Squeezed states at 1550 nm and across the wavelengths

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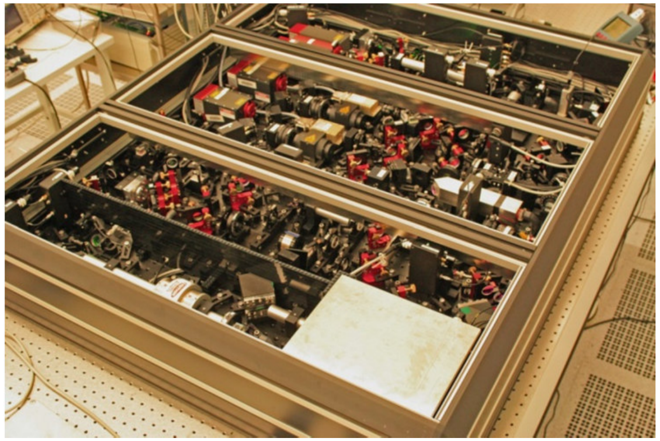
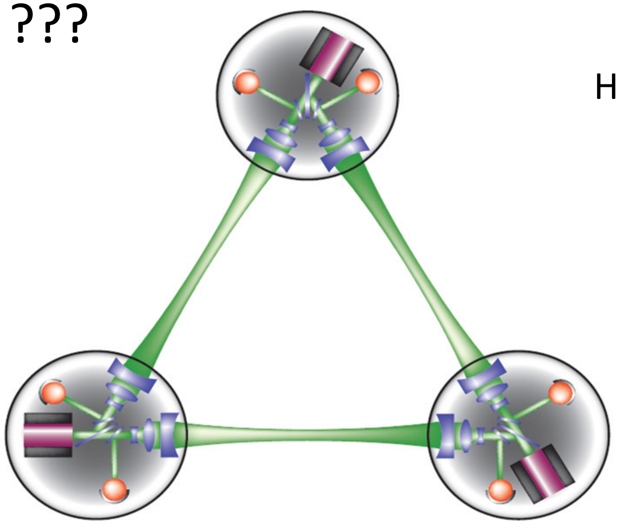
Wavelengths for gravitational wave detection

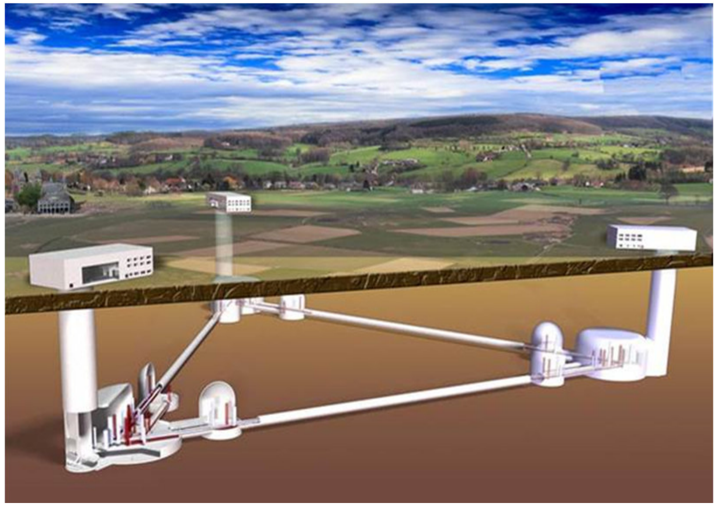
- GEO 600 (1064 nm)
- Space-based DECIGO (532 nm)
- Ground-based ET (1064 nm and 1550 nm)
- In future ???



H. Vahlbruch et al., Class. Quantum Grav. **27** (2010) 084027

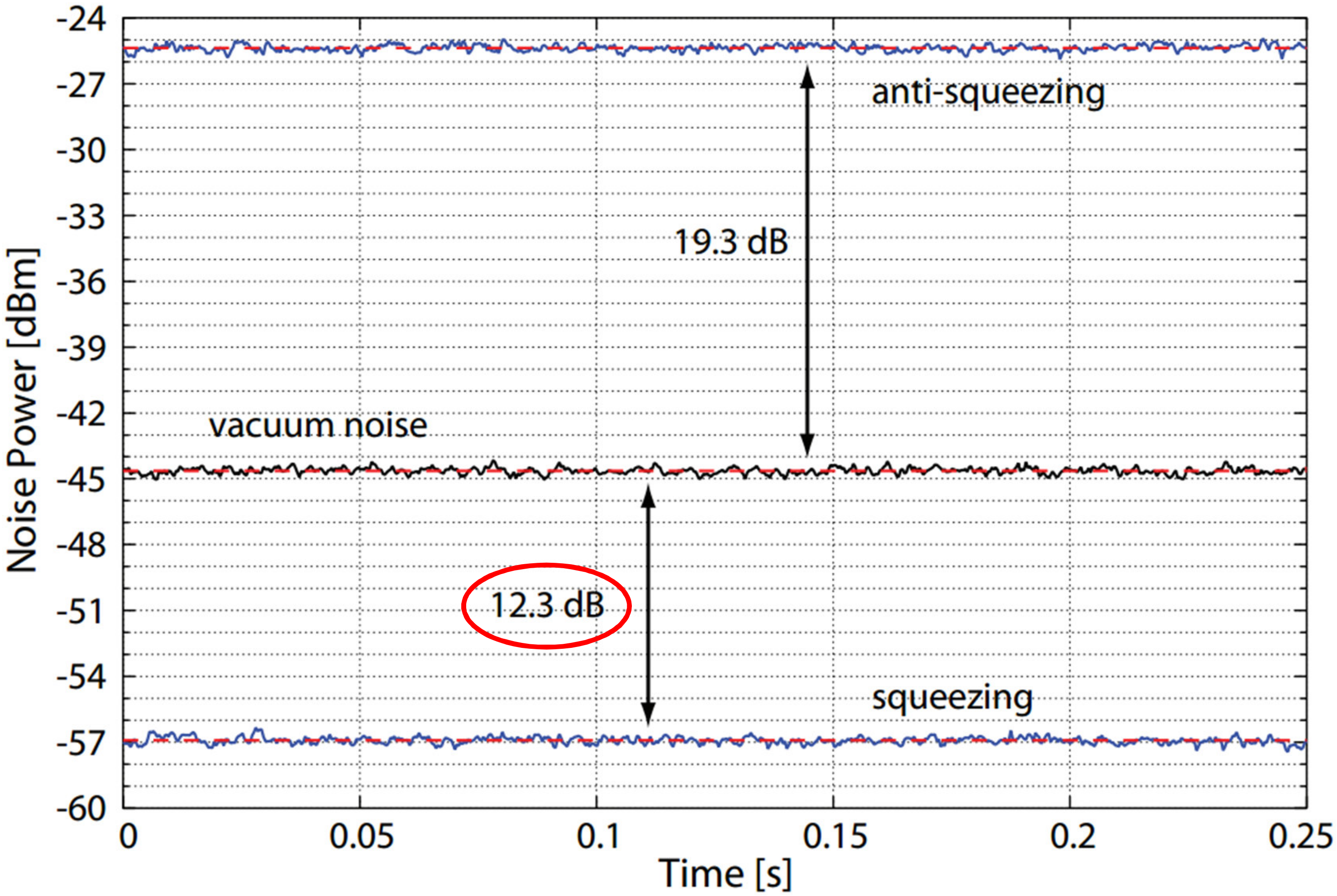


S. Sato et al., DECIGO: The Japanese space gravitational wave antenna, J. Phys.: Conf. Ser. **154,** 012040 (2009)



European design study

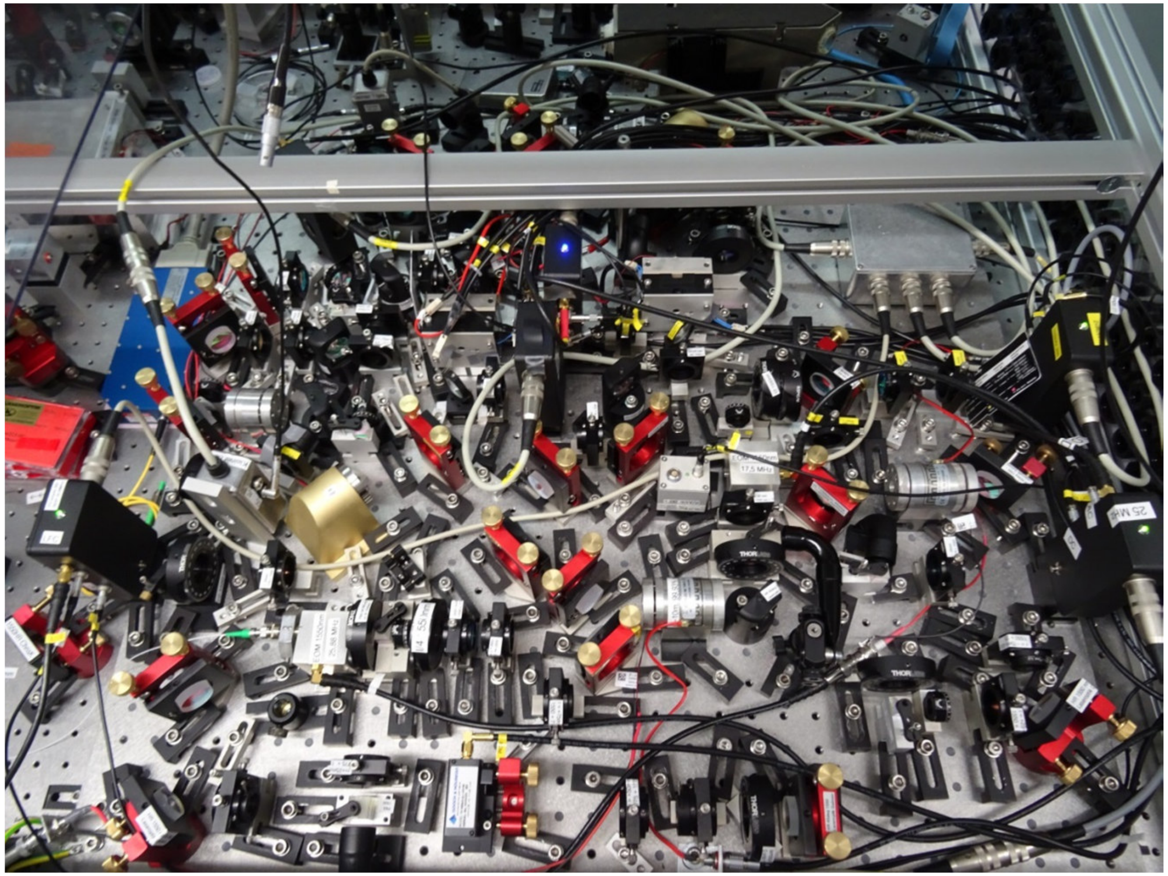
Squeezing at 1550 nm



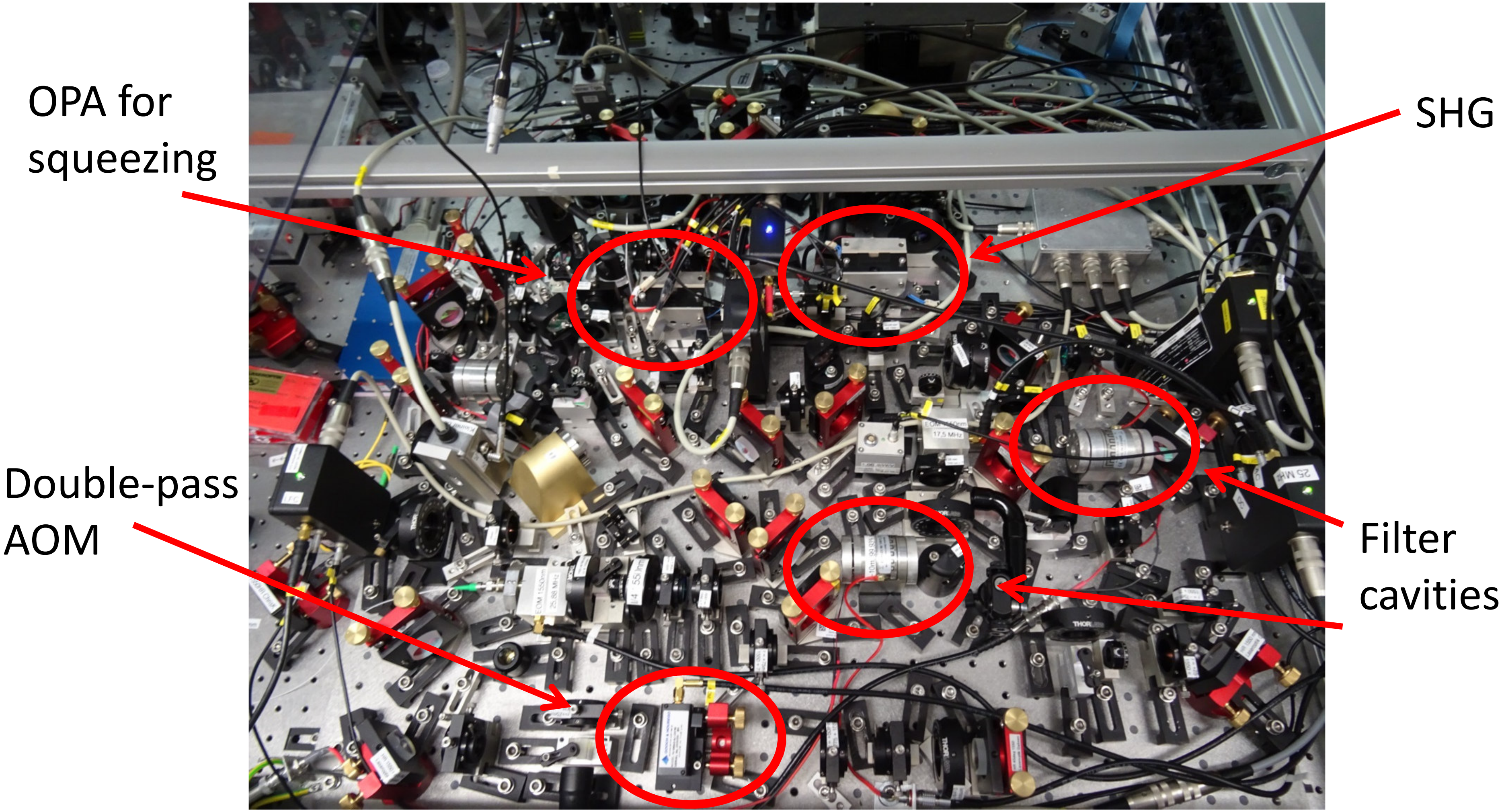
M. Mehmet et al., Optics Express Vol. 19, Issue 25, 25763-25772 (2011)

New squeezed light source at 1550 nm

- Audio band for GW detection
- On breadboard to allow for easy transportation
- Small footprint (80 x 80 cm)



New squeezed light source at 1550 nm



Nonlinear processes for squeezing generation

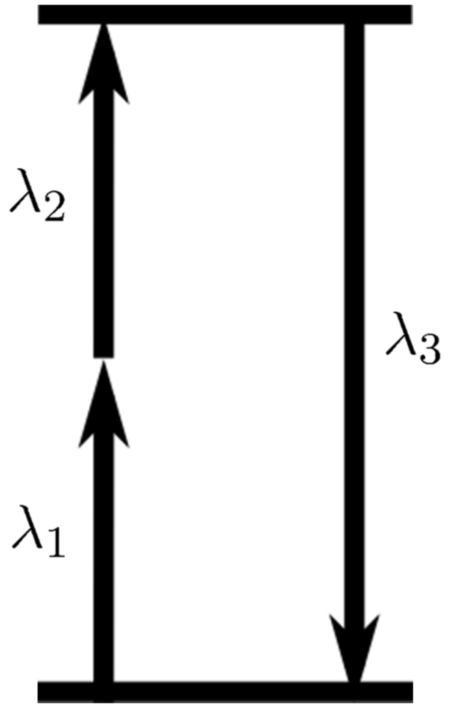
- Conversion between wavelengths with nonlinear crystals
- Taylor expansion of the polarization of the medium:

$$\mathbf{P} = \epsilon_0 \left(\chi^{(1)} \mathbf{E} + \chi^{(2)} \mathbf{E}^2 + \chi^{(3)} \mathbf{E}^3 + ... \right)$$

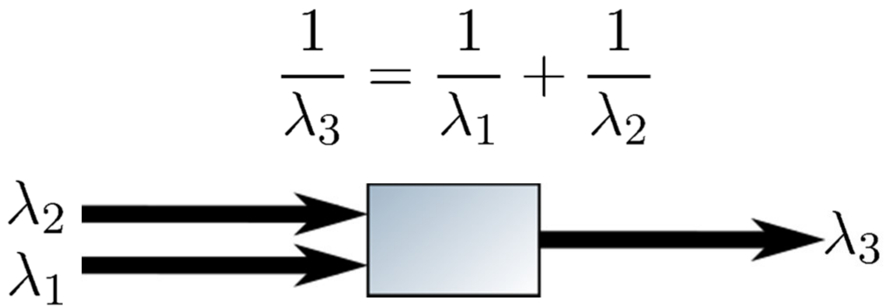
2nd order nonlinearity allows for the generation of new wavelengths from pump fields

Sum frequency generation for pump field generation

- Two photons at λ_1 and λ_2 are combined to one at $\frac{1}{\lambda_3} = \frac{1}{\lambda_1} + \frac{1}{\lambda_2}$

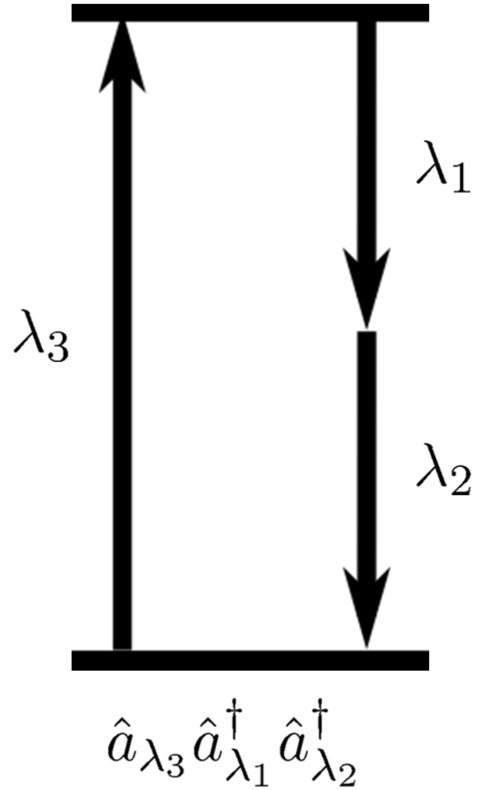


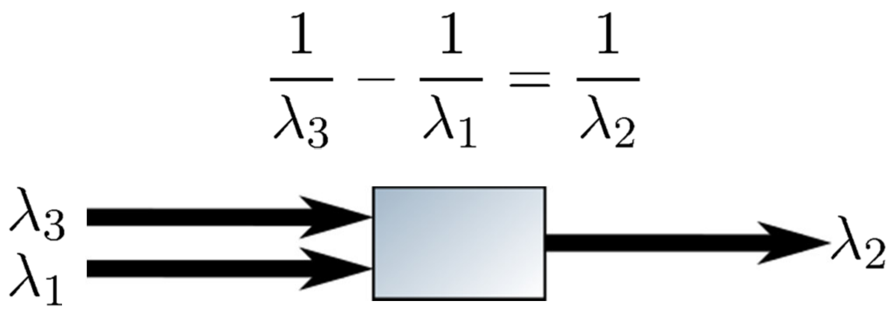
$$\hat{a}_{\lambda_1} \hat{a}_{\lambda_2} \hat{a}^\dagger_{\lambda_3}$$



Parametric generation of squeezing

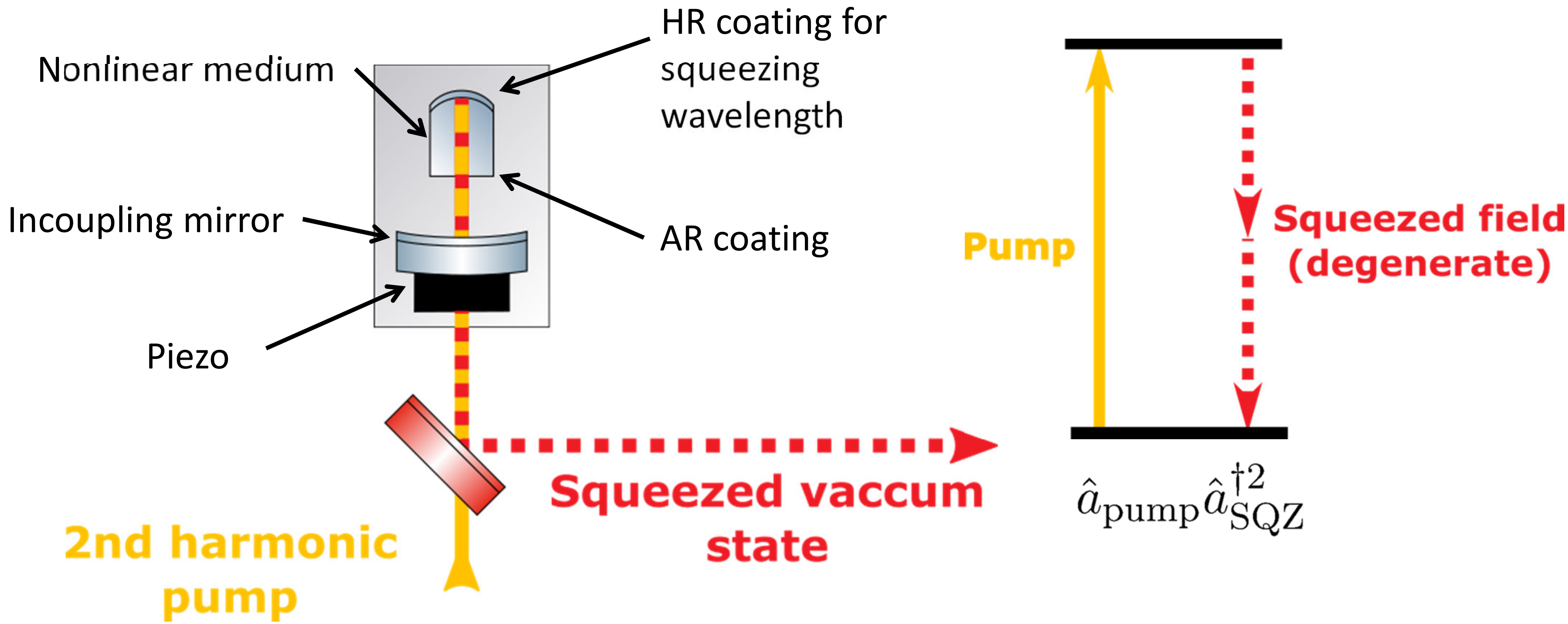
- Two photons at λ_3 and λ_1 are combined to one at $\frac{1}{\lambda_3} - \frac{1}{\lambda_1} = \frac{1}{\lambda_2}$





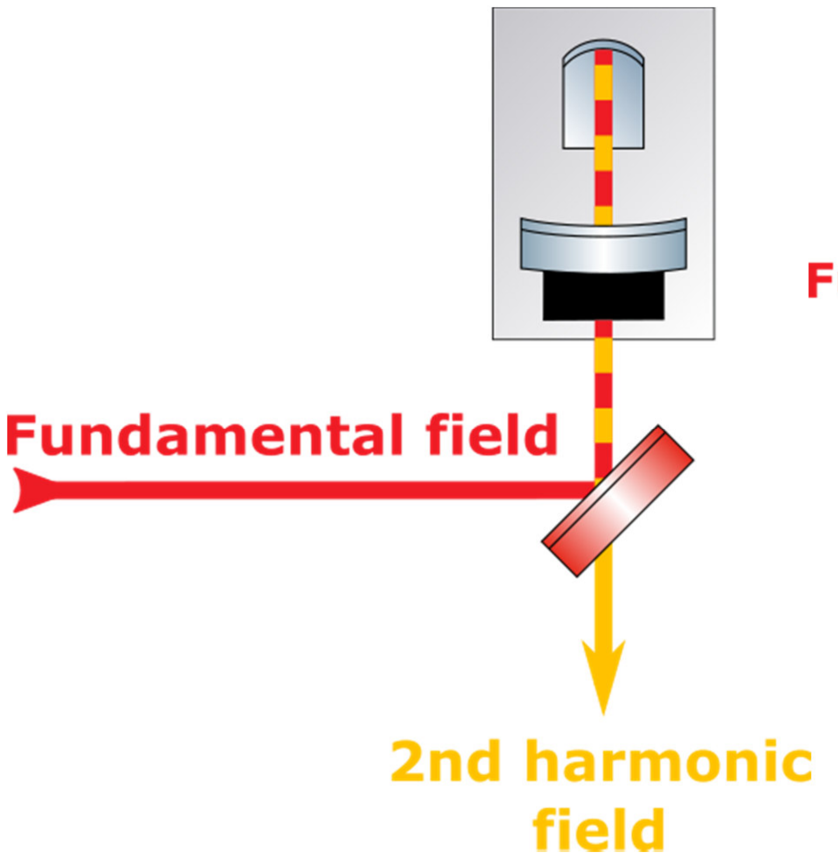
Generation of squeezed states

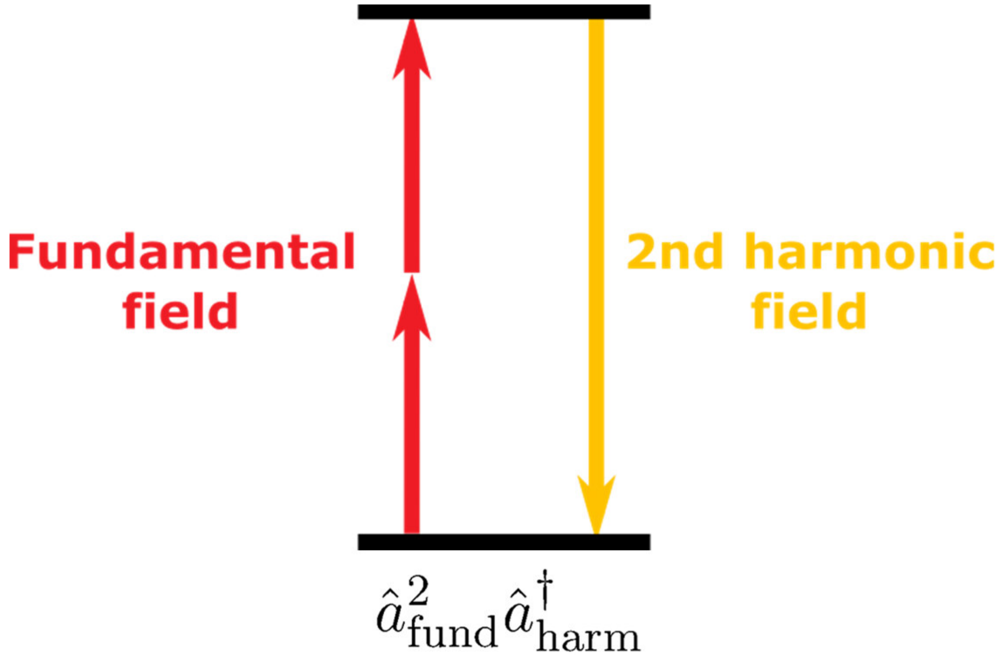
- Parametric down conversion in a cavity with temperature stabilized PPKTP as a nonlinear medium



Pump field generation

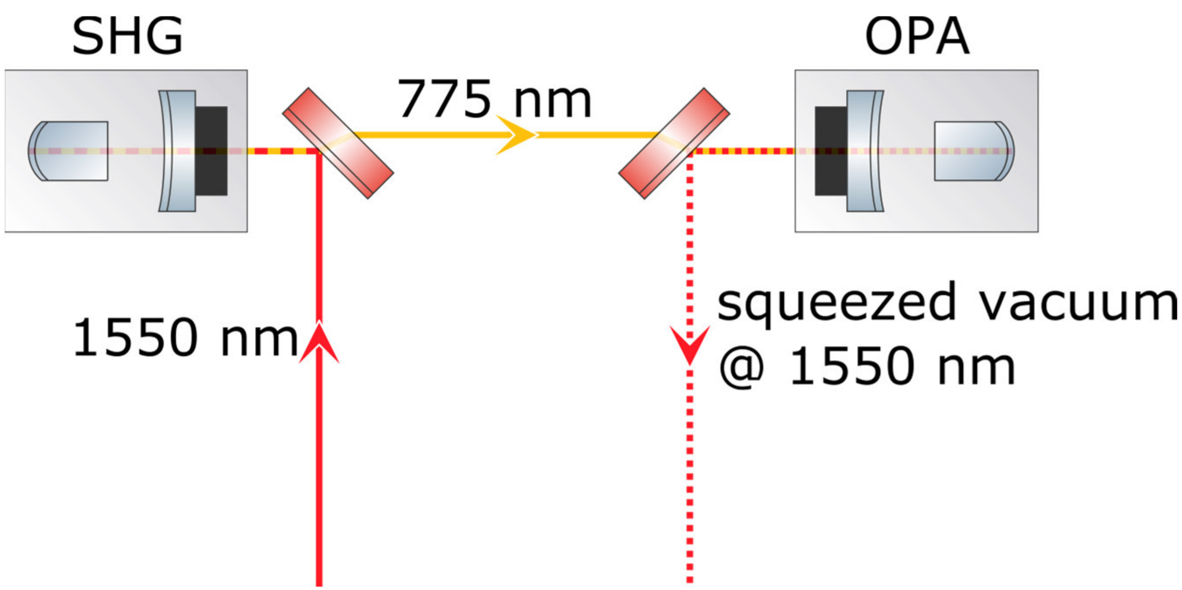
- Second harmonic pump field is generated in SFG process

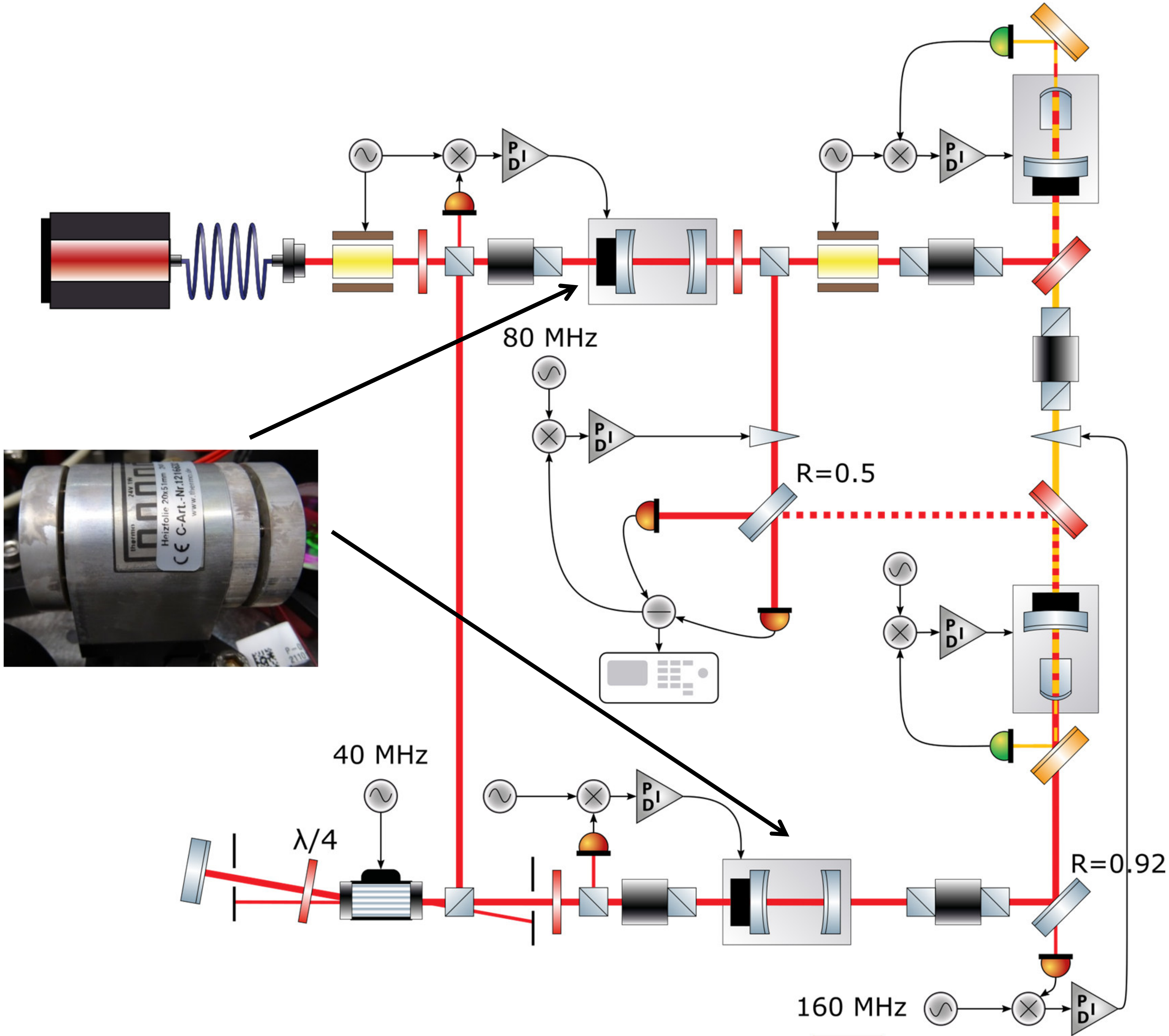




Generation of squeezed states

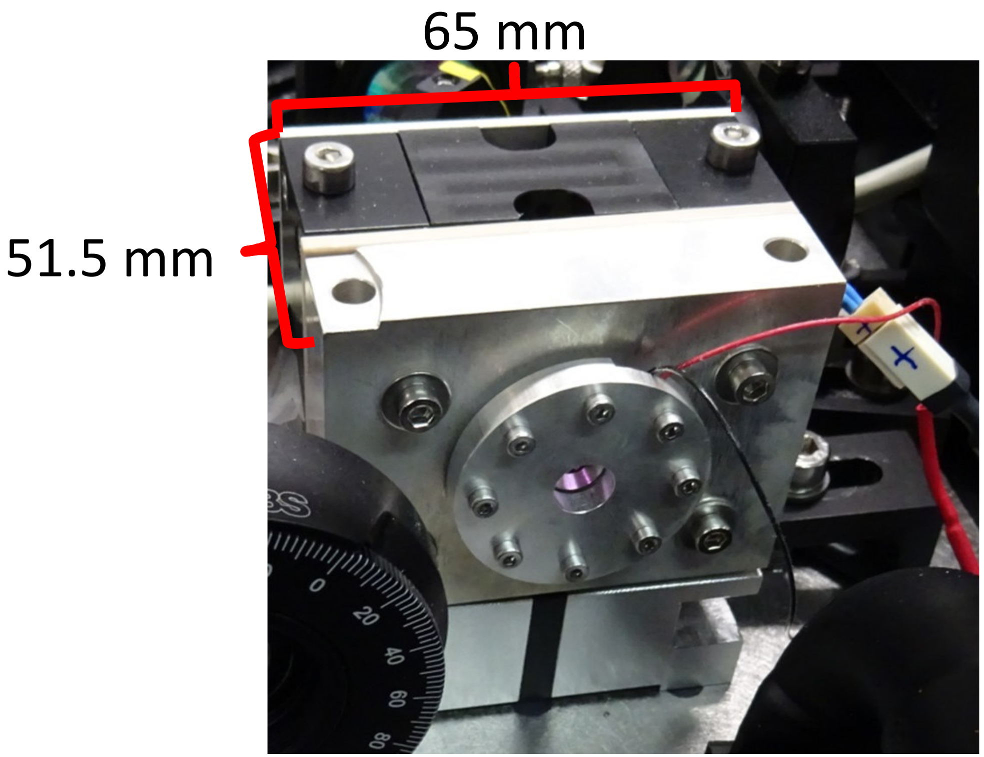
- Configuration to generate squeezing in the experiments presented in this talk
- SHG and OPA are doubly resonant for 775 nm and 1550 nm
- Strong squeezing with low pump powers

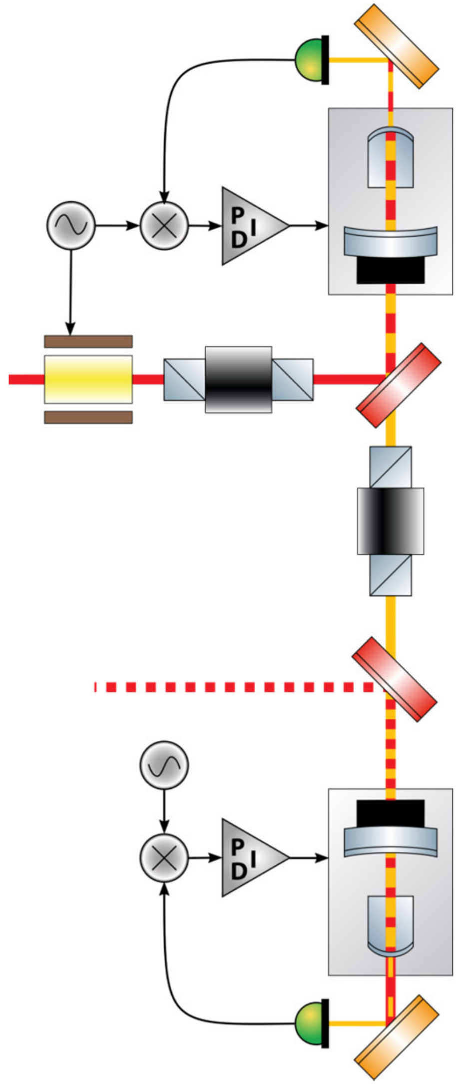



80 MHz
R=0.5
40 MHz
λ/4
R=0.92
160 MHz
PDI

Squeezing generation

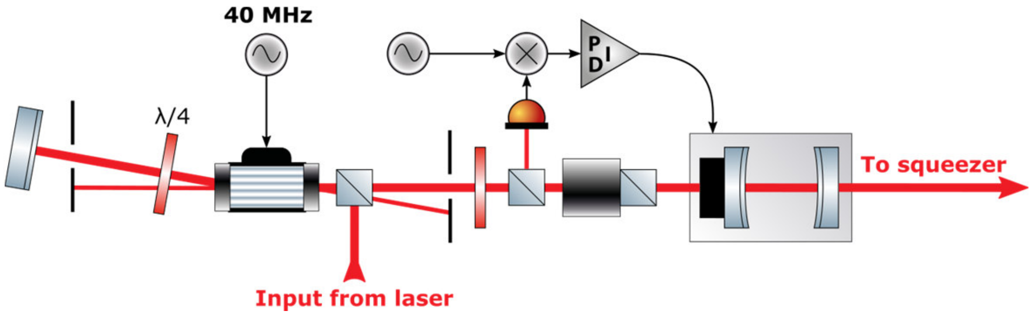
- Both cavities resonant for 775 nm and 1550 nm
- Length control with PDH and sidebands on the 775 nm field

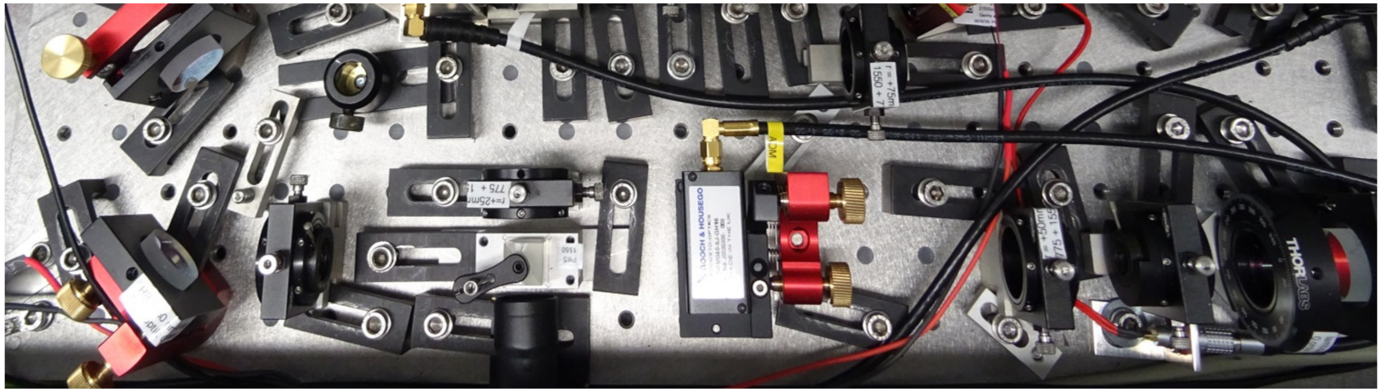




Phase control for squeezed vacuum

- Squeezing at low frequencies requires locking techniques that do not introduce noise or photons at the carrier frequency
- Coherent control scheme with single sideband was used

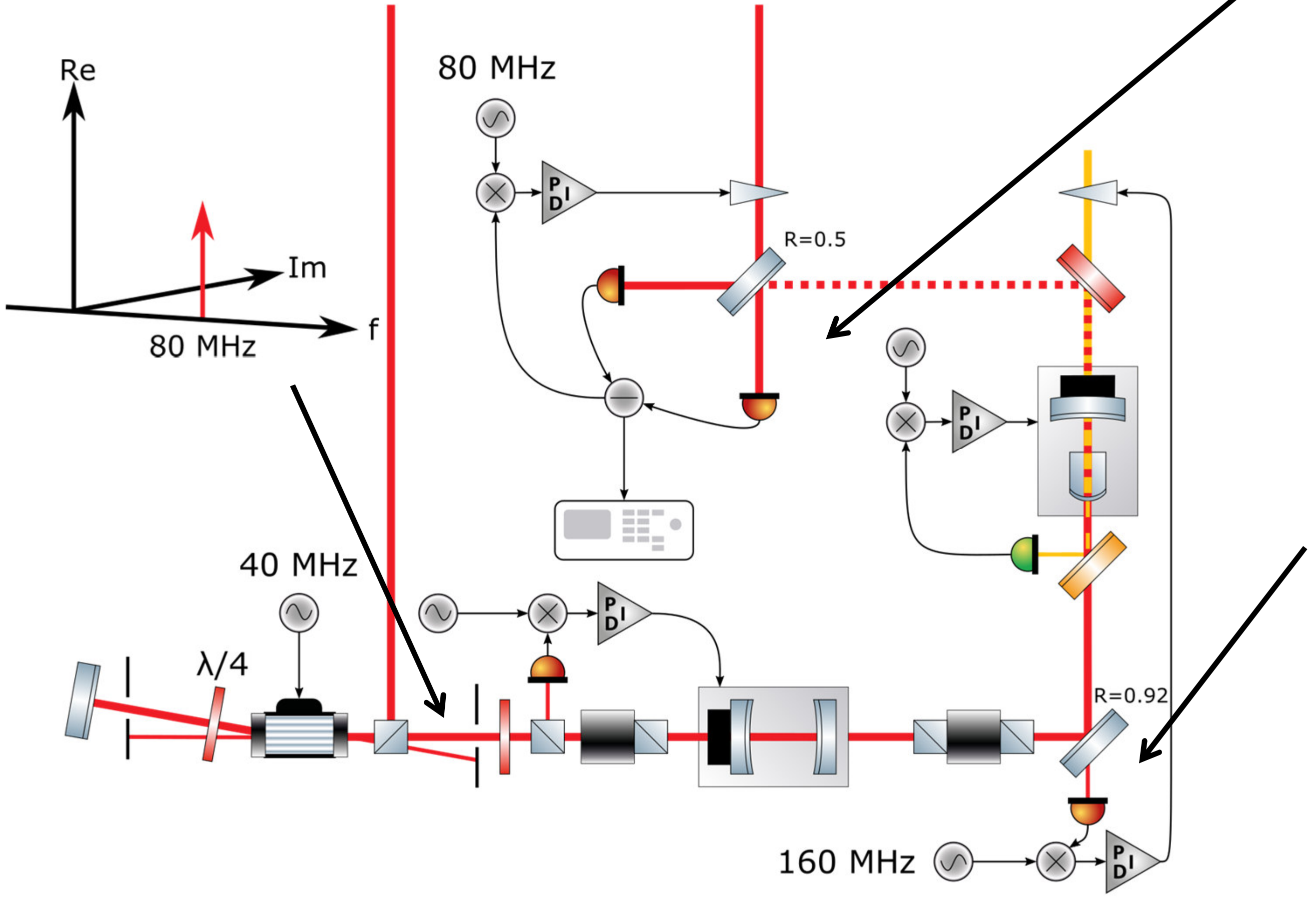


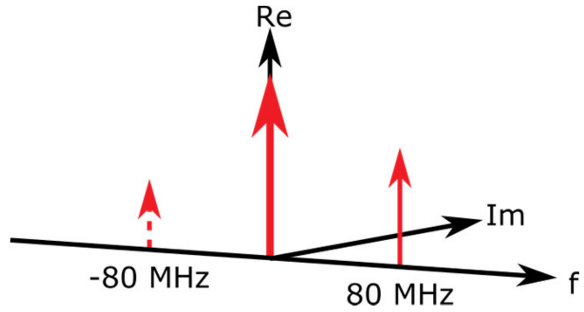


Single sideband generation

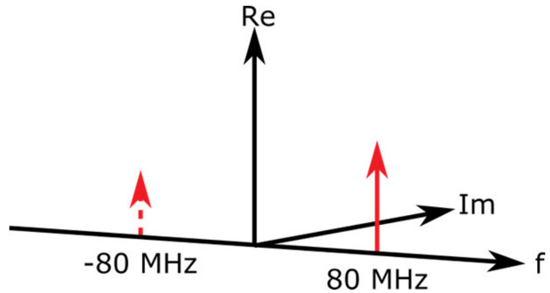
Coherent control

- Single sideband at 80 MHz senses the nonlinearity of the crystal





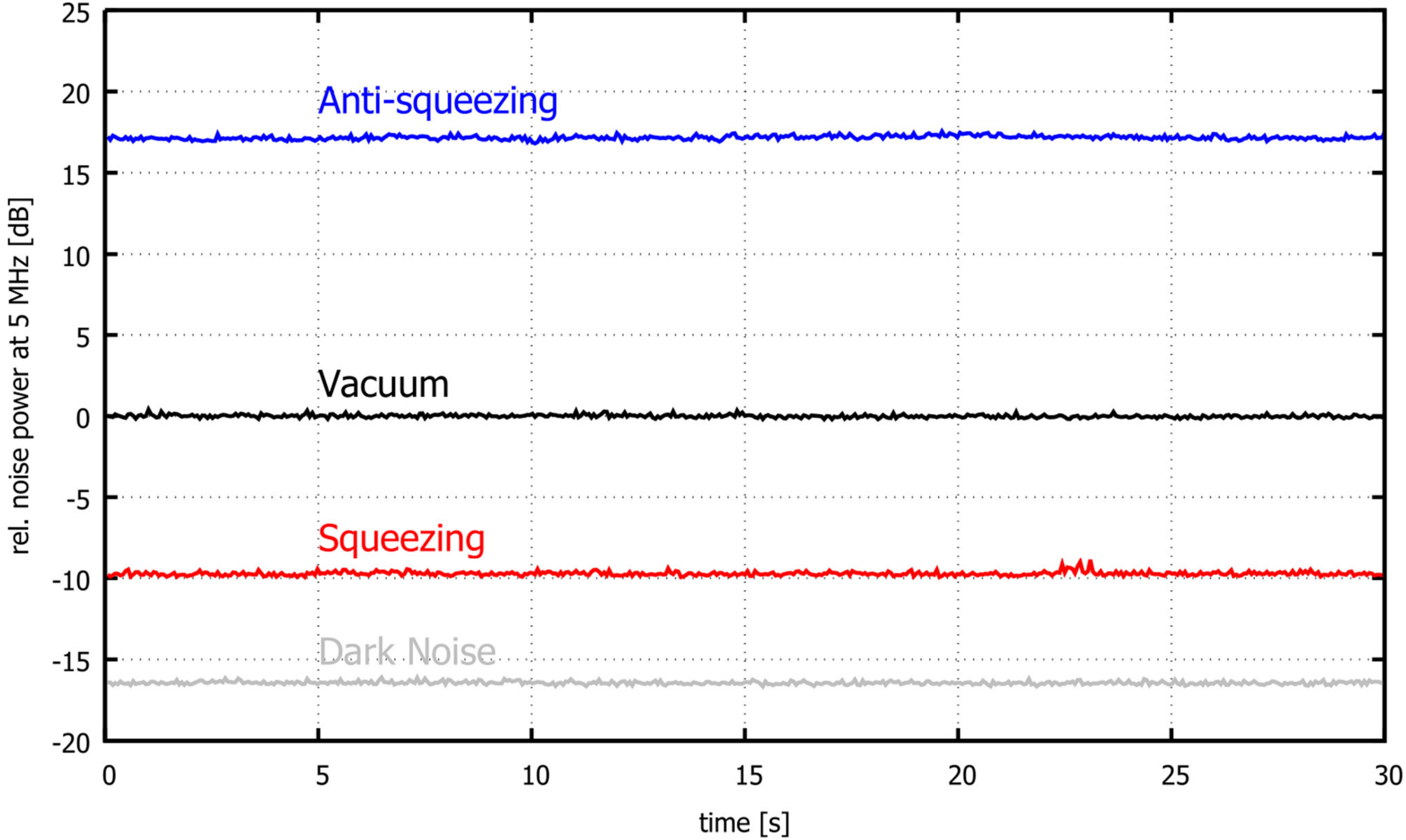
$$S_{\mathrm{Err}}^{\mathrm{LO}} \propto \sin\left(2\phi + \Phi\right)$$
$$\Phi = \text{phase LO} - \text{Pump}$$



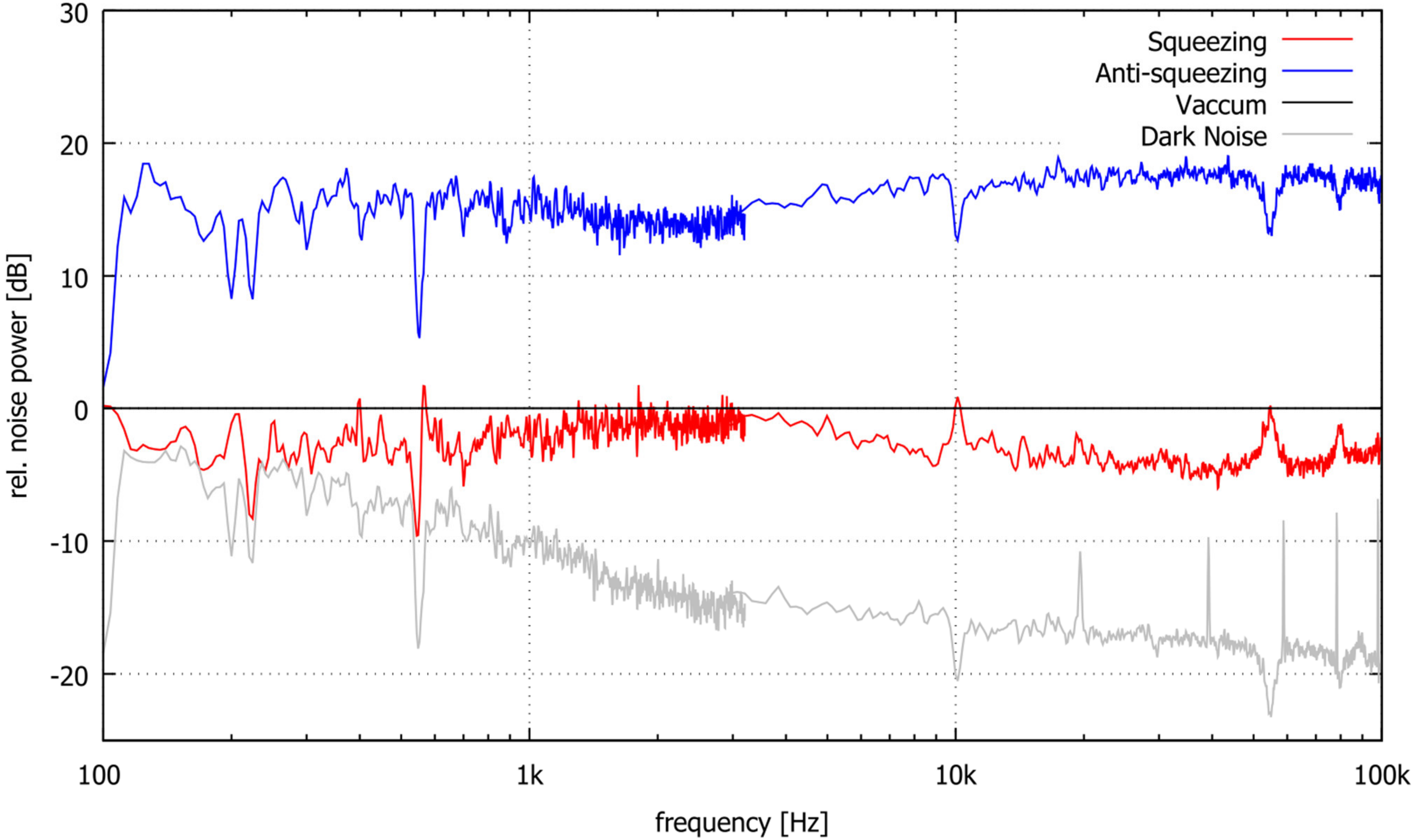
$$S_{\mathrm{Err}}^{\mathrm{Pump}} \propto \sin\left(2\phi\right)$$
$$\phi = \text{squeezing angle}$$

H. Vahlbruch et al.,Phys. Rev. Lett.,97, 011101 (2006)

Squeezing at 1550 nm (preliminary)

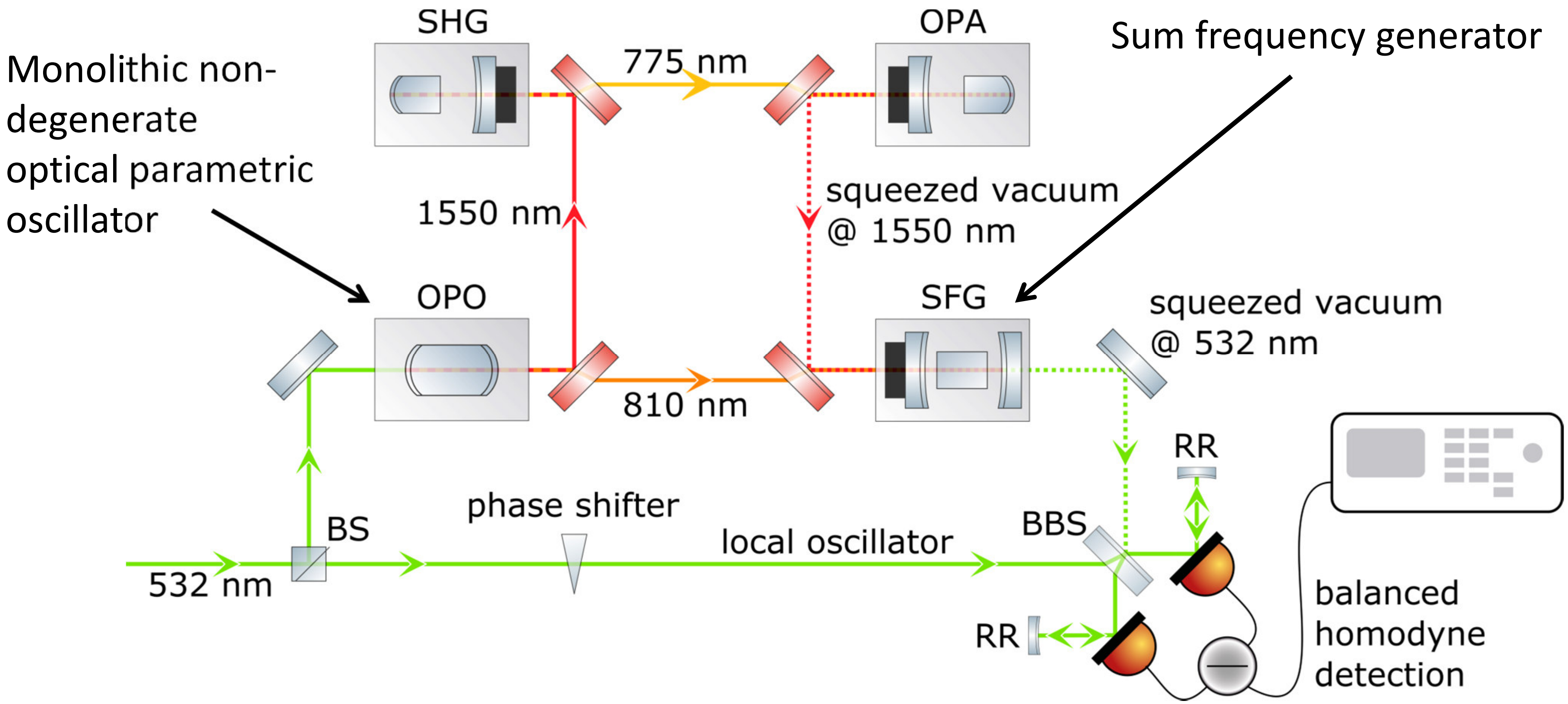


Squeezing at 1550 nm (preliminary)



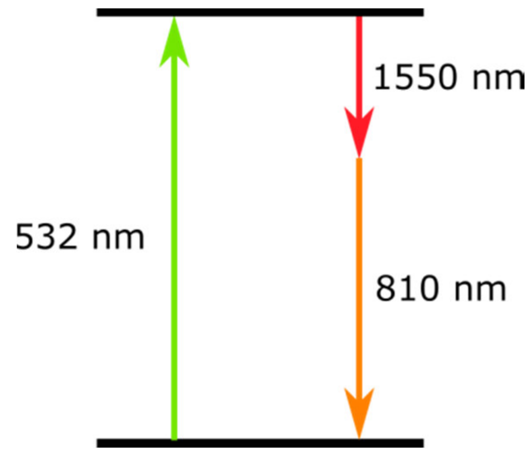
Squeezing at visible wavelengths (532 nm)

- Only one 532 nm source for the setup, allows for homodyne detection

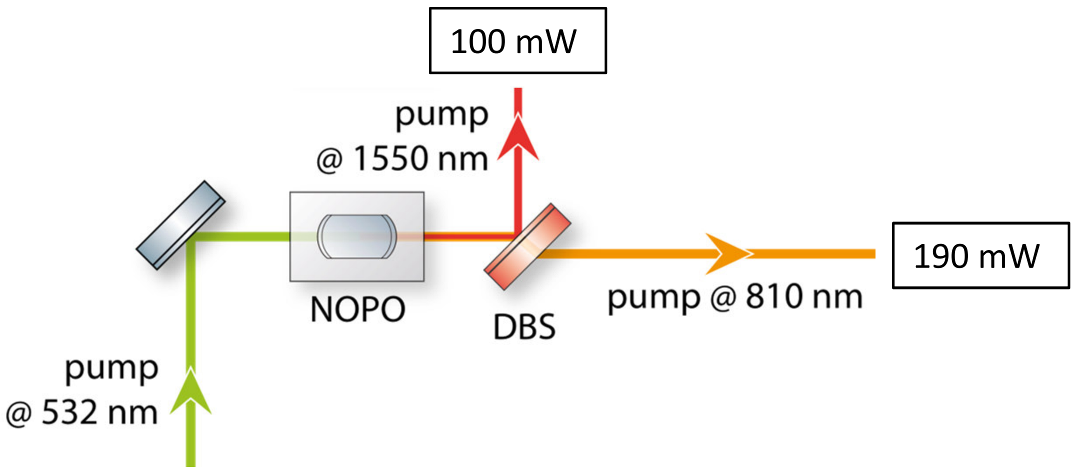


Generation of pump fields for up-conversion

- Monolithic non-degenerate optical parametric oscillator
- PPKTP, actively temperature stabilized
- Mirrors coated directly on curved crystal surfaces
- 532 nm → 810 & 1550 nm

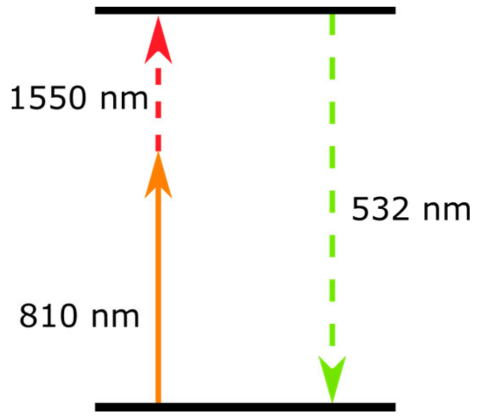


$$\hat{a}_{532}\hat{a}^{\dagger}_{810}\hat{a}^{\dagger}_{1550}$$

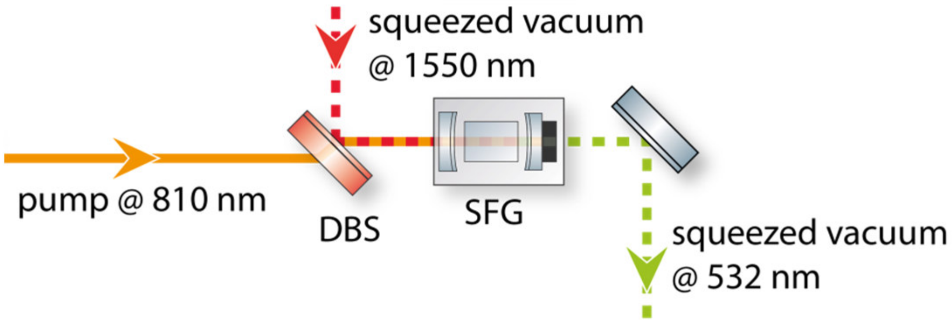


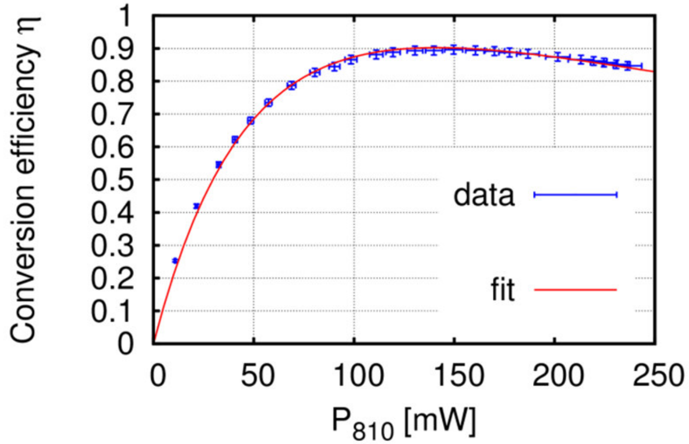
Squeezing up-conversion

- Up-conversion does not change the quantum properties of a state (P. Kumar, Opt. Lett. 15, 1990)
- Higher conversion efficiency in cavity, two coupling mirrors around PPKTP crystal
- Efficiency dependent on pump power, measured with dim classical 1550 nm

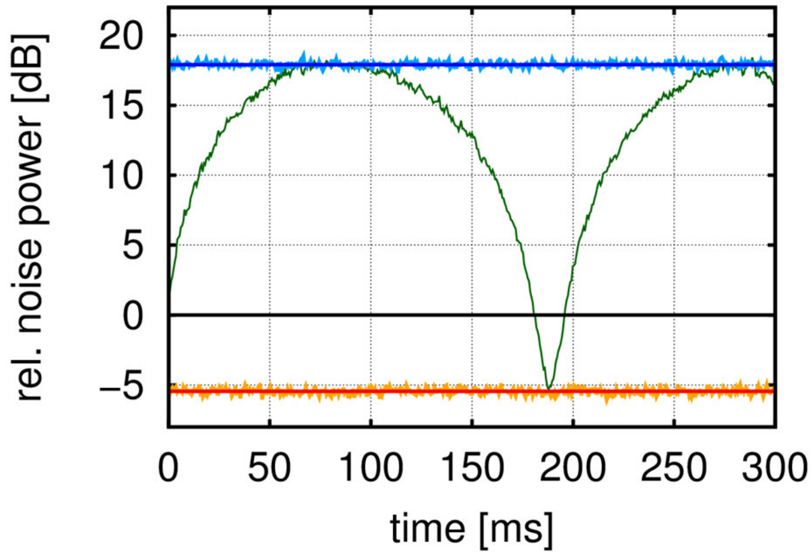


$$\hat{a}_{810}\hat{a}_{1550}\hat{a}^{\dagger}_{532}$$





Squeezing at 532 nm



18 dB anti-squeezing (@ 532 nm)

scanned phase

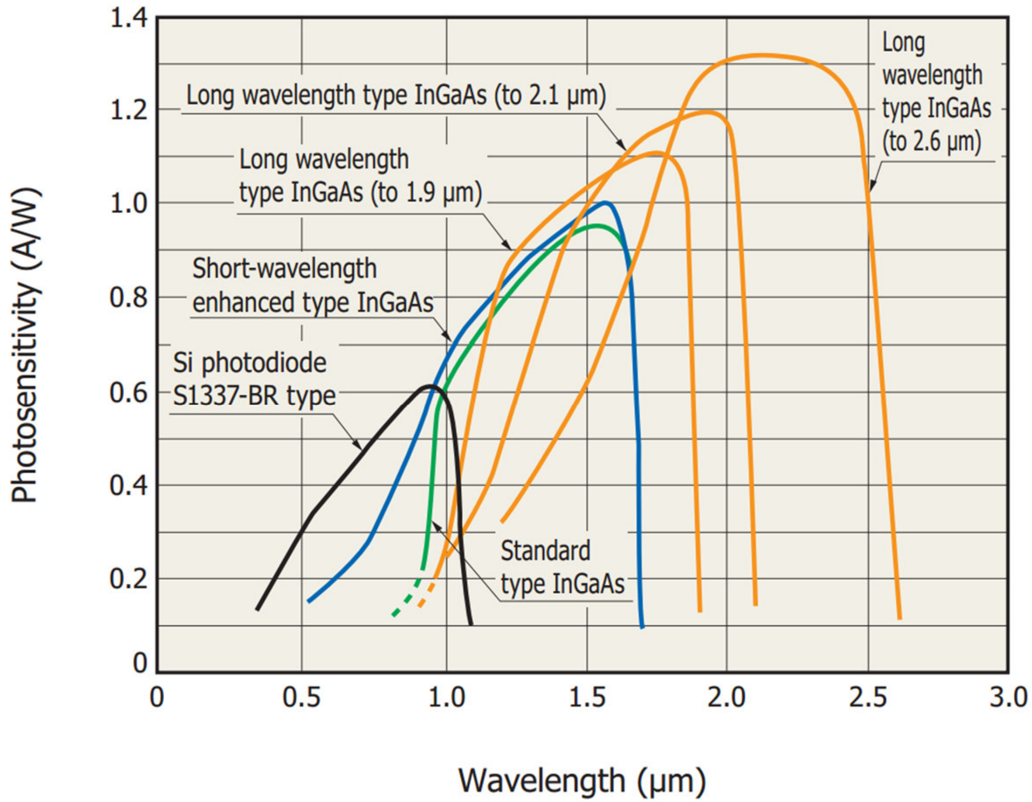
-5.5 dB squeezing (@ 532 nm)

C. Baune et al.,Optics Express ,Vol. 23, No. 12, 16035-16041 (2016)

- Zero-span measurement at 5 MHz
- Initial SQZ at 1550 nm of -8.8 dB
- About 27% loss
    - Finite conversion efficiency (90%)
    - Quantum efficiency of photodiodes (90%)
    - Propagation losses, mode matching, ...

PDs across the wavelengths

- Usage of a wavelength of 2 µm and even higher has been discussed (less absorption in silicon, less absorption in coatings, less scattering…)
- Squeezed-light generation above 2200 nm is fully limited by the efficiency of PDs



Hamamatsu InGaAs Photodiods selection guide (march 2015): https://www.hamamatsu.com/resources/pdf/ssd/ingaas_kird0005e.pdf

Summary

- Different wavelengths for gravitational wave detectors are suggested
- Squeezing at 532 nm, 1064 nm and 1550 nm has been demonstrated
- Higher wavelengths are difficult to obtain because of the limited quantum efficiency of photo detectors

End