $r_+=r_{fc}(\Omega)$ and $r_-=r_{fc}(-\Omega)$

Squeezed light in practice: step 2, controlling ellipse angle



$\delta = \omega - \Omega$

$2\omega - \delta = \omega + \Omega$

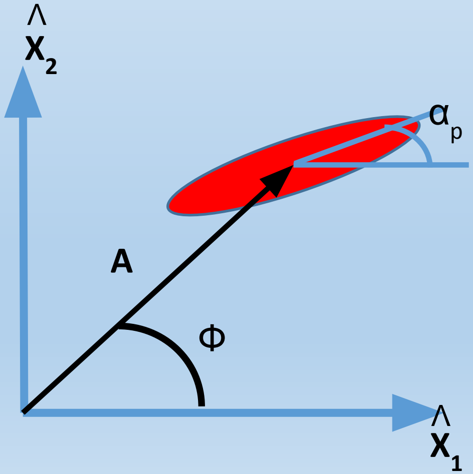


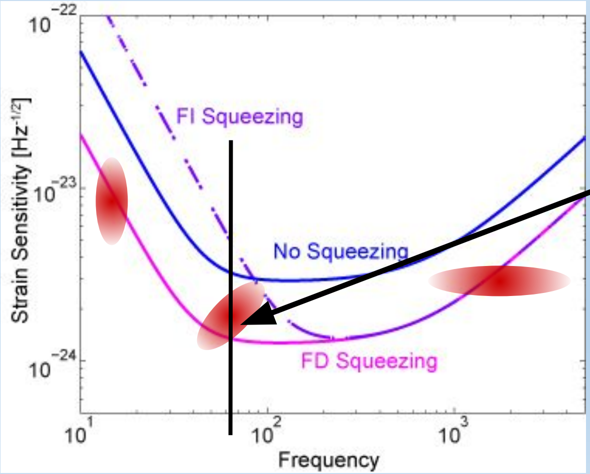
$$r_{fc}(\Omega) = r_1 - \frac{t_1^2 r_{rt} e^{-i\Phi(\Omega)}}{r_1(1 - r_{rt} e^{-i\Phi(\Omega)})}$$

$$\gamma_{fc} = \frac{\pi.c}{2.L.F} \qquad \gamma_{\text{fc}} = \frac{\Omega_{\text{SQL}}}{\sqrt{2}}$$

Then we have α_{pm}=arg(r±) and $\alpha_{pm} = \frac{\alpha_+ \pm \alpha_-}{2}$

$$\alpha_p(\Omega) = arctan\left(\frac{2\gamma_{fc}\Delta\omega_{fc}}{\gamma_{fc}^2 - \Delta\omega_{fc}^2 + \Omega^2}\right)$$

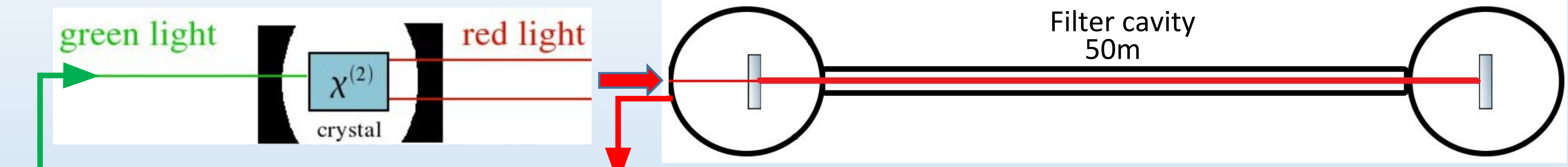


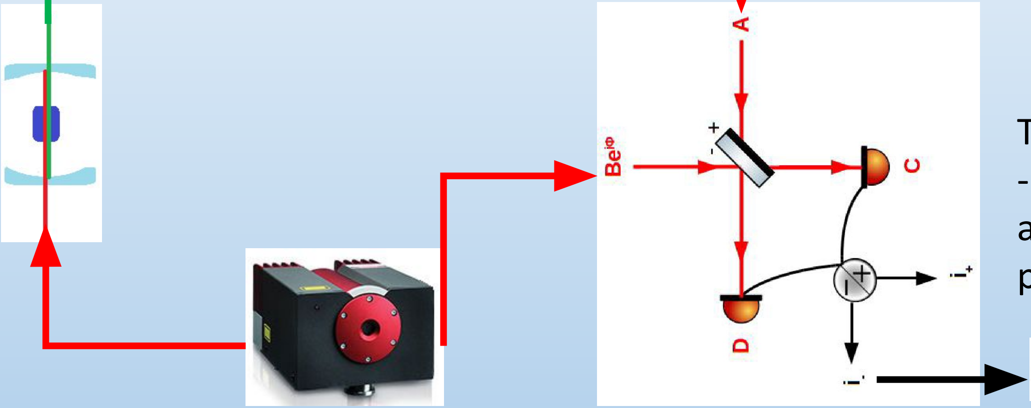


44 Hz for 42 kg mirrors of Virgo

$$\Omega_{\text{SQL}_0} \simeq \frac{8}{c}\sqrt{\frac{P_{\text{arm}}\omega_0}{mT_{\text{arm}}}}$$

Squeezed light in practice: step 3, squeezing detection





Main 1064nm laser

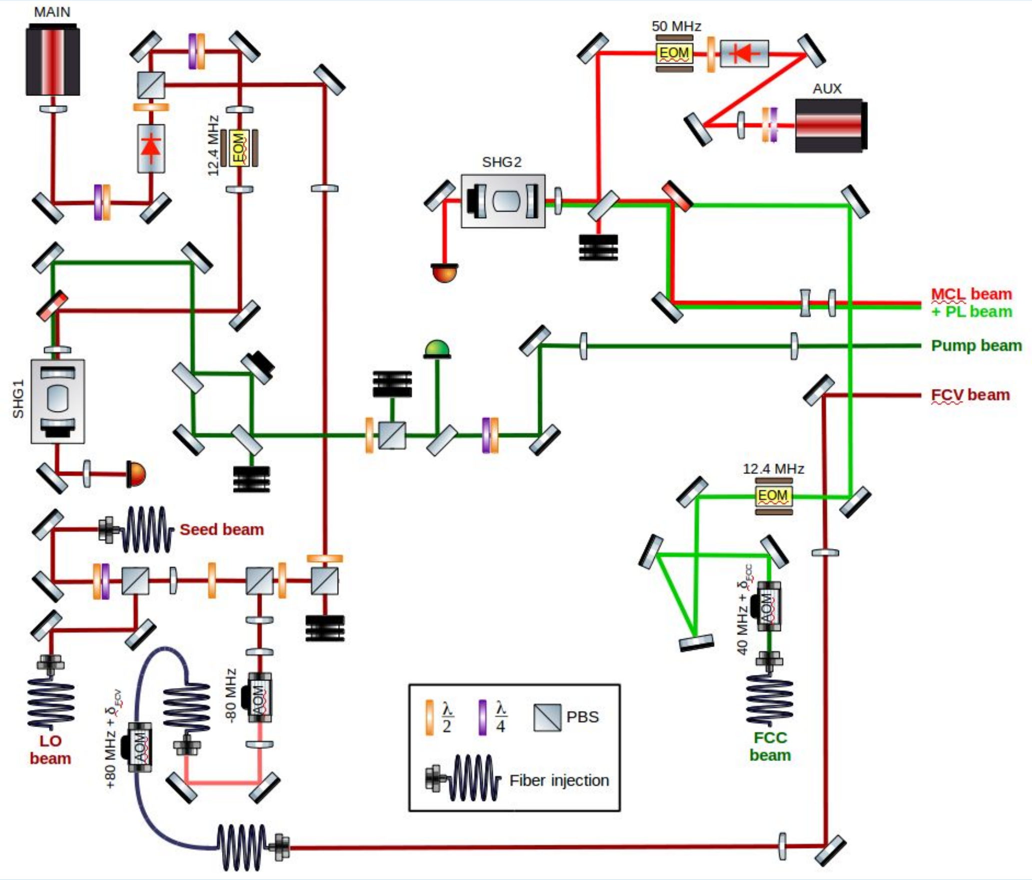
The squeezed field has very low power (a few fW) -> use of a homodyne detection scheme to amplify low-power squeezed signal with a high power local oscillator (main laser)

$$i_- \simeq 2\overline{A}\overline{B}cos(\Phi) + \overline{B}[\delta X_1^A cos(\Phi) + \delta X_2^A sin(\Phi)]$$

Squeezed field amplified by local oscillator field

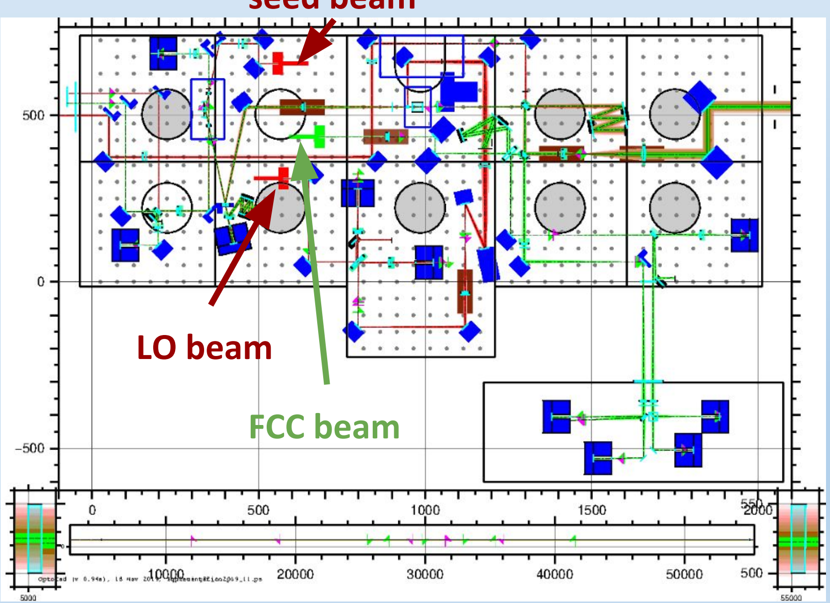
By tuning the relative phase Φ between LO and SQZ we can choose the observed quadrature

Squeezed light in practice: optical schemes



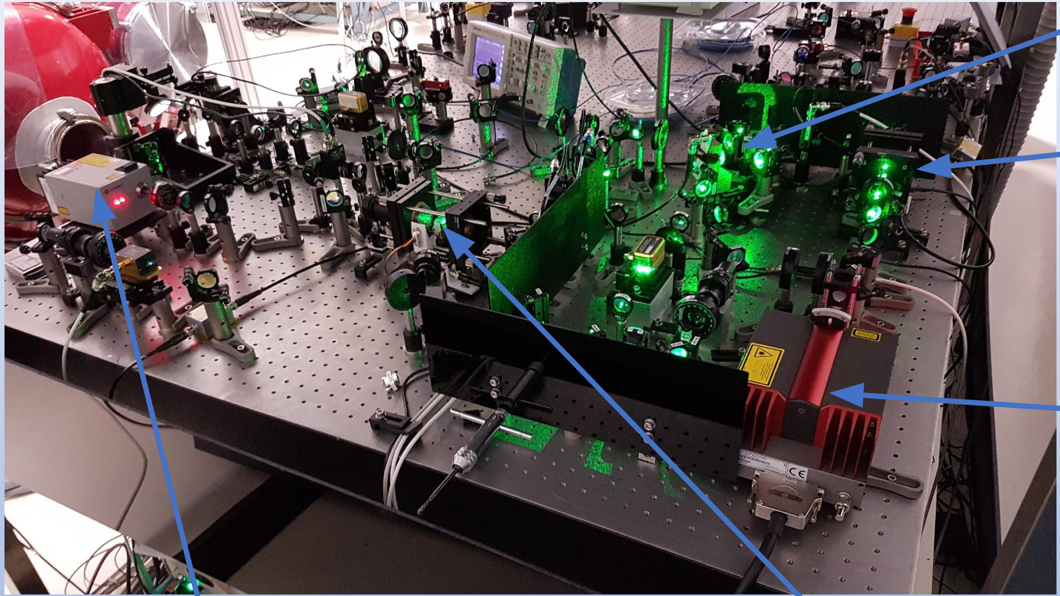
In-air laser preparation bench

7 beams generated on the in-air laser preparation bench and sent to the in-vacuum bench
2 IR laser
2 Second Harmonic Generators (SHG) to produce green beams



In-vacuum bench

Laser preparation bench



Mach-Zehnder for pump power control

Frequency doubler 200 mW at 532nm
(pump beam)

Main laser, 2W at 1064nm
- Beam to generate pump
- Local oscillator beam
- Seed beam
- Filter Cavity Verification beam

Frequency doubler 50mW at 532nm
(Filter Cavity Control beam)

Auxiliary laser, 500 mW at 1064nm
- Modified Coherent Locking beam
- Beam to generate FCC

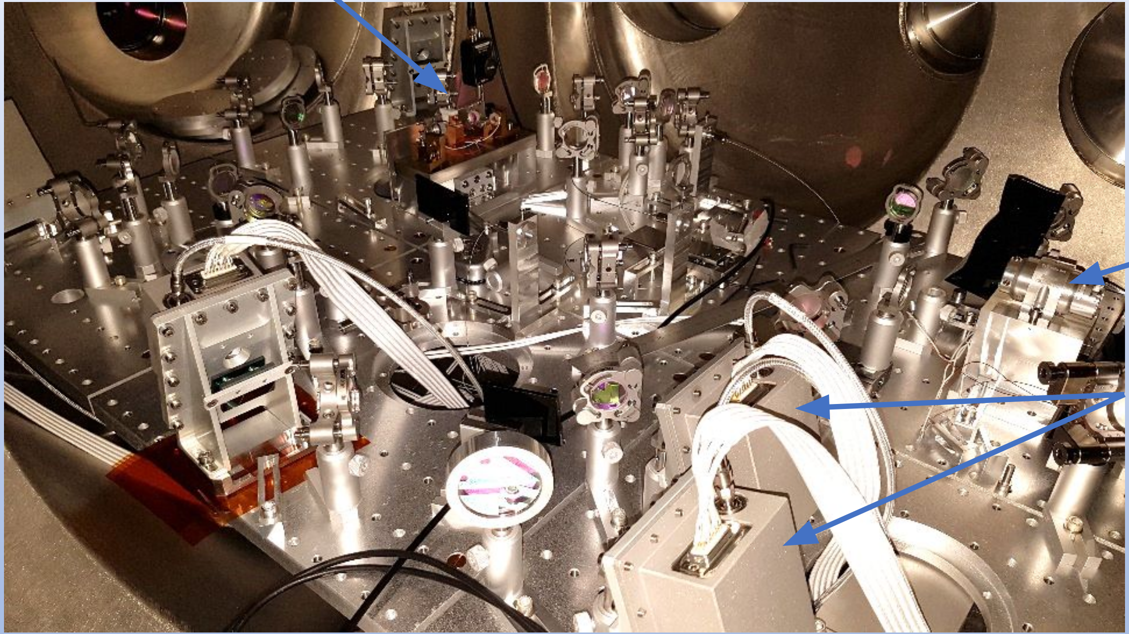
-> This bench is nearly 100% completed

In-vacuum bench

OPO

~ 10^{-6} – 10^{-7} mbar

(~ 10^{-4} – 10^{-5} Pascal)



Faraday Isolator

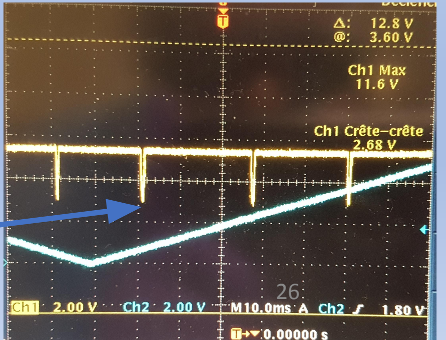
Homodyne detection

(high quantum efficiency photodiodes)

-> Everything is installed, commissioning ongoing

- Mode-matching of pump and MCL into the OPO => cavity resonances

- Tuning of homodyne detection

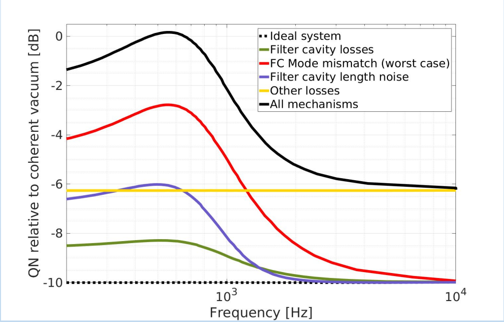


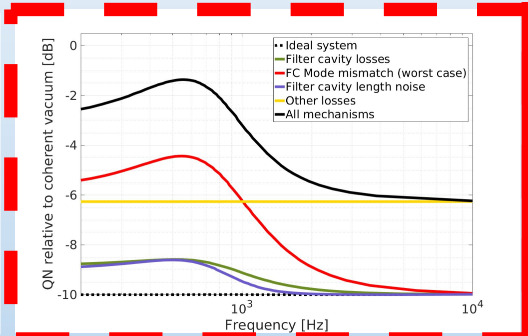
Losses, a crucial point in squeezing

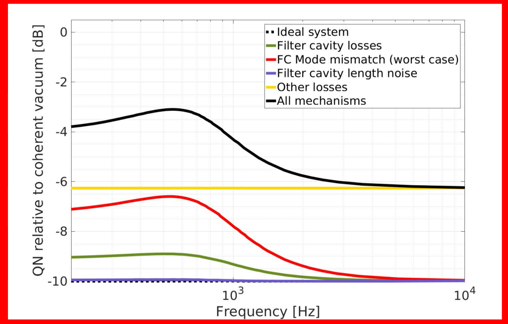
Mismatch = 15%,
Length noise = 10 pm,
RTL = 50ppm

Mismatch = 10%,
Length noise = 5 pm,
RTL = 40ppm

Mismatch = 5%,
Length noise = 1 pm,
RTL = 30ppm







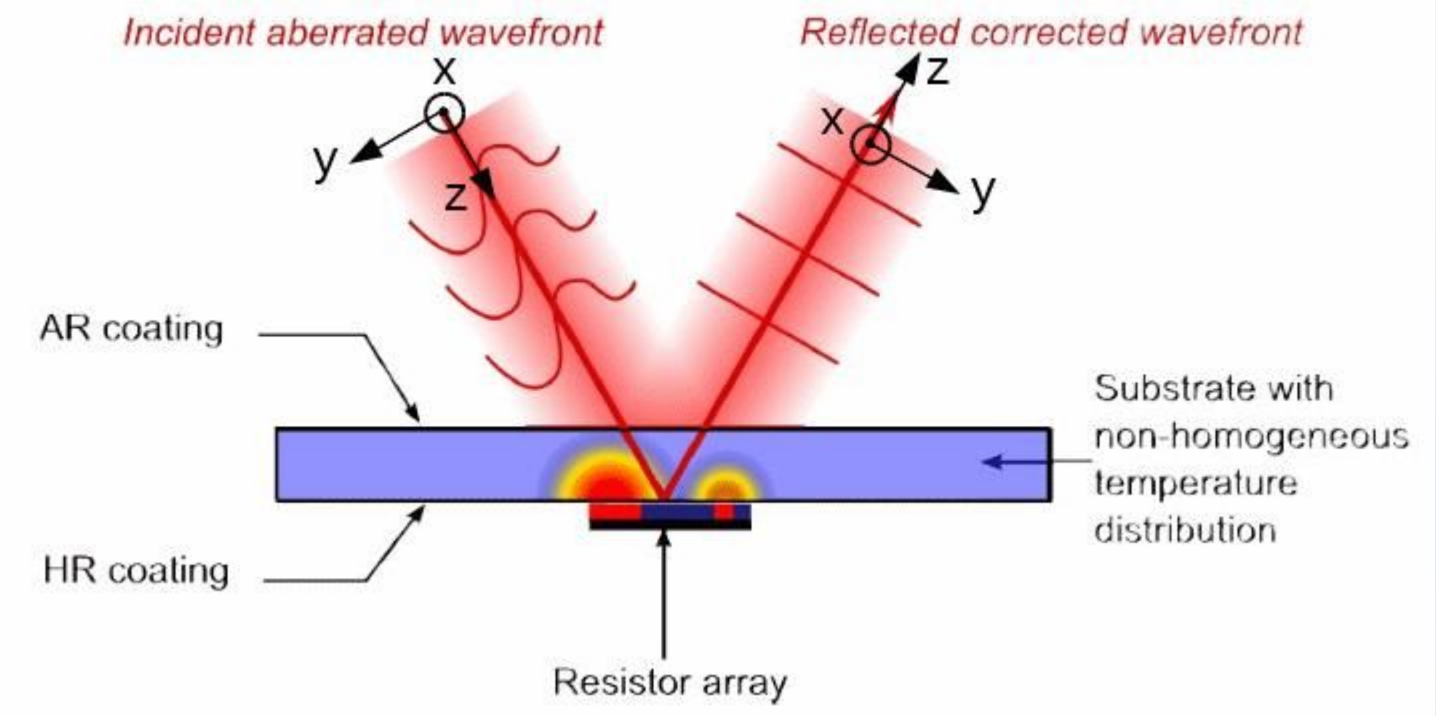
With 10dB injected squeezing we expect ≈3-6dB of FDS performance

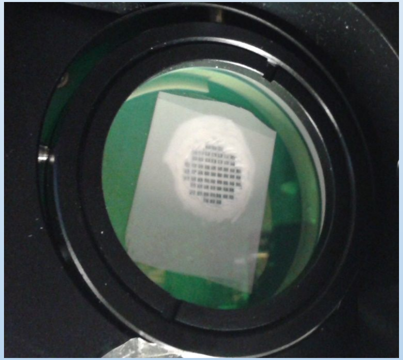
- There are irreducibles frequency independent losses arising mainly from injection losses and readout losses.
- Filter cavity losses reduce the squeezing performance at low frequencies.
- The length noise of the cavity should be reduced as much as possible.
- The matching of the squeezed beam to the filter cavity is of crucial importance to reduce squeezing losses at low frequencies.

Thermally Deformable Mirrors (TDM)

To improve the beam matching to a Fabry-Perot cavity we can use an adaptive optics system => test on CALVA of TDM

started with Marie Kasprzack thesis (2014)





Resistor array composed of 61 actuators

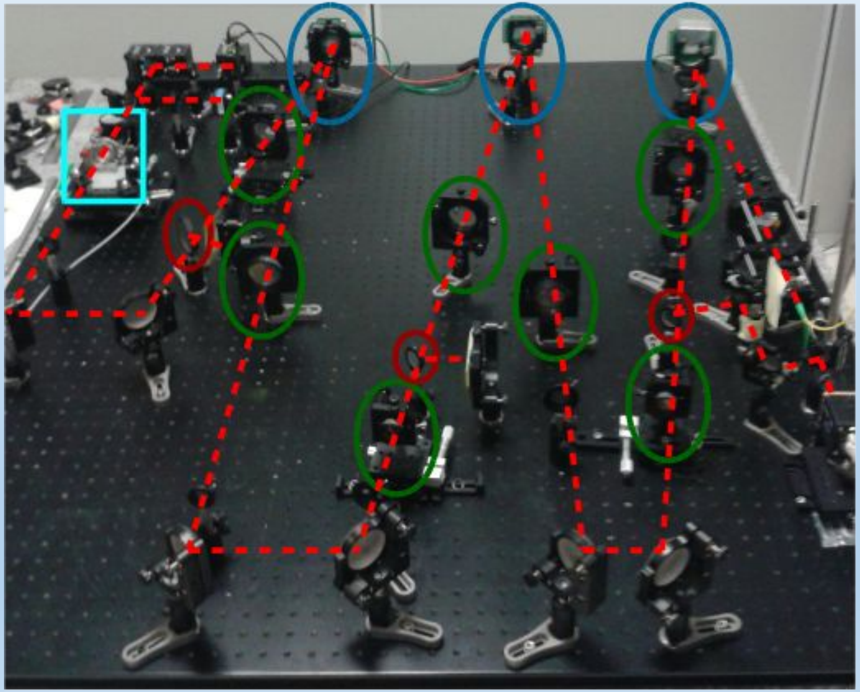
Beam radius ~ 2.6 mm

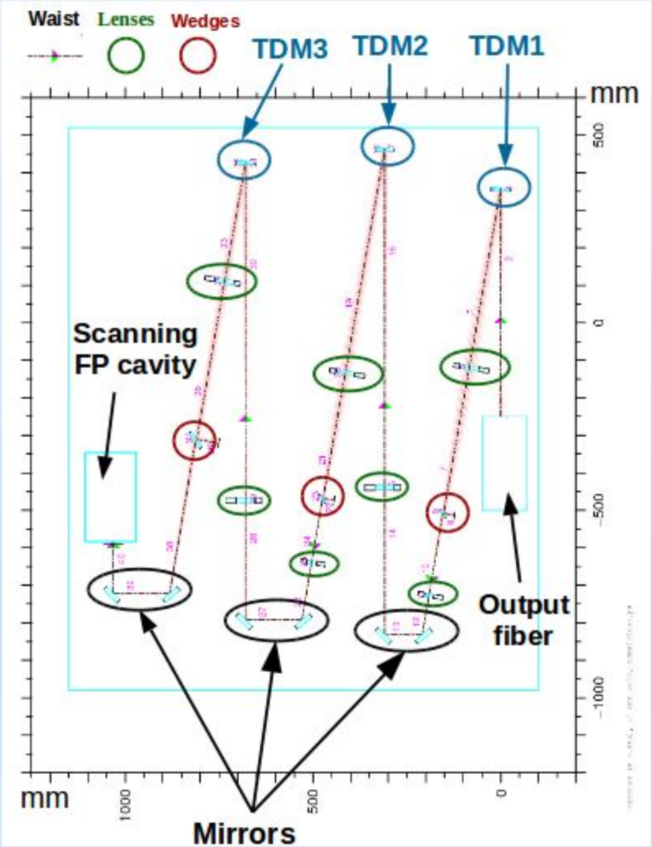
Vacuum compatible

Thermally Deformable Mirrors (TDM)

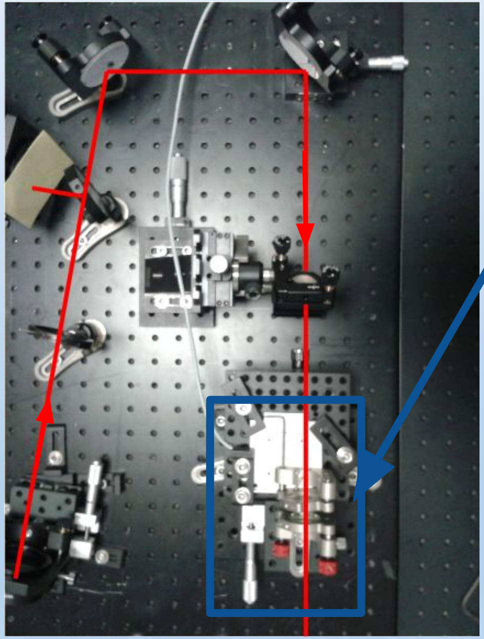
Need 2 TDMs to completely correct beam aberrations

1 more TDM to generate a test defect

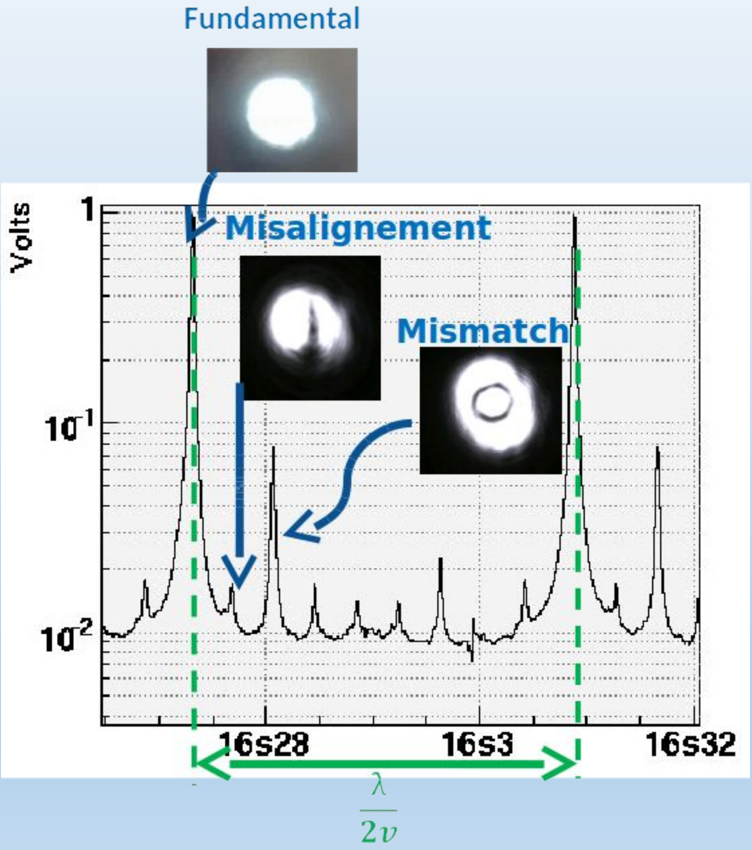




Beam analysis with a Fabry-Perot cavity



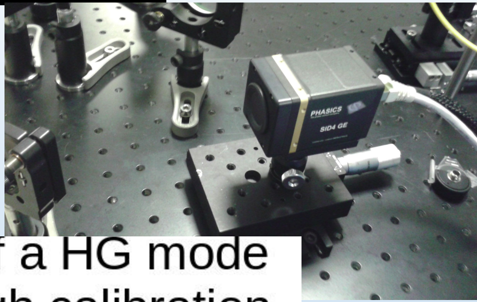
- Hemispherical cavity from ~3 mm to a few cm according to the beam waist size
- Finesse ~ 90
- Plan input mirror on piezo (precision of 10 pm)
- Spectrum by scanning cavity length
  ⇒ study of the beam content
- Minimizing misalignment to reduce order 1 and mismatch to reduce order 2

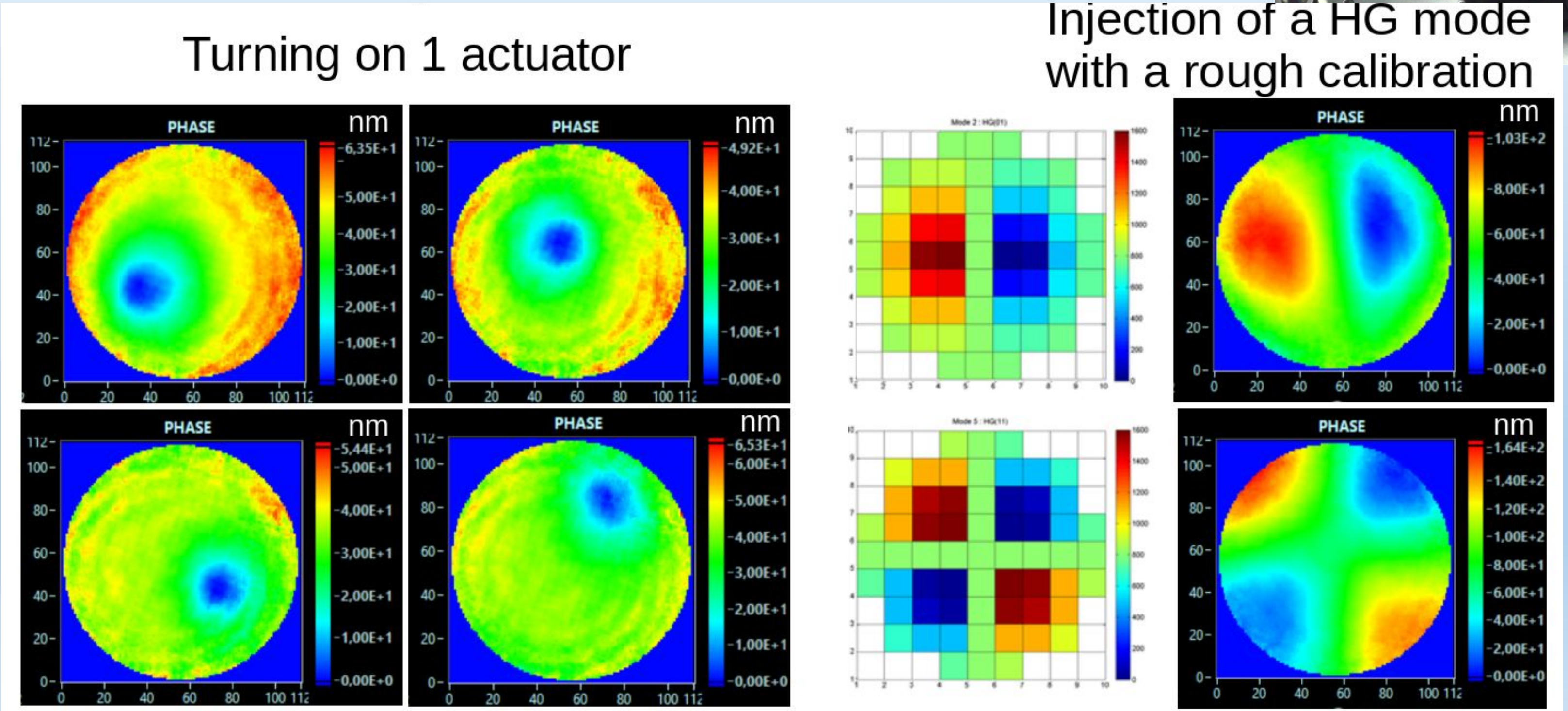


Beam analysis with a wavefront sensor: Phasics

Wavefront analysis of the beam on the TDM by positioning the Phasics in the image plane of the TDM

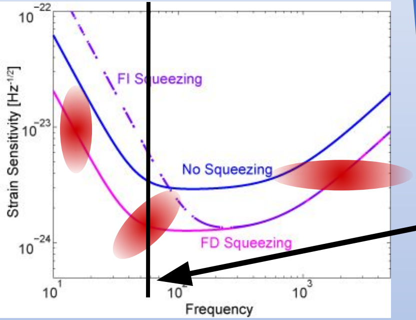
Phasics in common with the ALEA team of the Accelerator division





Beyond Exsqueez: Quantum Filter

≈ with variable R

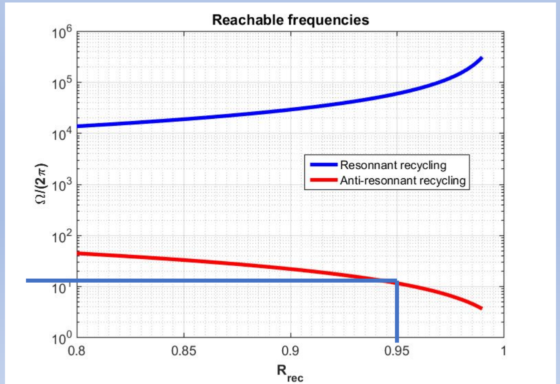


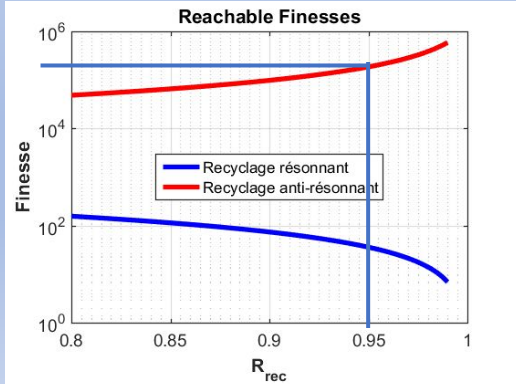
$$\Omega_{\mathrm{SQL}_0} \simeq \frac{8}{c}\sqrt{\frac{P_{\mathrm{arm}}\omega_0}{mT_{\mathrm{arm}}}} \rightarrow \gamma_{fc} = \frac{2.\pi.\Omega_{SQL}}{\sqrt{2}} \rightarrow \gamma_{fc} = \frac{\pi.c}{2.L.F}$$

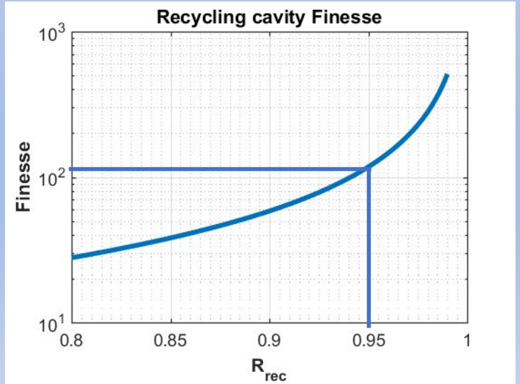
44 Hz for 42 kg mirrors of Virgo

Not very flexible once length and finesse (mirror coating) have been fixed

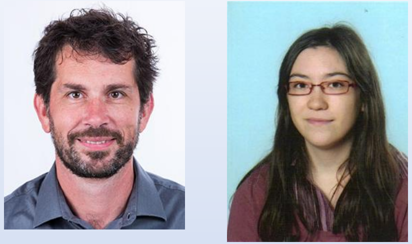
Solution is to add another mirror to form a recycling cavity to get a variable Finesse

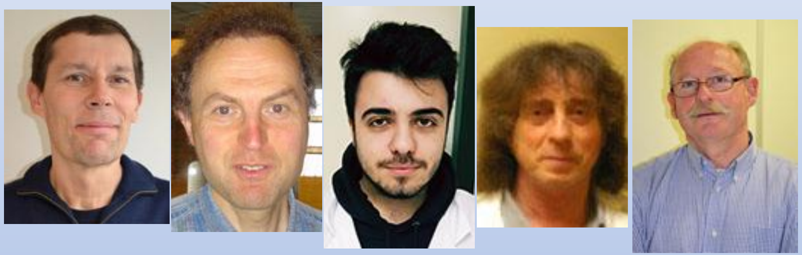




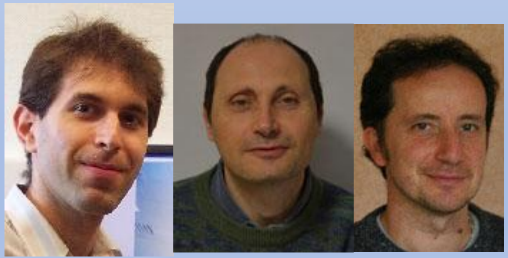


Mechanics : conception and realization





Electronics : conception and realization



Vacuum : conception and realization

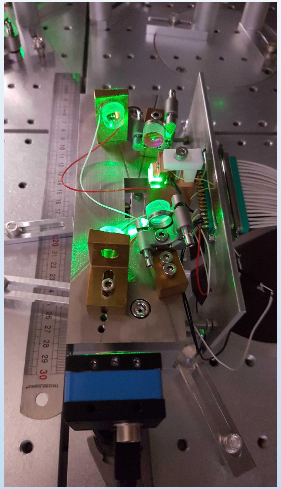
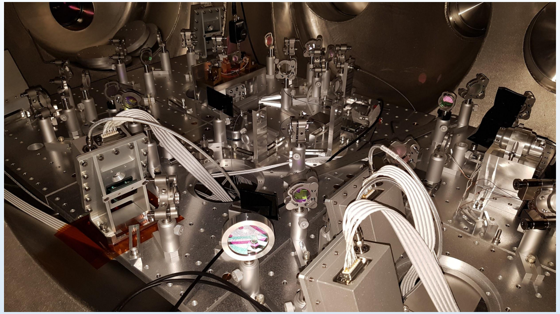
Laserix

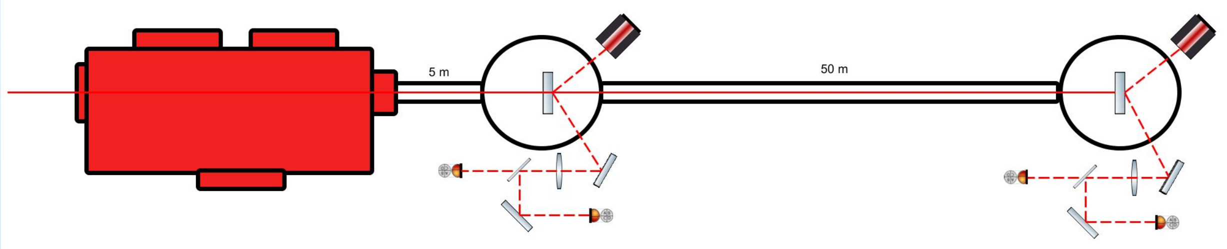
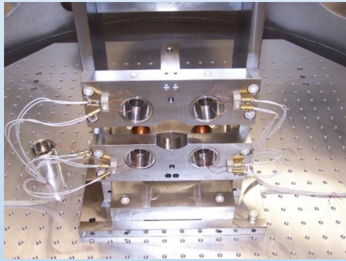
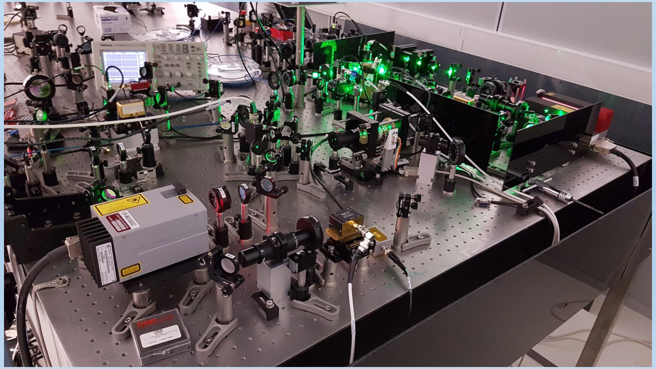
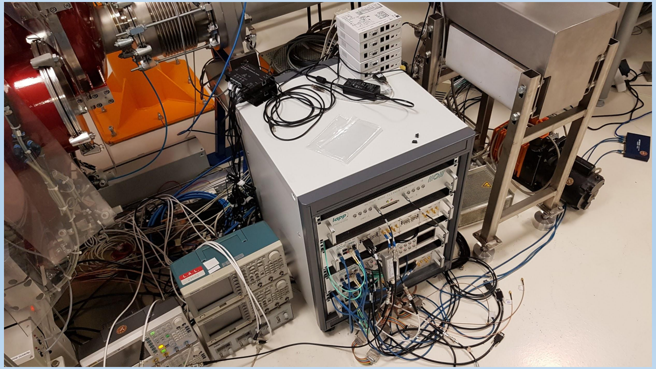
ESPCI PARIS

and many more !!!!

Conclusions

- Experimental platform dedicated to GW interferometer
- Tests new techniques - preparation of present project and future generation
- Collaboration with LIGO-Kagra-Virgo groups
- Creation and exploitation possible thanks to large use of engineering, infrastructure and administration teams
- Host large numbers of internships
- It is possible to visit - please contact us !

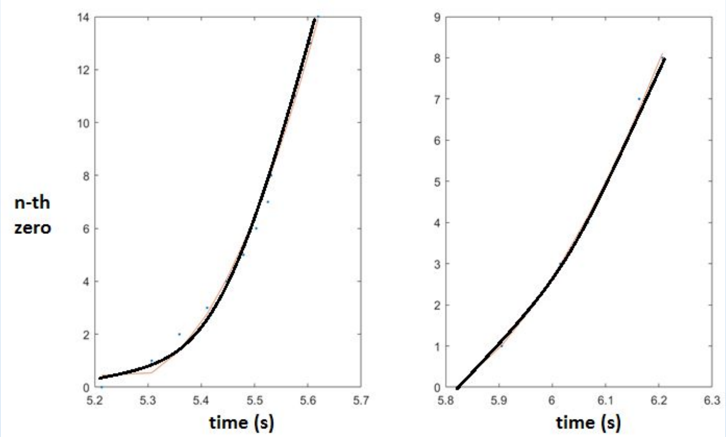





5 m
50 m





BACKUP

Calva : Cavity for the Lock of Advanced Virgo

Lock on 1064 nm laser



By fitting the n-th zero of the derivative vs time with the expression:

$$n_{zero} = p_1 + p_2.t_{zero} + p_3.t^2_{zero} \qquad \text{With } p_3 = \frac{c.v}{\lambda.L}$$

On the 2 resonances we get v = 20.11 µm/s and 5.83 µm/s

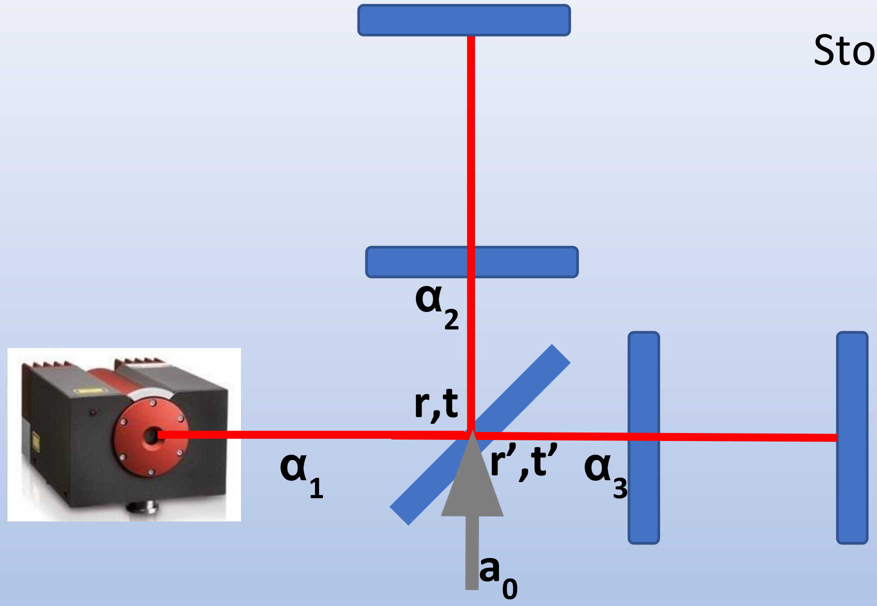
Whereas the maximum speed should be: $v_{max} = \frac{\lambda.\pi.c}{4.L.F^2}$ = 18 µm/s

(build-up time of the laser field in the cavity)

Also: $v_{Fmax} = \frac{\lambda.F_{max}}{2.F.m}$ = 7 µm/s (Maximum acceptable speed due to maximum applicable force of the actuators)

$v_{Bmax} = \frac{\pi.\lambda.B}{F}$ = 6.7 µm/s (Maximum acceptable speed due to respond speed of the feedback loop)

Quantum noise in GW detectors



Stokes reciprocity relations: $|r|^2 + |t|^2 = 1$ $\quad |r| = |r'|$

$rt^* + r^*t = 0$ $\quad |t| = |t'|$

$\left.\begin{array}{l}\alpha_2 = r\alpha_1 \\ \alpha_3 = t\alpha_1\end{array}\right\}$ $|\alpha_2|^2 + |\alpha_3|^2 = (|r|^2 + |t|^2)|\alpha_1|^2 = |\alpha_1|^2$

(Energy is conserved)

<u>Now we apply the same treatment to quantum fields:</u>

$\alpha_1, \alpha_2, \alpha_3 \Rightarrow \hat{a}_1, \hat{a}_2, \hat{a}_3$ and $[\hat{a}_j, \hat{a}_j^+] = 1$ with j=1,2,3

$[\hat{a}_2, \hat{a}_3^+] = 0$

?

$[\hat{a}_2, \hat{a}_2^+] = |r|^2[\hat{a}_1, \hat{a}_1^+] = |r|^2$

$[\hat{a}_3, \hat{a}_3^+] = |t|^2[\hat{a}_1, \hat{a}_1^+] = |t|^2$

$[\hat{a}_2, \hat{a}_3^+] = rt^* [\hat{a}_1, \hat{a}_1^+] = rt^*$

$\hat{a}_2 = r\hat{a}_1 + t\hat{a}_0$ and $\hat{a}_3 = t\hat{a}_1 + r\hat{a}_0$

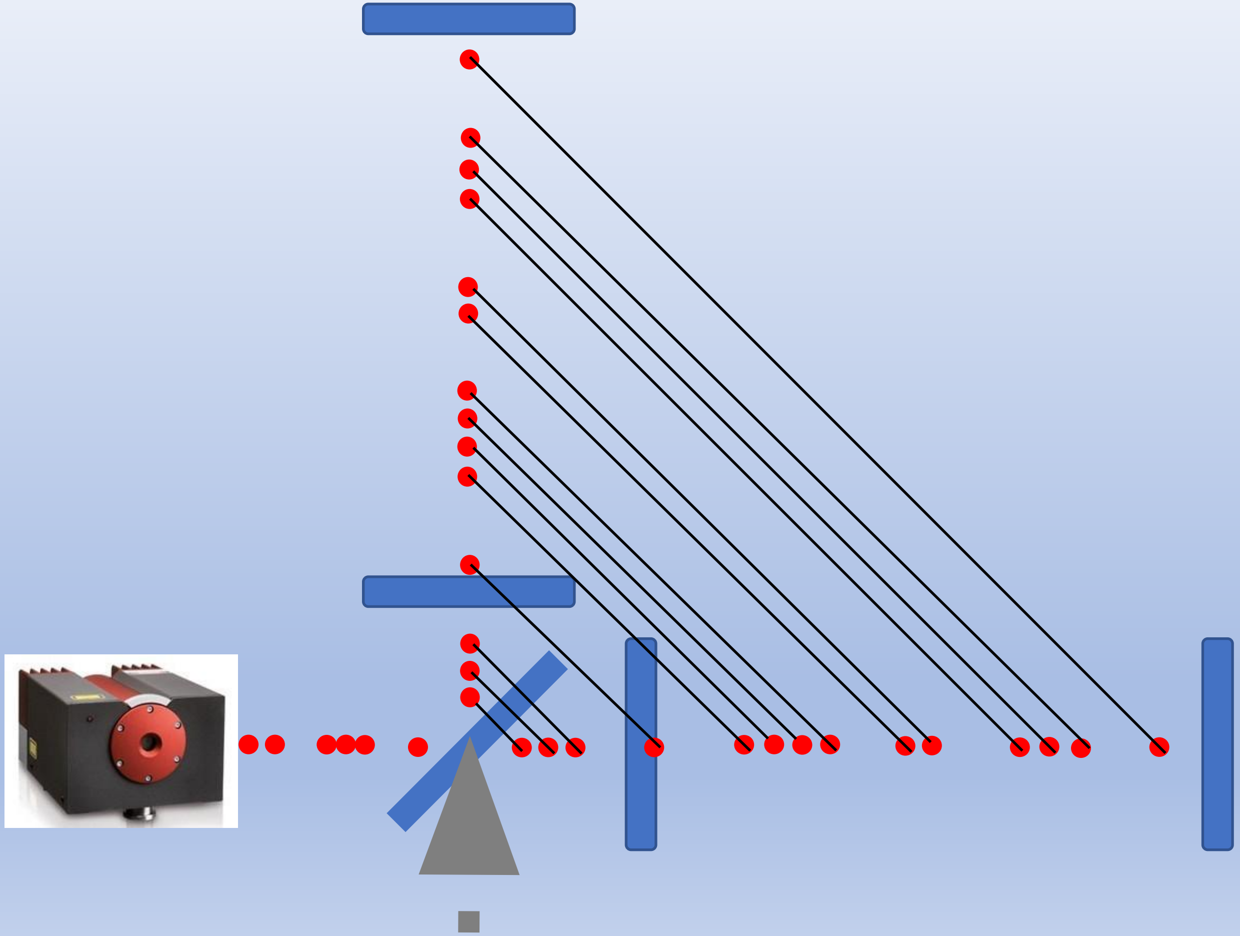
OK!

$[\hat{a}_2, \hat{a}_2^+] = |r|^2[\hat{a}_1, \hat{a}_1^+] + |t|^2[\hat{a}_0, \hat{a}_0^+] = |r|^2 + |t|^2 = 1$

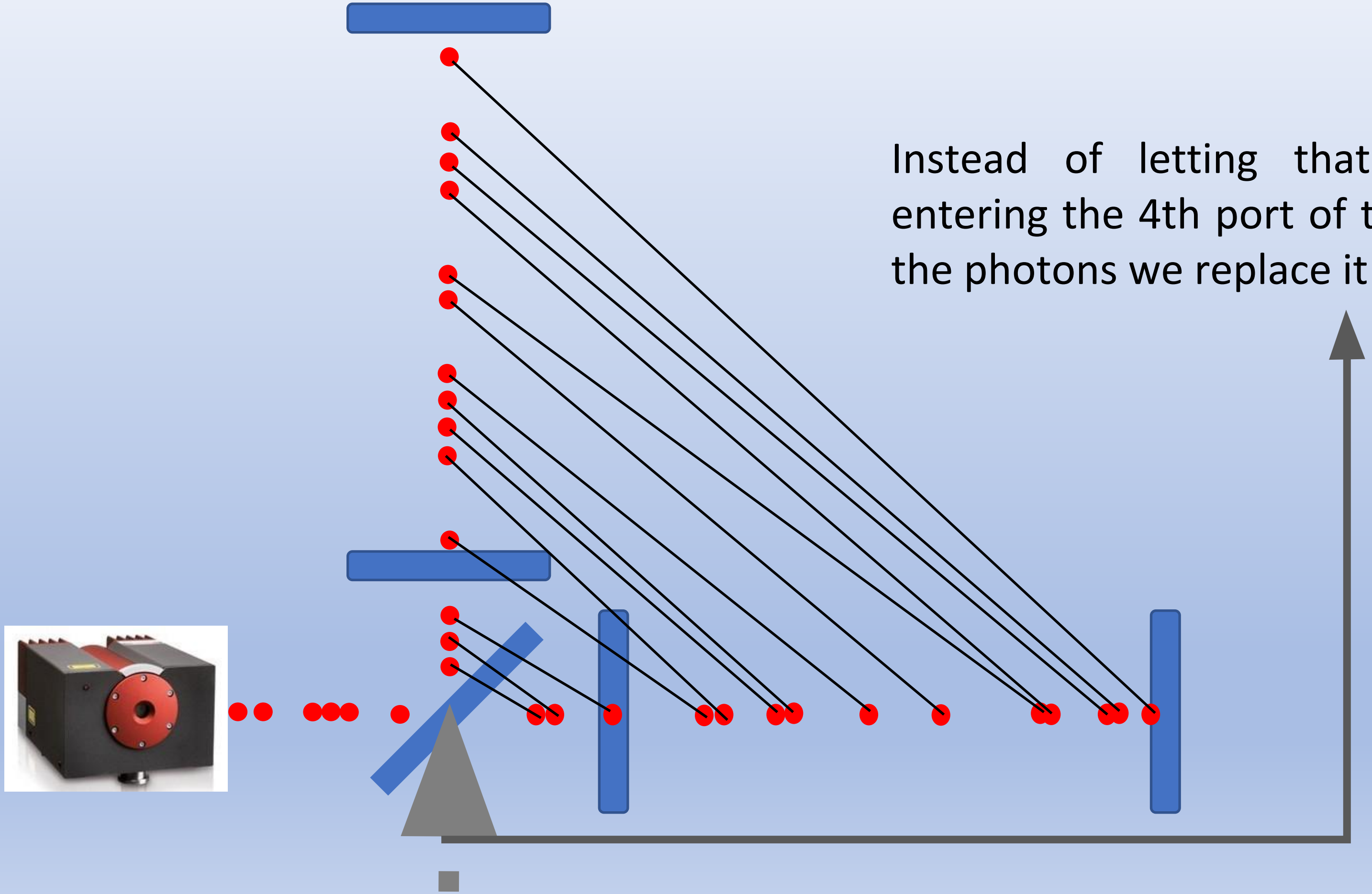
$[\hat{a}_2, \hat{a}_3^+] = rt^*[\hat{a}_1, \hat{a}_1^+] + rt^*[\hat{a}_0, \hat{a}_0^+] = rt^* + r'^*t' = 0$

In the classical description we could ignore the 4th input port because no light was entering, in the quantum field description this is wrong!

Quantum noise in GW detectors

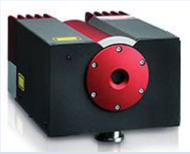


Quantum noise in GW detectors

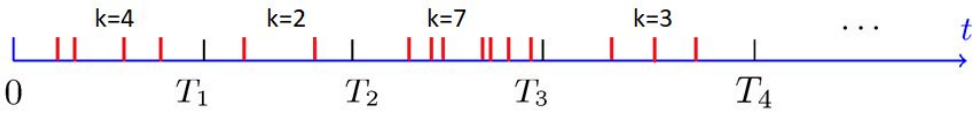


Instead of letting that noisy vacuum field entering the 4th port of the ITF and messing up the photons we replace it by the squeezed field.

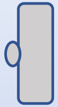
Beat the standard quantum limit using squeezed light



Coherent light



Photodiode



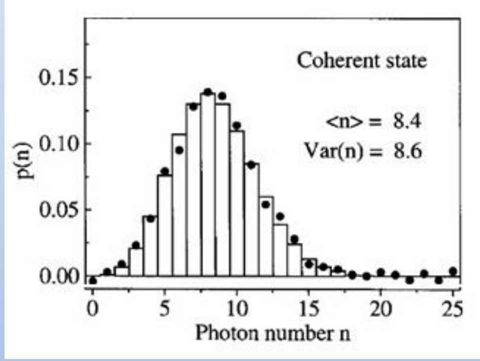
Probability to find k photons in an interval (binomial law)

$$P(X = k) = \frac{n!}{k!(n-k)!}\left(\frac{\lambda}{n}\right)^k\left(1-\frac{\lambda}{n}\right)^{n-k}$$

Limit when total photon number -> ∞

$$\lim_{n\to\infty} P(X = k) = \lim_{n\to\infty} \frac{n!}{k!(n-k)!}\left(\frac{\lambda}{n}\right)^k\left(1-\frac{\lambda}{n}\right)^{n-k}$$

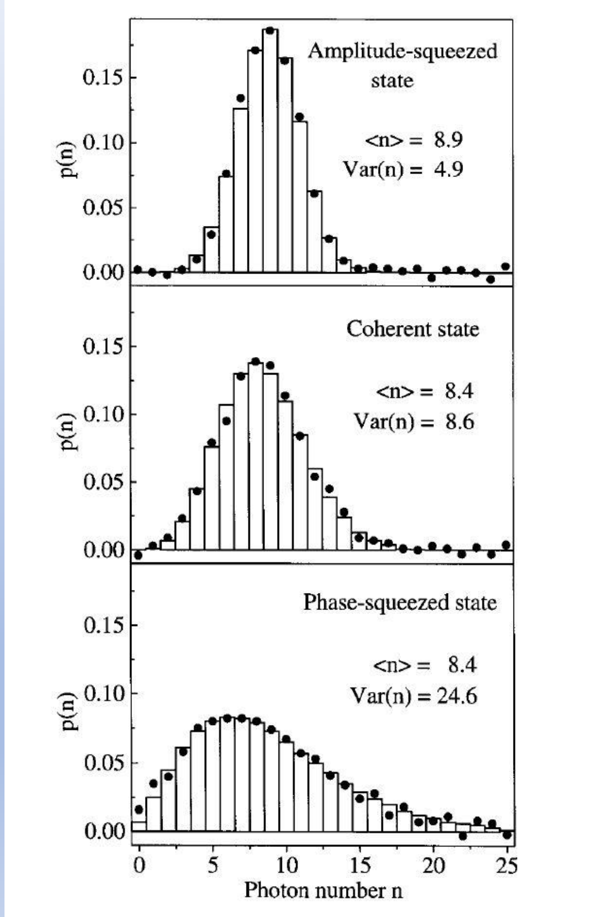
Measure photon distribution



$$P(\lambda, k) = \left(\frac{\lambda^k e^{-\lambda}}{k!}\right)$$

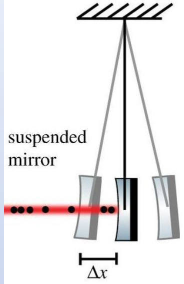
Poisson law

Beat the standard quantum limit using squeezed light



Sub-Poisson distribution

Higher probability to have ≈ same photon number per interval « mirror has more chances to be hit by the same amount of photons per time interval and thus oscillates less hazardous »

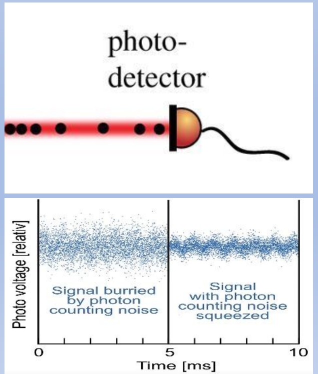


Poisson distribution

Photon distribution badly affects both quadratures

Super-Poisson distribution

Higher probability to have a nearly constant photon flux « photodetector has less probability to be hit by packets of photons followed by empty time periods »



A few words about vacuum squeezing

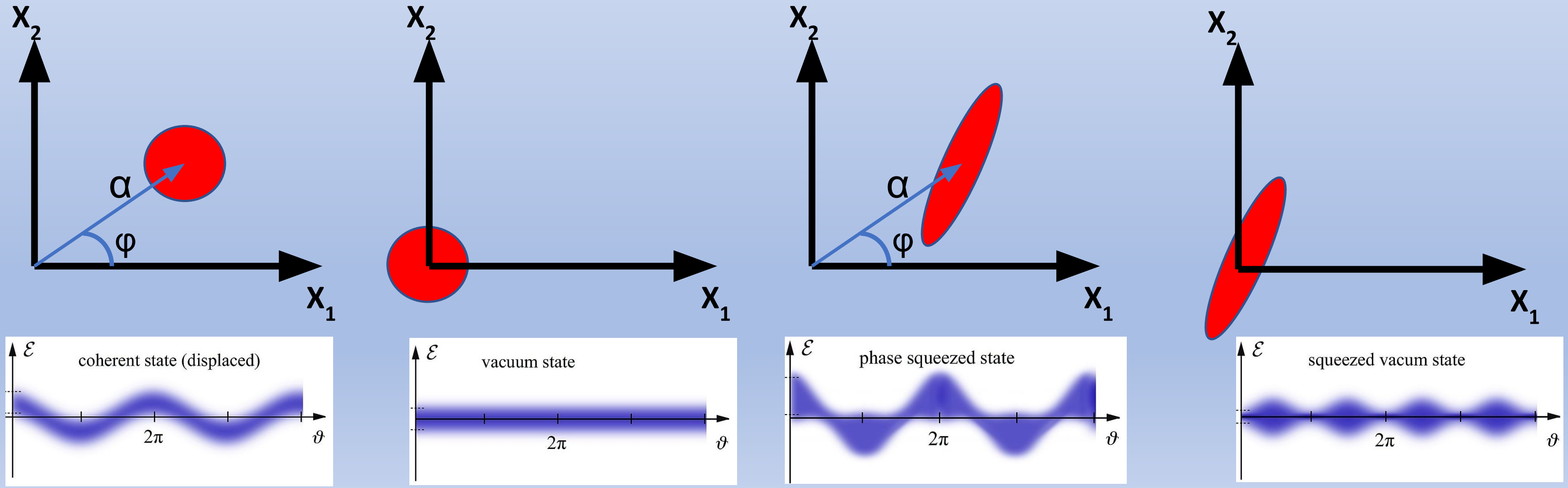
Vacuum squeezing:
The squeezed vacuum field has no coherent amplitude but its mean photon number is ≠ 0
-> this leads to a power of a few fW in the beam. It can be interpreted as the required power to rearange the noisy vacuum field into a less noisier squeezed vacuum field.

$N_{coherent} = |\alpha|^2$

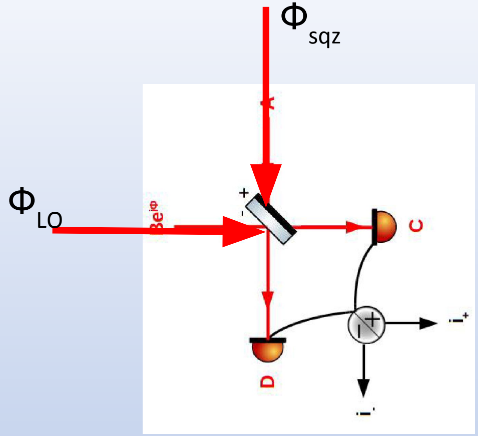
$N_{vacuum} = 0$

$N_{bright\ squeezed\ field} = |\alpha|^2 + \sinh(r)$

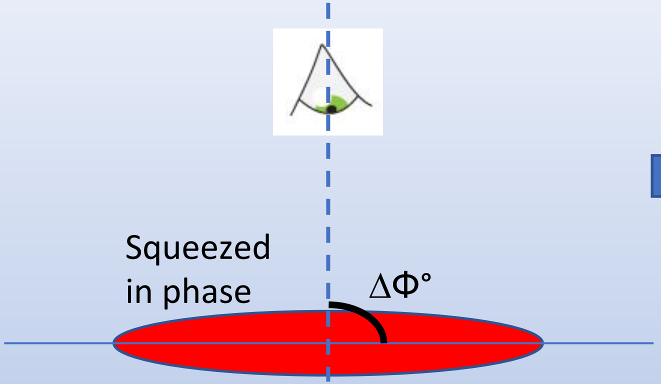
$N_{vacuum\ squeezed\ field} = \sinh(r)$
$\neq 0$ when $r \neq 0$

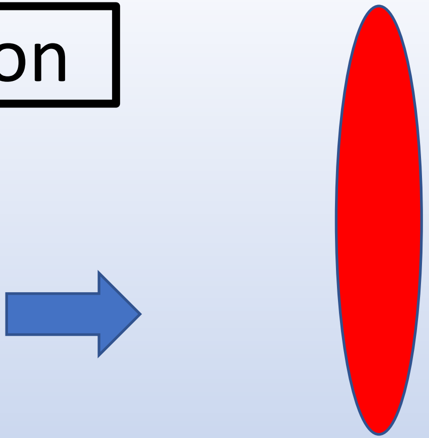


Squeezing detection

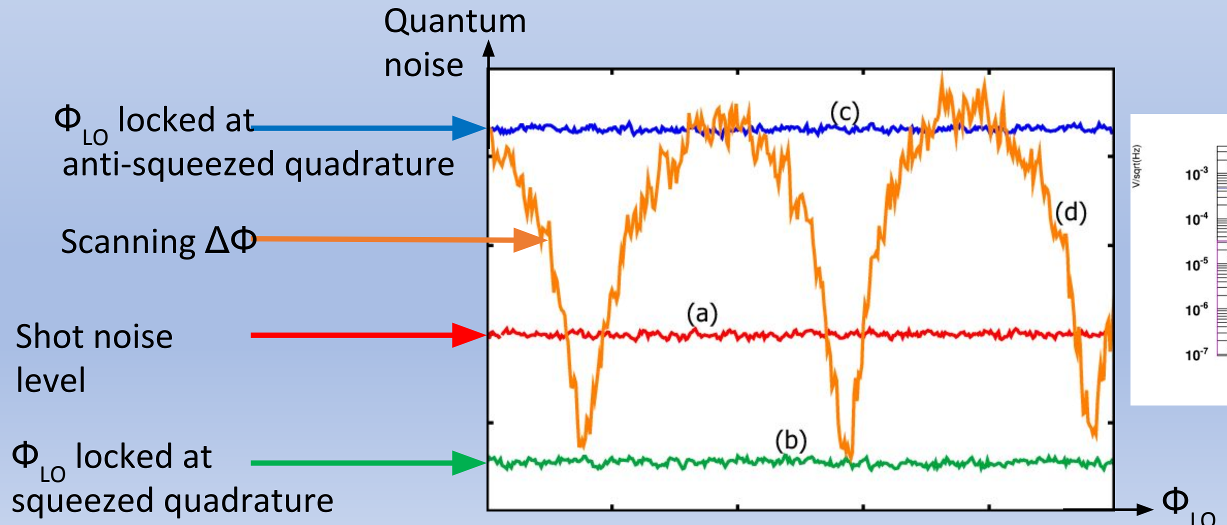


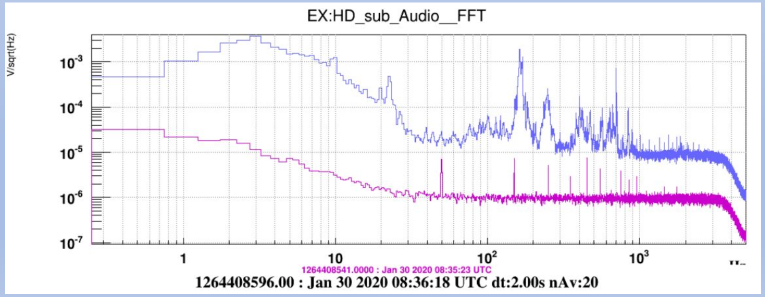
$\Delta\Phi = \Phi_{LO} - \Phi_{sqz}$



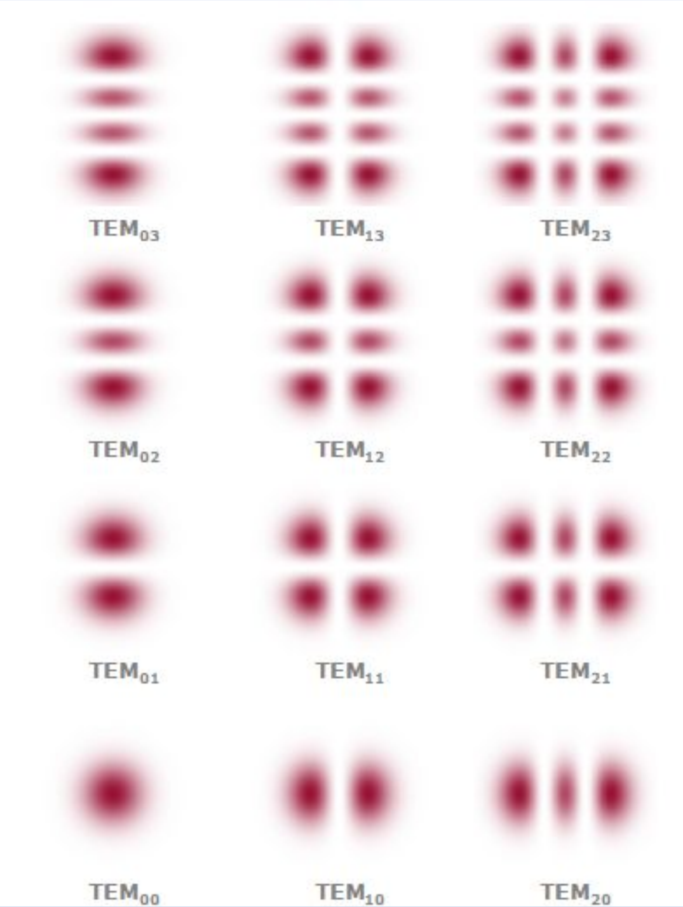


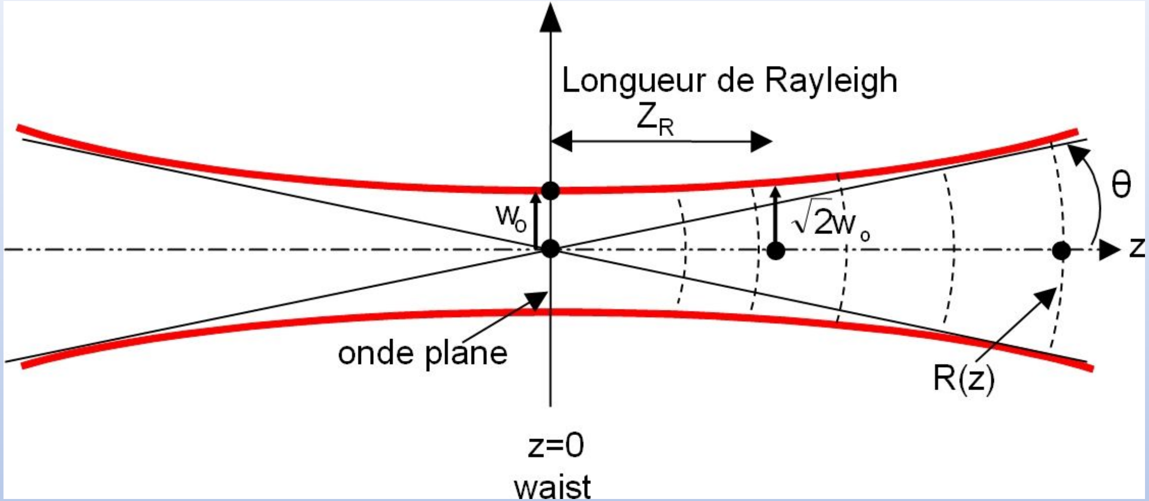
Depending on $\Delta\Phi$, the observer will see anti-squeezing in amplitude instead of squeezing in phase





Gaussian beam





Gouy phase (propagation): $\varphi_{z_1}{}^{mn} = (m + n + 1)\, Arctan\left(\frac{z}{z_R}\right)$

Modes d'ordres différents => Déphasages de propagation différents