Two-color Einstein-Podolsky-Rosen entangled state in the sub-kHz regime

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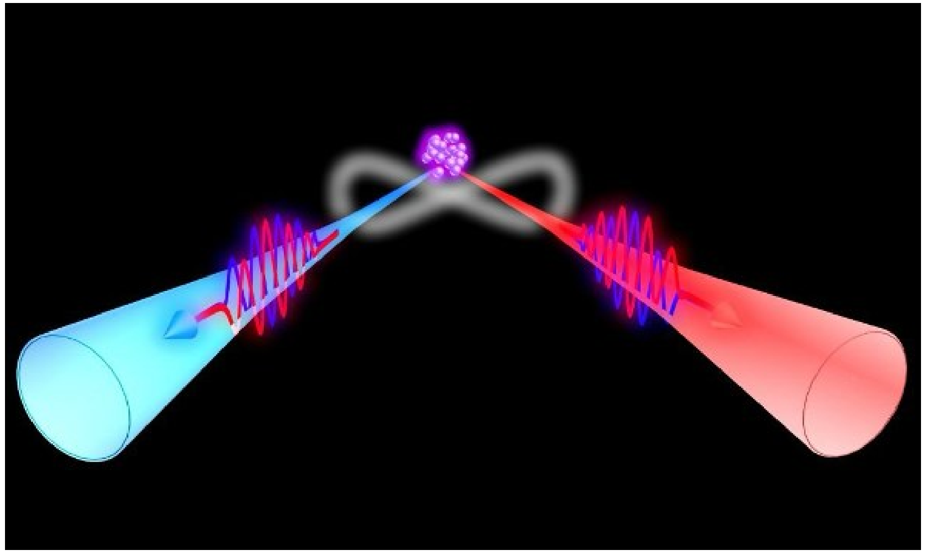
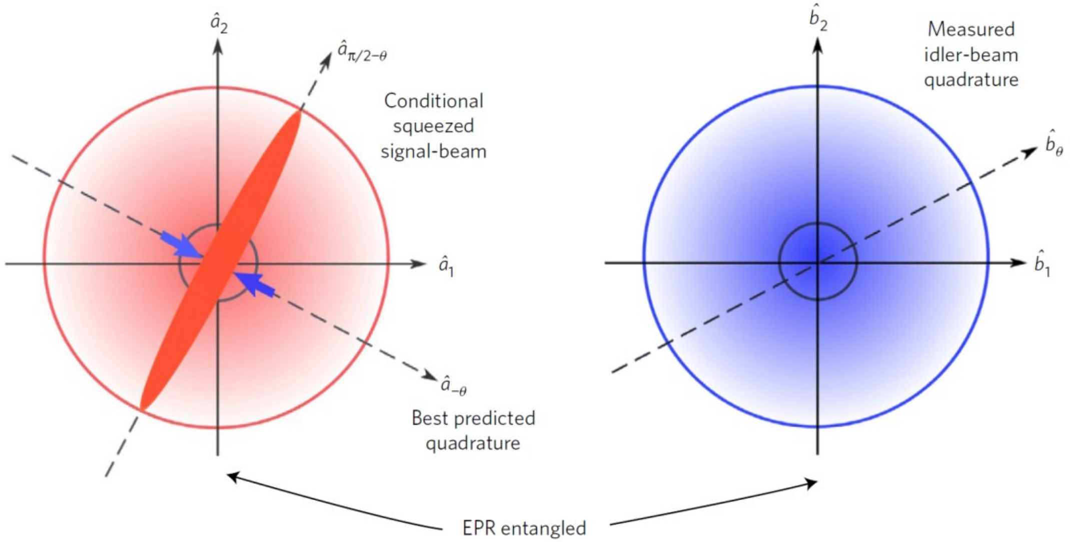
What is entanglement?

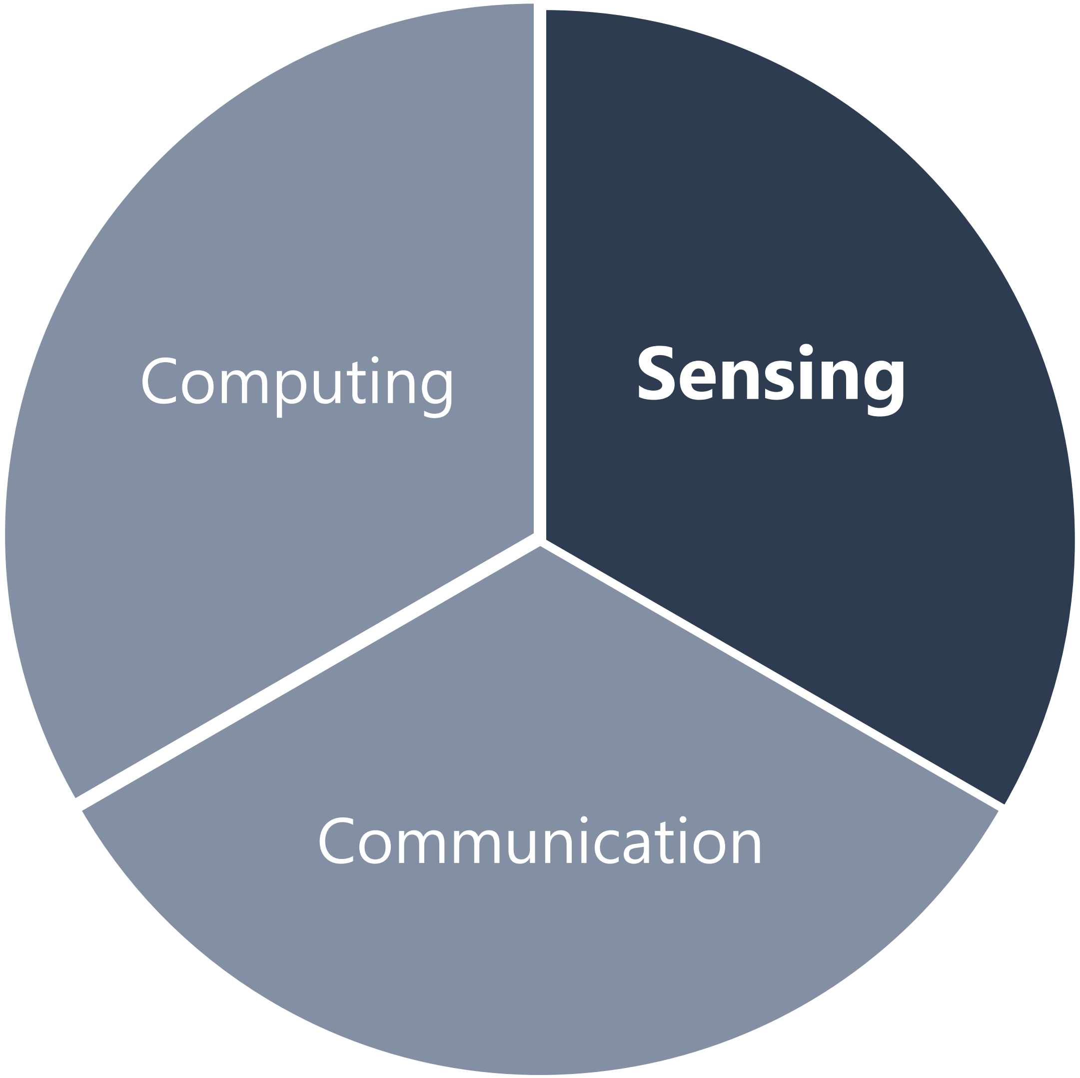
Two systems which cannot be separately described by pure states.

They are linked by a correlation which cannot be classically explained.





Multiple applications

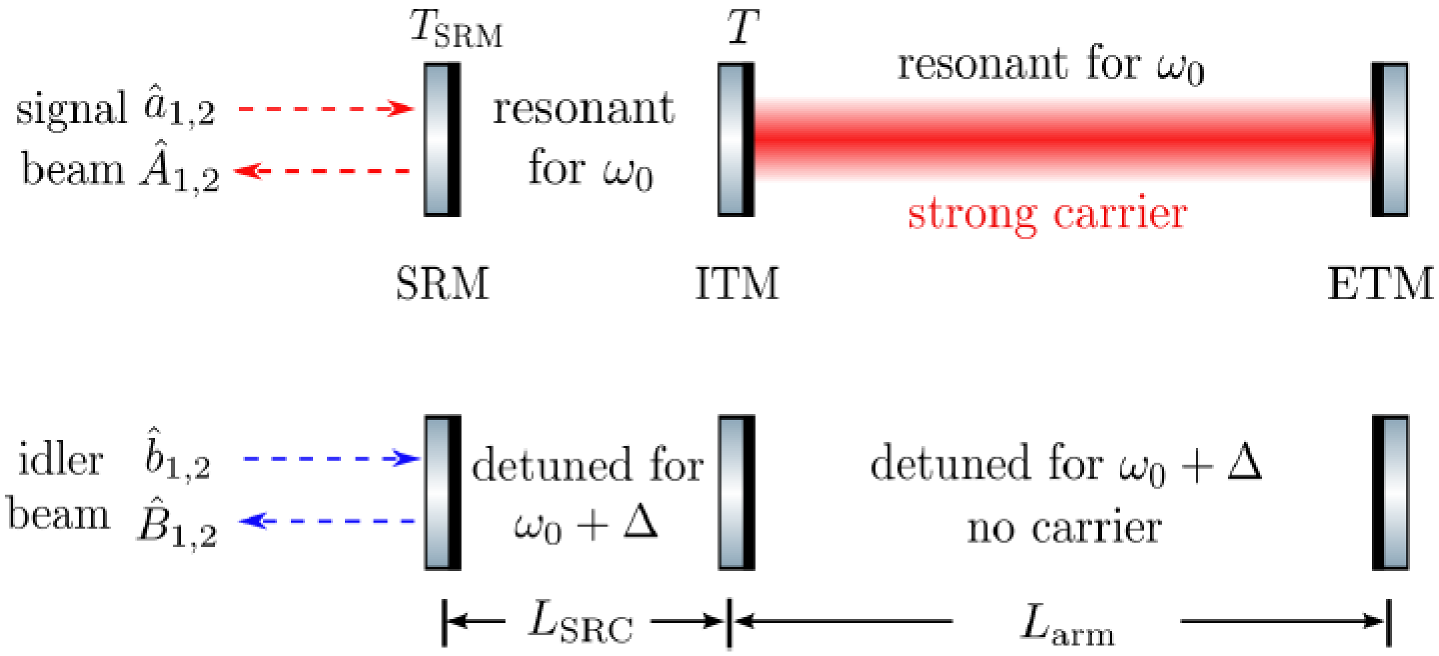


Entanglement for Quantum Sensing

"*Indirect*" manipulation of the probe state.

Resonant with the ITF

Signal probes the sensor

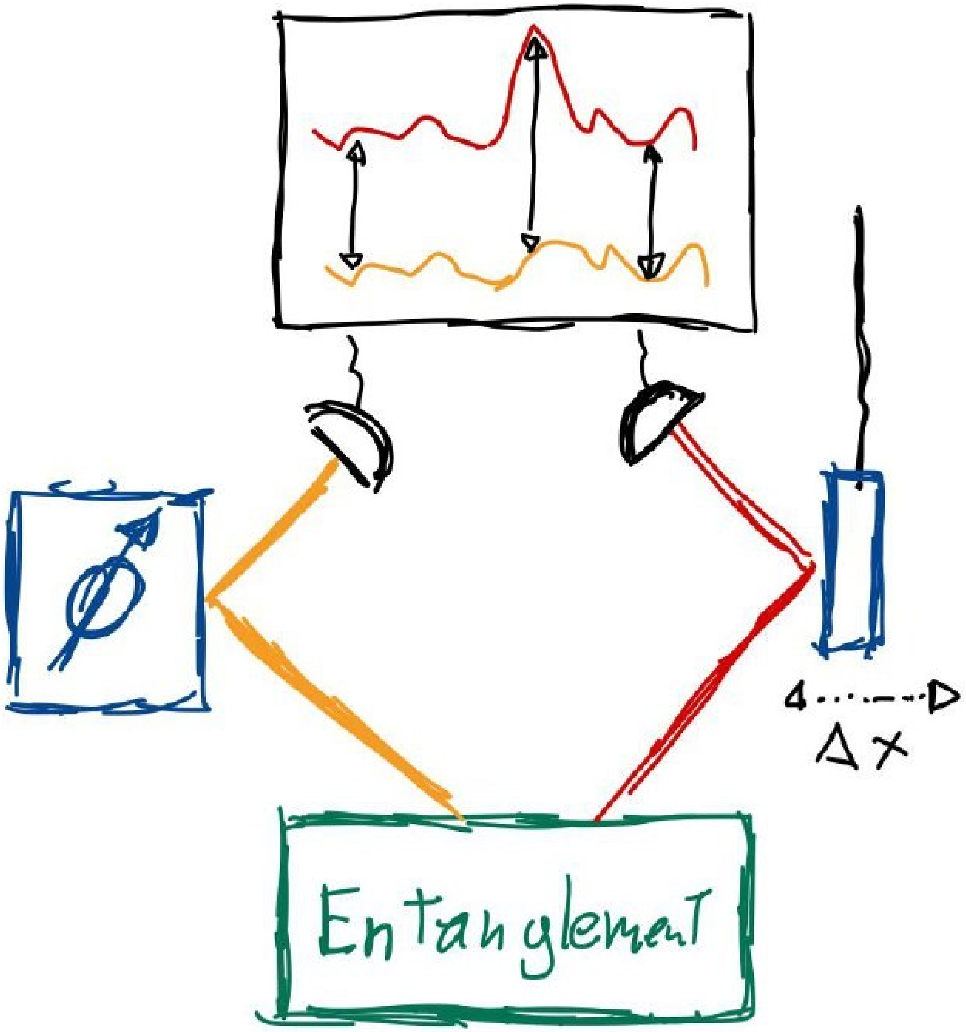


Idler is manipulate to generate Frequency Dependent Squeezing

Detuned from the ITF
See the SR as Filter Cavity

Ma, Y. et al. Proposal for gravitational-wave detection beyond the standard quantum limit through EPR entanglement. Nat. Phys. 13, 776–780 (2017).

Entanglement for Quantum Sensing



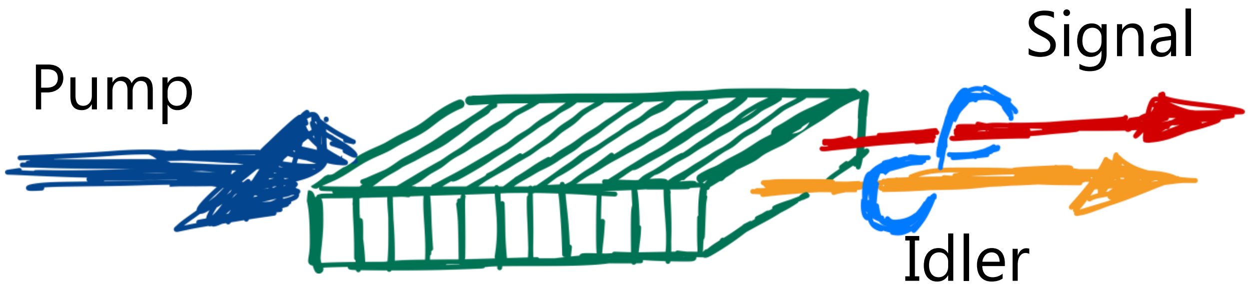
Measurements of two non-commuting variables by using an external reference frame with an effective negative mass.

Signal probes the sensor

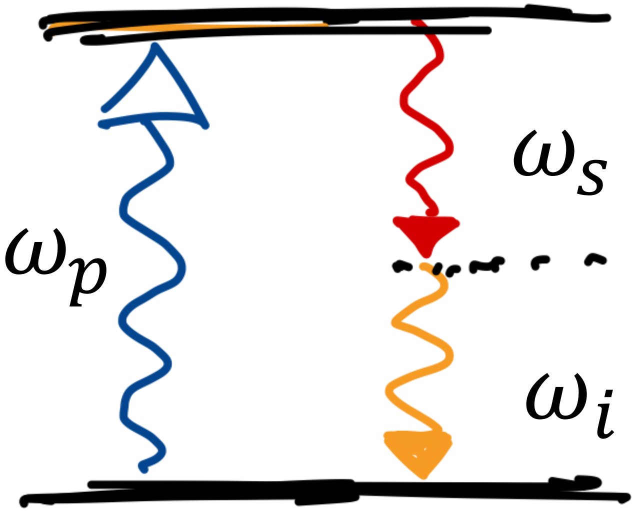
Idler probes the Reference Frame

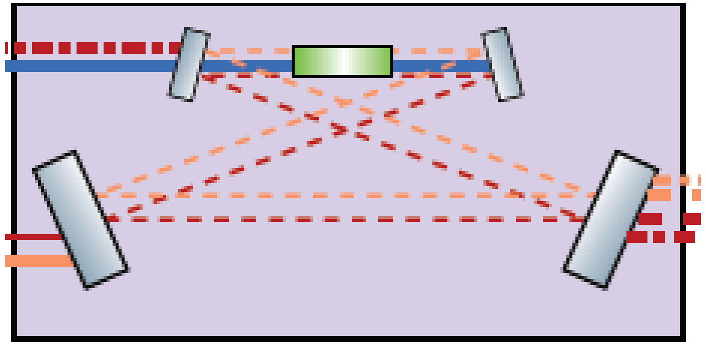
The relative position $\boldsymbol{X} - \boldsymbol{X_r}$ and the total momentum $\boldsymbol{P} + \boldsymbol{P_r}$ can be measured **at the same time with *arbitrary precision***.

How to generate entanglement?



$$\omega_p = \omega_s + \omega_i$$





Optical Resonator enhances the process, and select the frequencies ω_s and ω_i :

- ω_s matches the interferometer frequency
- ω_i is defined by the protocol

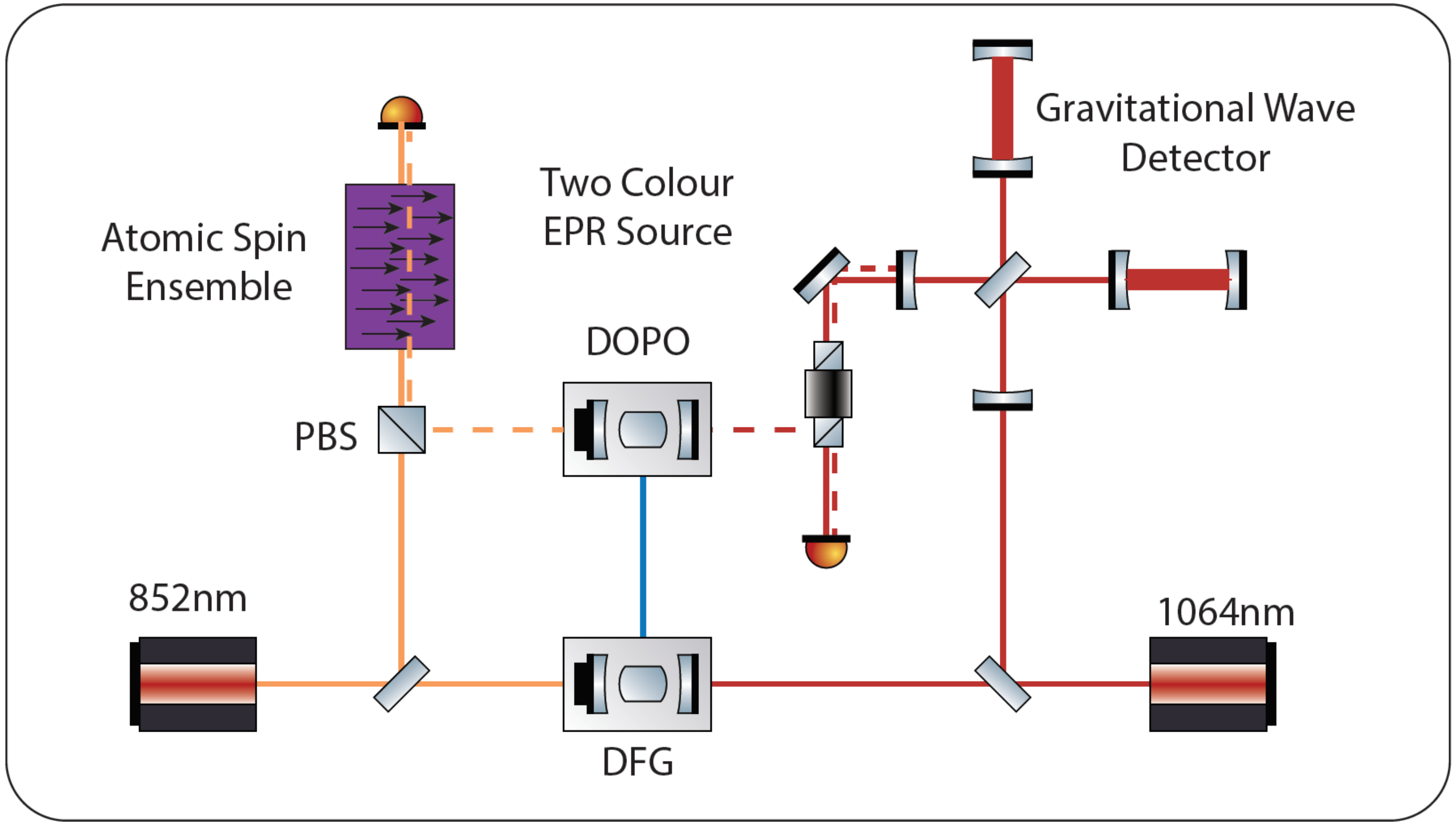
What do we need?

Coupling the ITF with the external Quantum Reference.

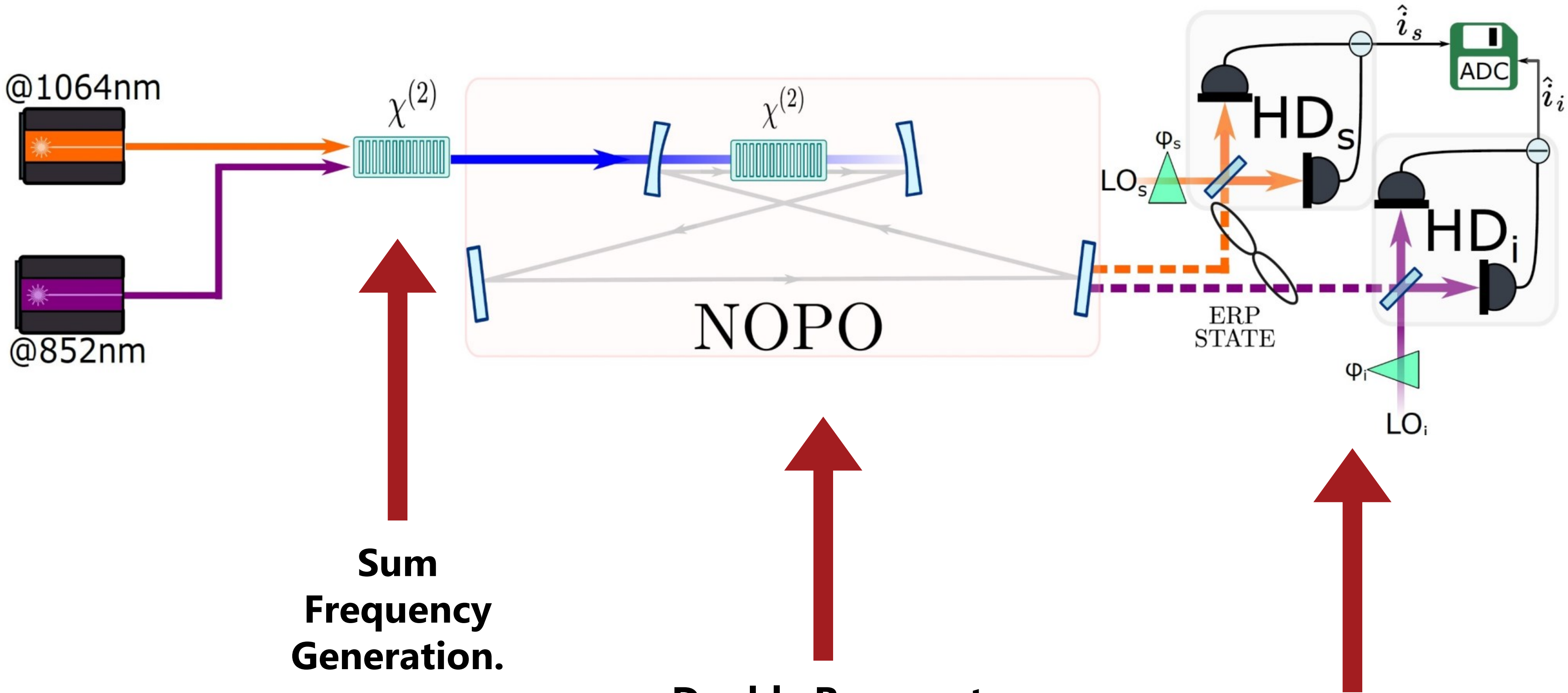
Two different Wavelength:

- Interferometer works at 1064nm
- External Quantum Reference works at 852nm

Two different Colour



How to generate entanglement between two wavelenght?

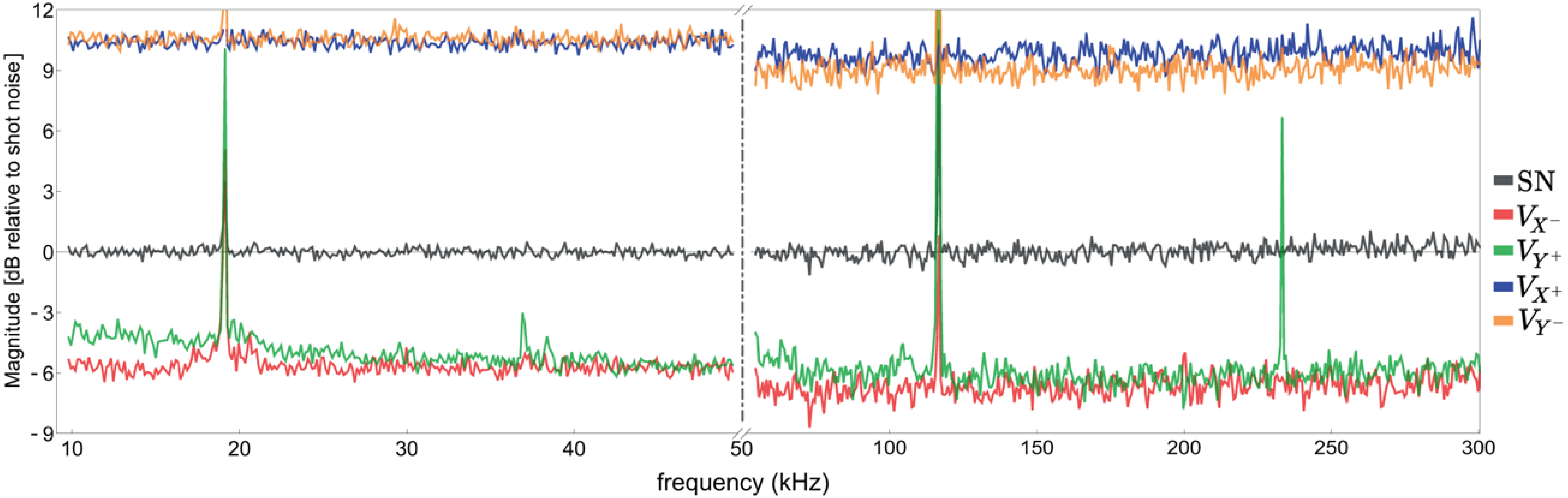


Sum Frequency Generation.

Double Resonant Optical Cavity

Two Homodyne Detectors

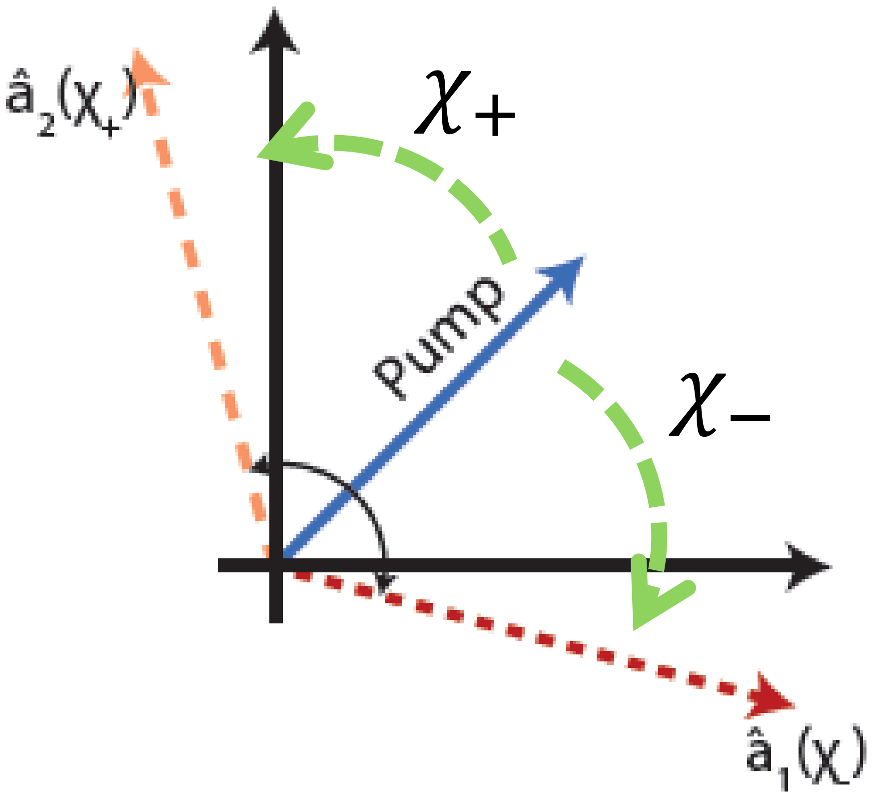
Entanglement witness by Quantum Noise Reduction



EPR Variables

$$\boldsymbol{V}_{\boldsymbol{X}^{\mp}} = X_s \mp X_i \qquad \boldsymbol{V}_{\boldsymbol{P}^{\pm}} = P_s \pm P_i$$

Requirement on the detection phase



Generic Quadrature

$$q(\chi) = X\cos\chi + P\sin\chi$$

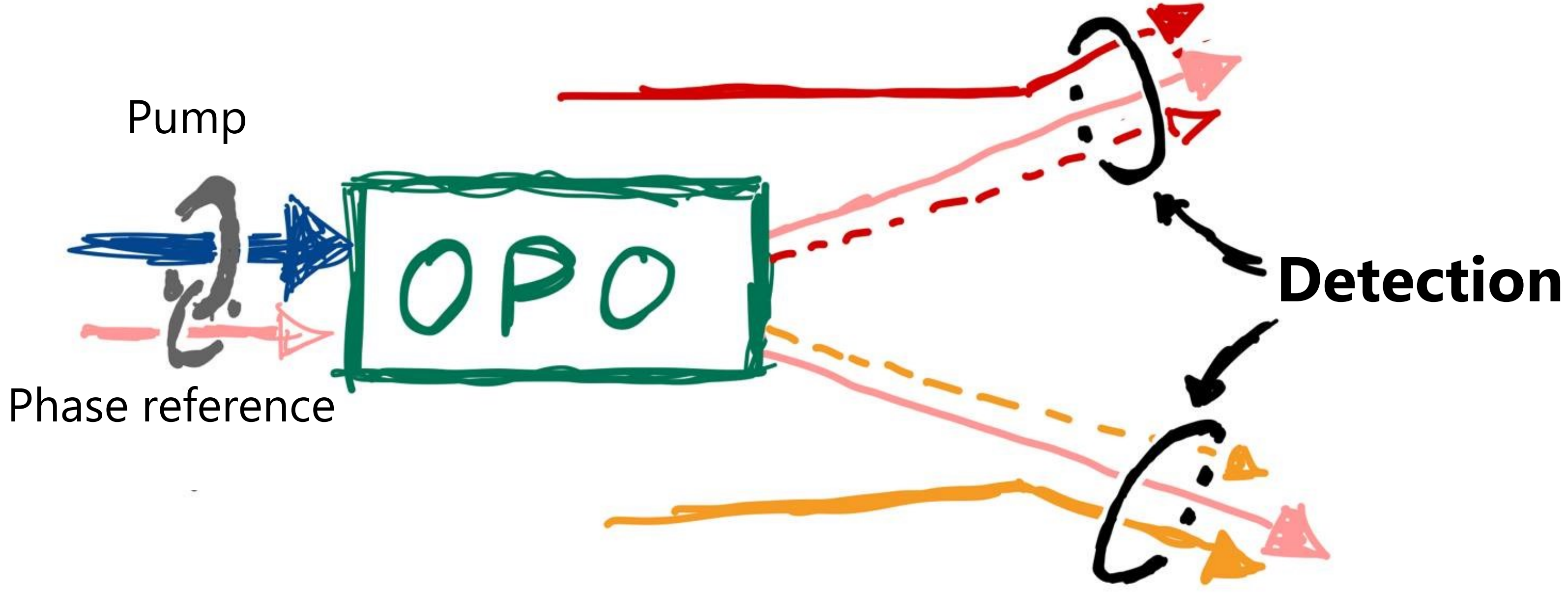
χ detection phase respect to the pump phase $\varphi_{pump}/2$

Quantum Noise reduction is obtained when **measuring symmetrically respect the pump phase $\varphi_{pump}/2$**

$$\chi_+ = -\chi_-$$
$$Q(\chi) = q_s(\chi) - q_s(-\chi)$$

Schori, C., Sørensen, J. & Polzik, E. Narrow-band frequency tunable light source of continuous quadrature entanglement. Phys.Rev.A 66, 033802 (2002).

Coherent Control Phase lock



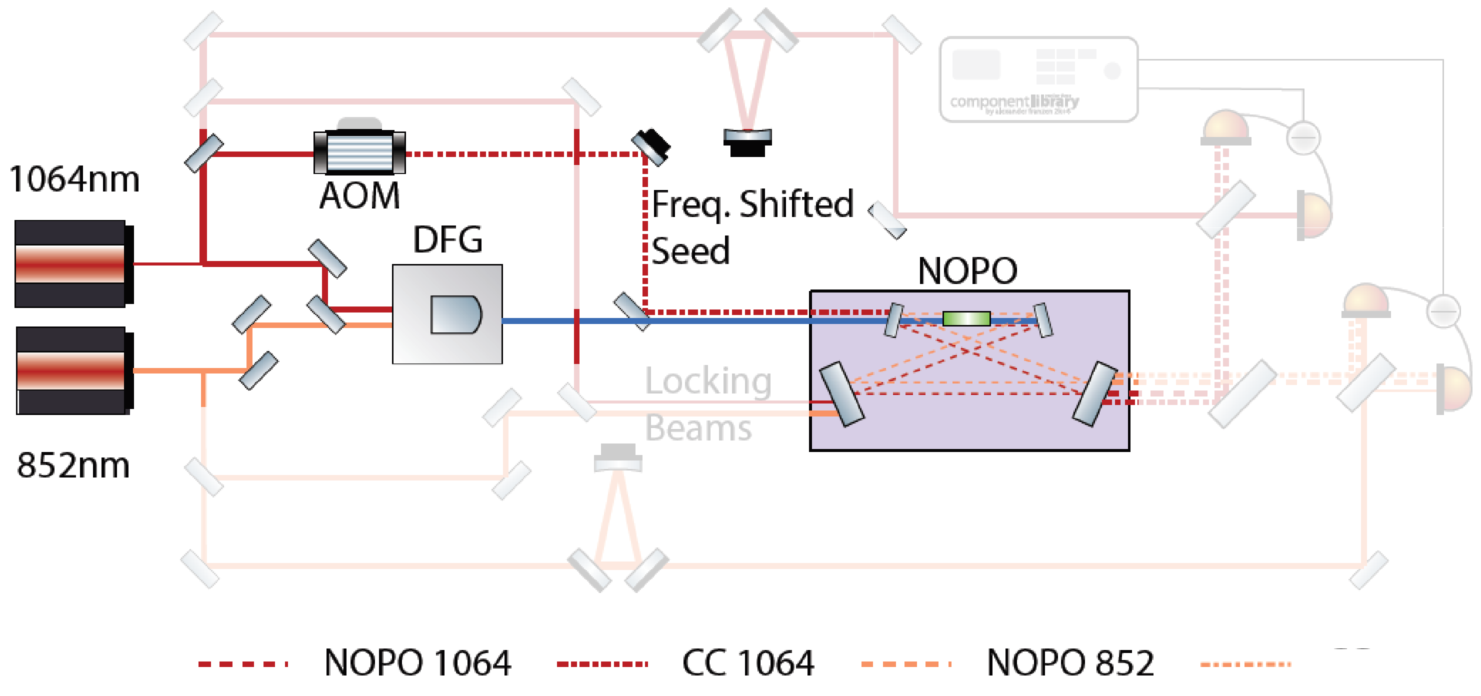
Create a
phase reference

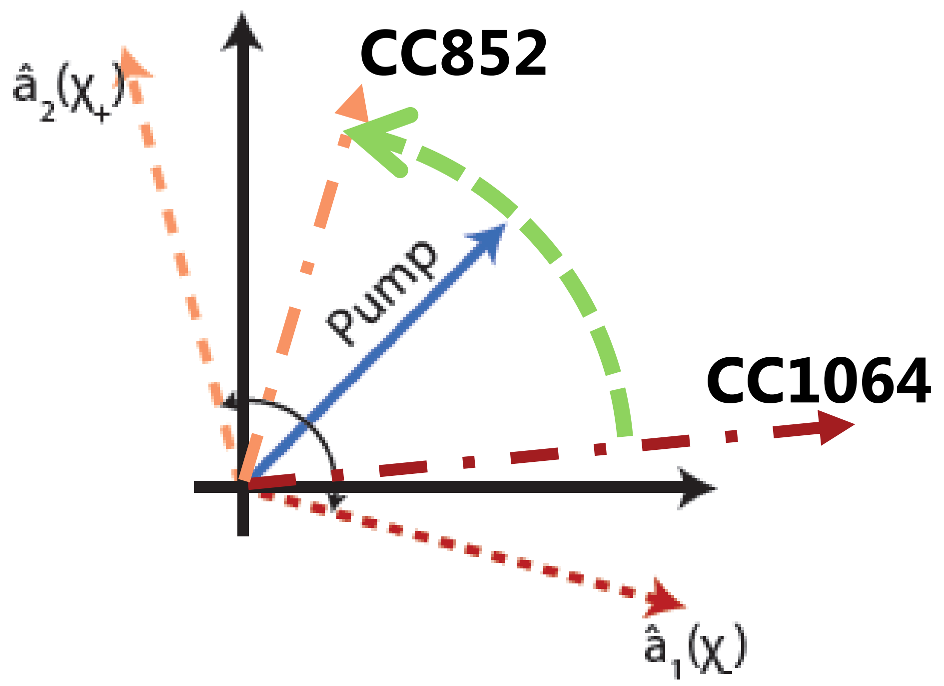
Lock
the phase reference
to **the pump**

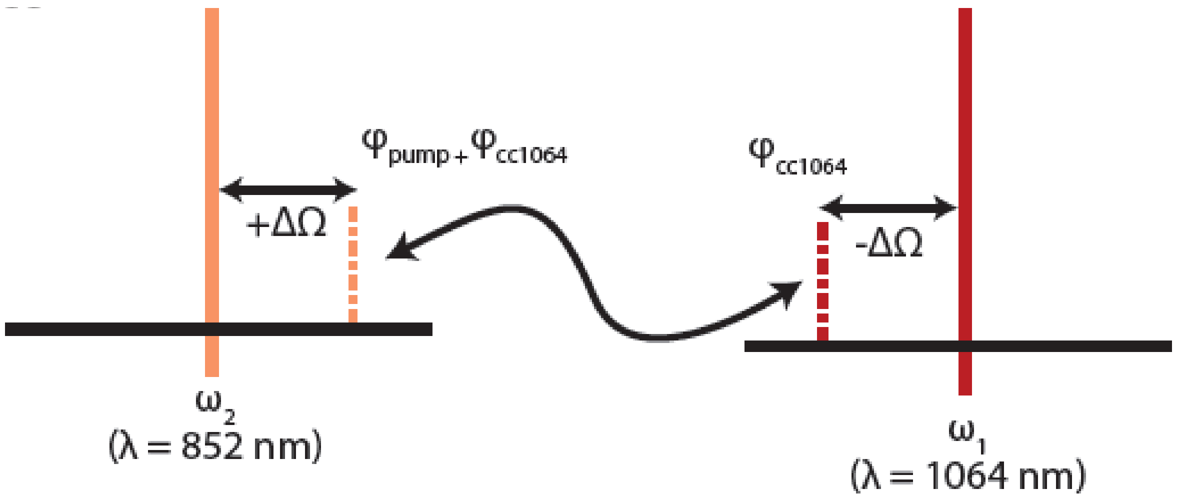
Use
the phase reference
to set the **detection phase**

Coherent Control of Vacuum Squeezing in the Gravitational-Wave Detection Band H. Vahlbruch et al., Phys. Rev. Lett. **97**, 011101 (2006)
Yap, M.J., Altin, P., McRae, T.G. et al. Generation and control of frequency-dependent squeezing via Einstein–Podolsky–Rosen entanglement. Nat. Photonics 14, 223–226 (2020).

New Locking Scheme

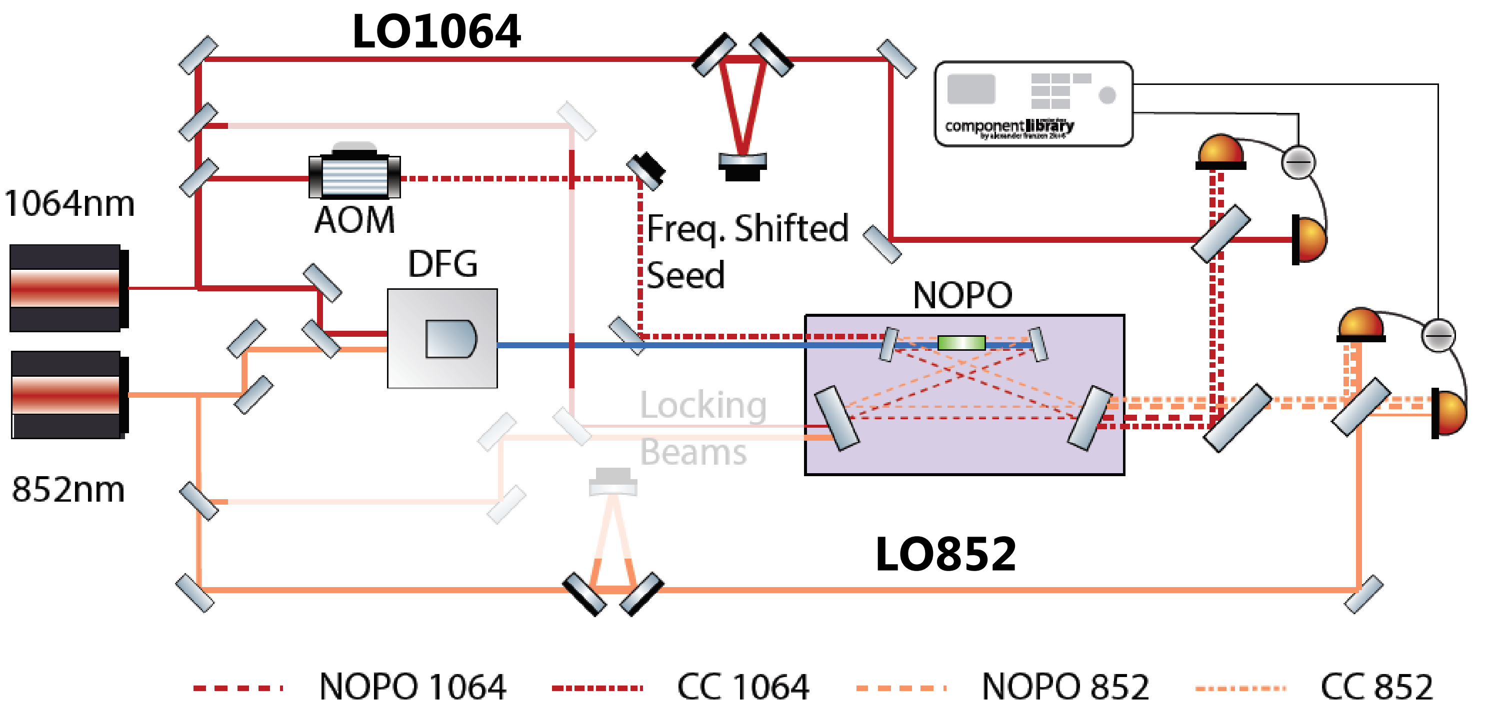






- **CC Seed** at 1064 is Frequency Shifted at ~2MHz
- **CC852** is generated by Difference Frequency Generation

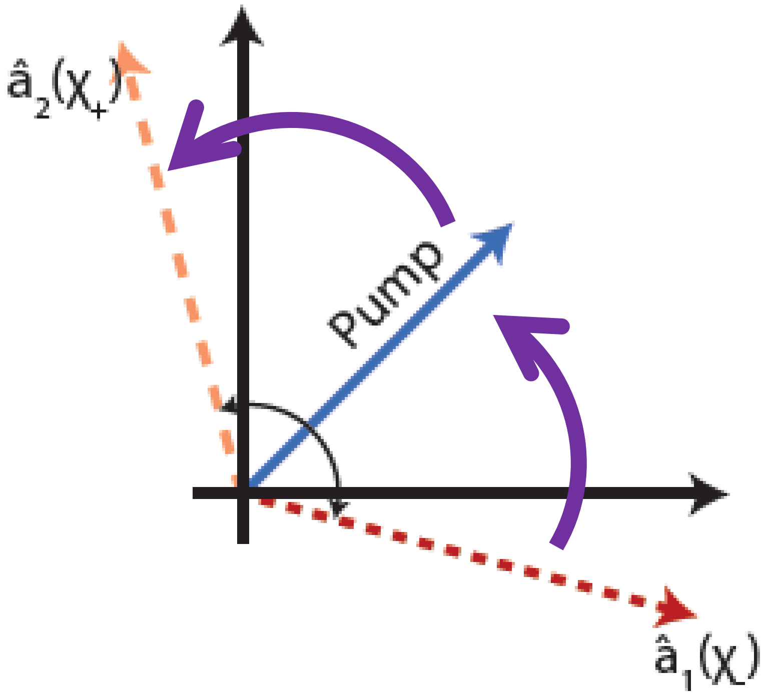
New Locking Scheme



LO1064 is free running

CC Seed is phase locked to the **LO1064**

LO852 is locked to **CC852**



Error Signals
Beat note between CC beams and Local Oscillator

Phase Noise Calibration.

Calibration of the CC signals

The calibration of the CC signal is based on the following model. When we scan the phase we have a signal that is:

$$V(\phi) = \frac{V_{pp}}{2}\sin(\phi)$$

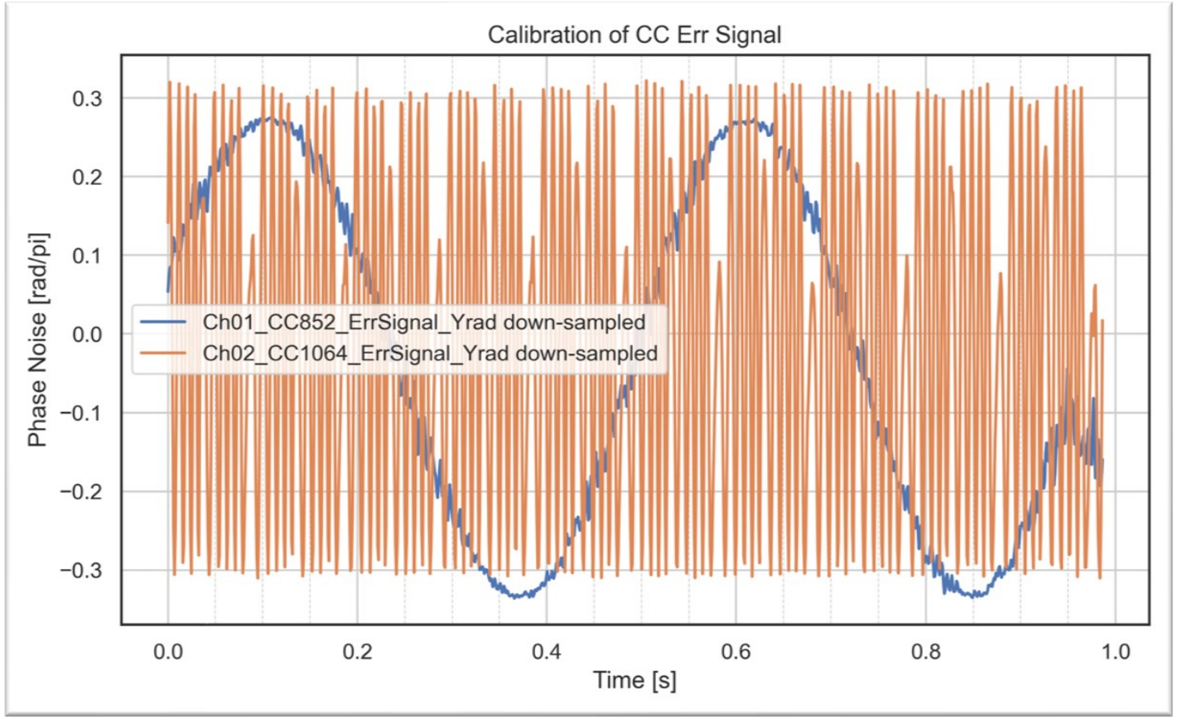
The phase in function of the voltage signal is given by:

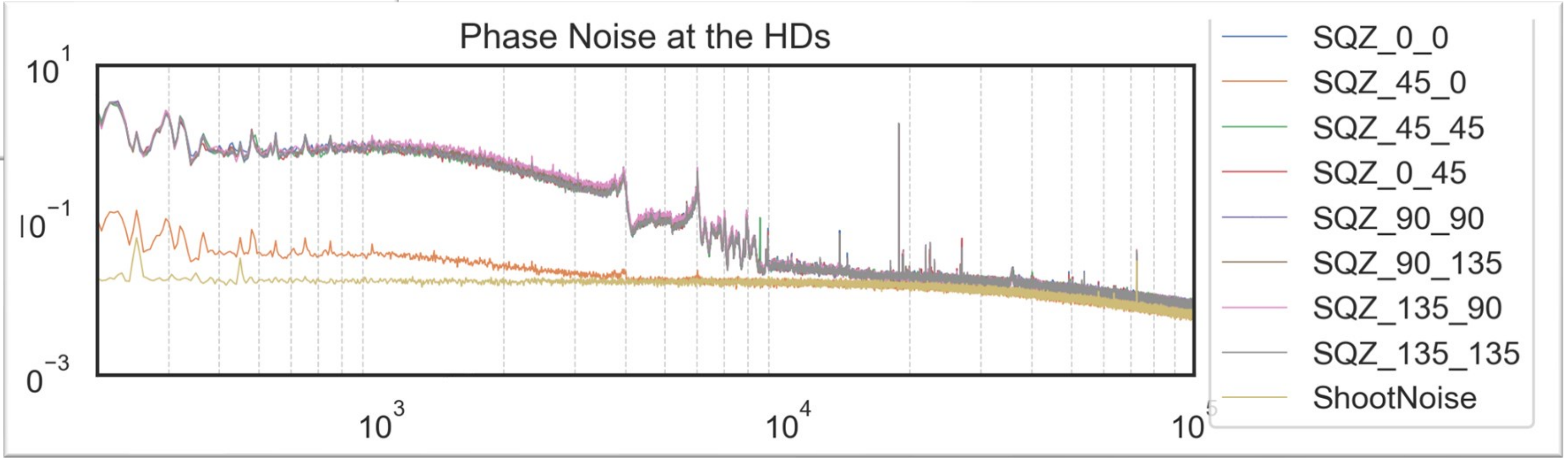
$$\phi = \arcsin\left(\frac{2V(\phi)}{V_{pp}}\right).$$

By linearizing this equation in $V(\phi) \approx 0$, we obtain

$$\phi(V) = \left.\frac{d\phi(V)}{dV}\right|_{V=0} = \frac{2}{V_{pp}} V(\phi),$$

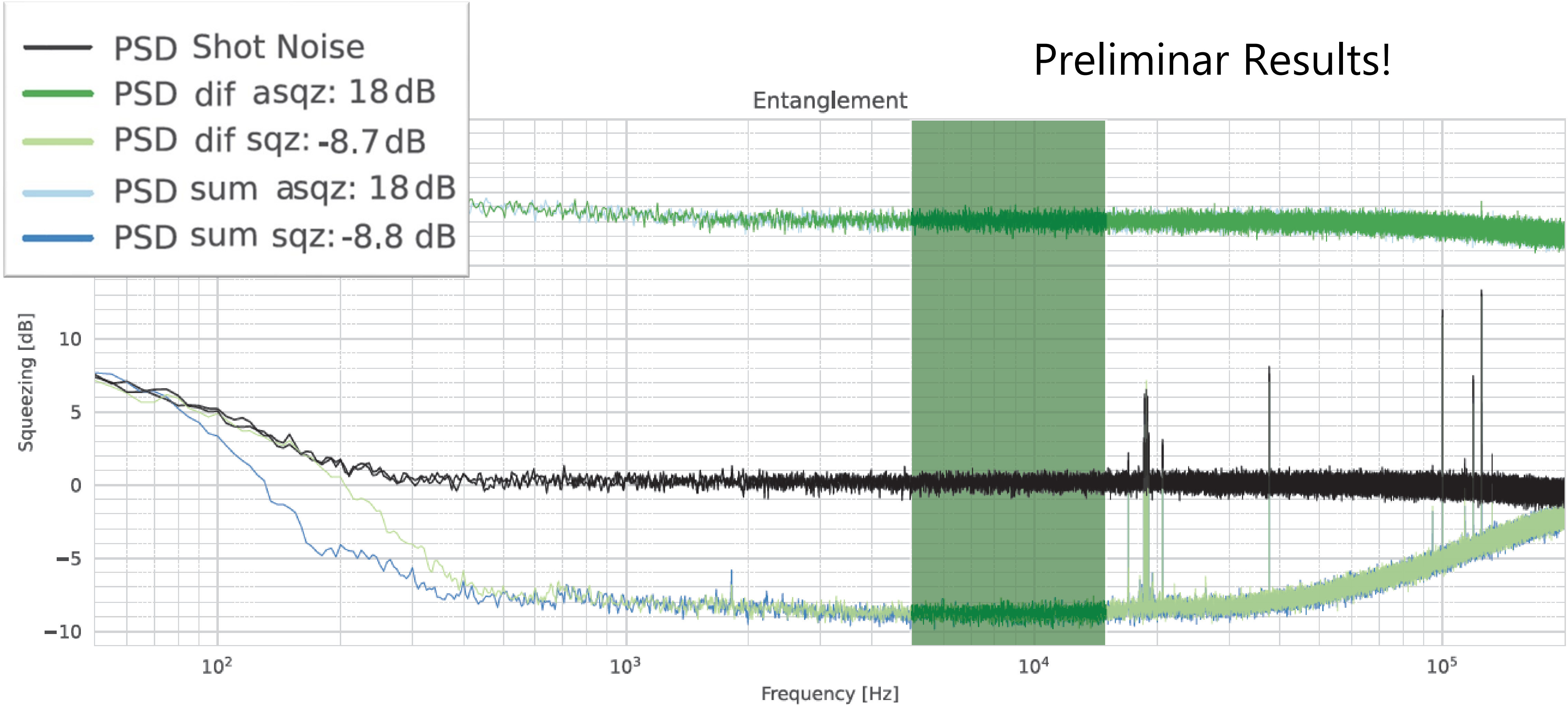
so the calibration factor is $\alpha = \frac{2}{V_{pp}}$



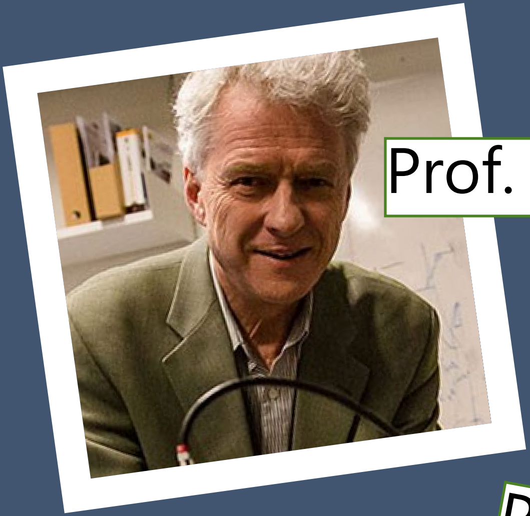


Sub Kilohertz Two Colour EPR entanglement

Preliminar Results!

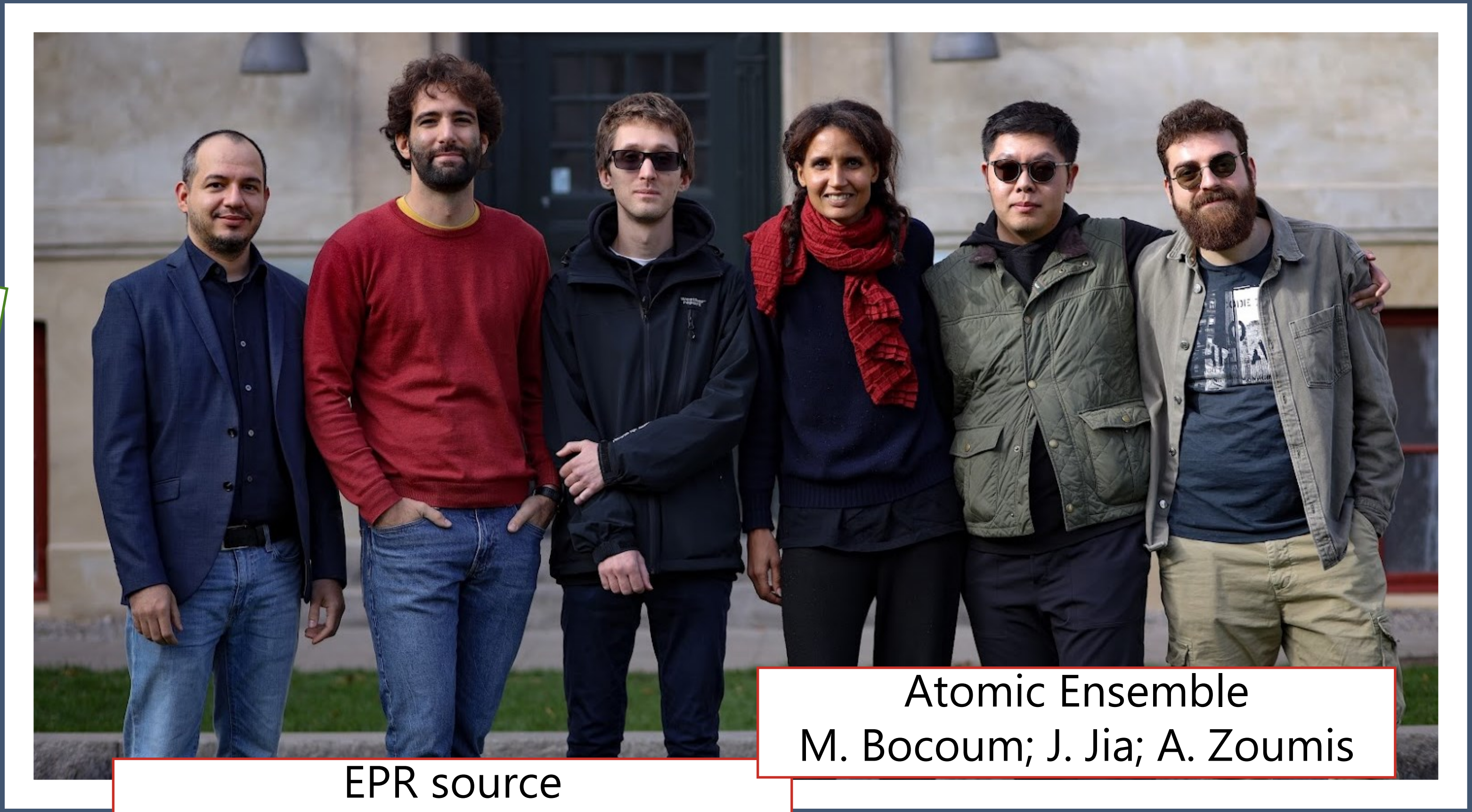


THANK YOU!



Prof. Polzik

Prof. Zeuthen



Atomic Ensemble
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EPR source
T.B. Brasil; A. Grimaldi; V. Novikov;

European Commission