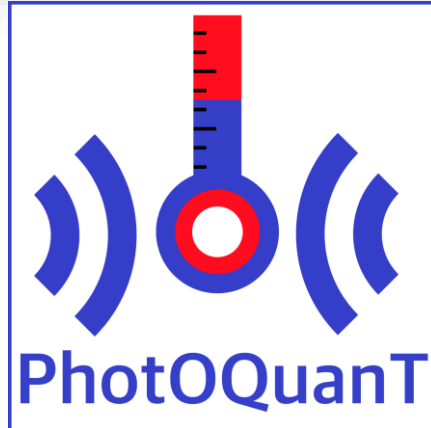


Towards practical integrated primary thermometry with photonic and quantum sensors in Europe



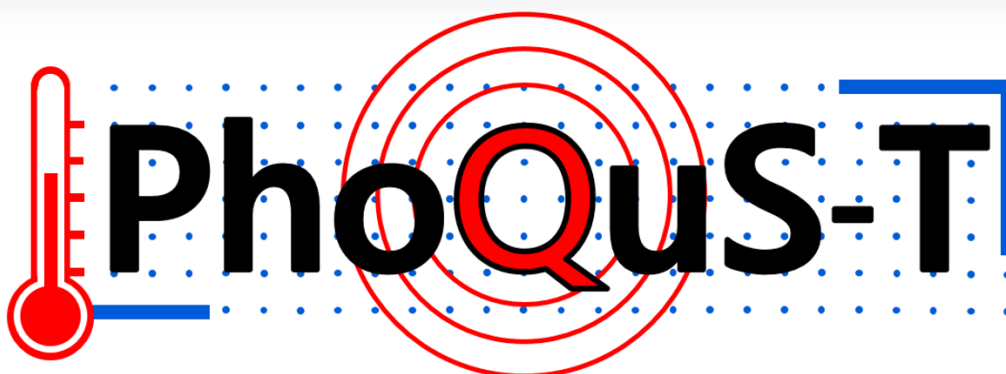
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JRP 17FUN05 PhotOQuant project : 2018 - 2021

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JRP 23FUN01 PhoQuS-T project : 2024 - 2027

Introduction

The kelvin redefinition has prompted new approaches to temperature traceability, focusing on practical primary thermometry that offers reliable, on-demand temperature measurements without the need for recalibration. In **PhotOQuant** and **PhoQuS-T** projects we explore innovative photonic and quantum-based methods, which promise significant advancements in thermometry by providing self-calibrating sensors.

Motivation

Metrology:

need for a practical primary thermometer with a wide range (4 K to 500 K) for the realisation and dissemination of the thermodynamic temperature according to the *mise-en-pratique* for the definition of the kelvin.

- **Practical Quantum Standard**
- **Replacement of SPRTs** (Standard Platinum Resistance Thermometer)

Industry:

need for integrated, in-situ, self-calibrated, wide-range temperature sensors

- **Applications:**
 - Photonics
 - Semiconductors
 - Quantum
 - Cryogenics
 - Aerospace
 - Hydrogen energy

Overall objective

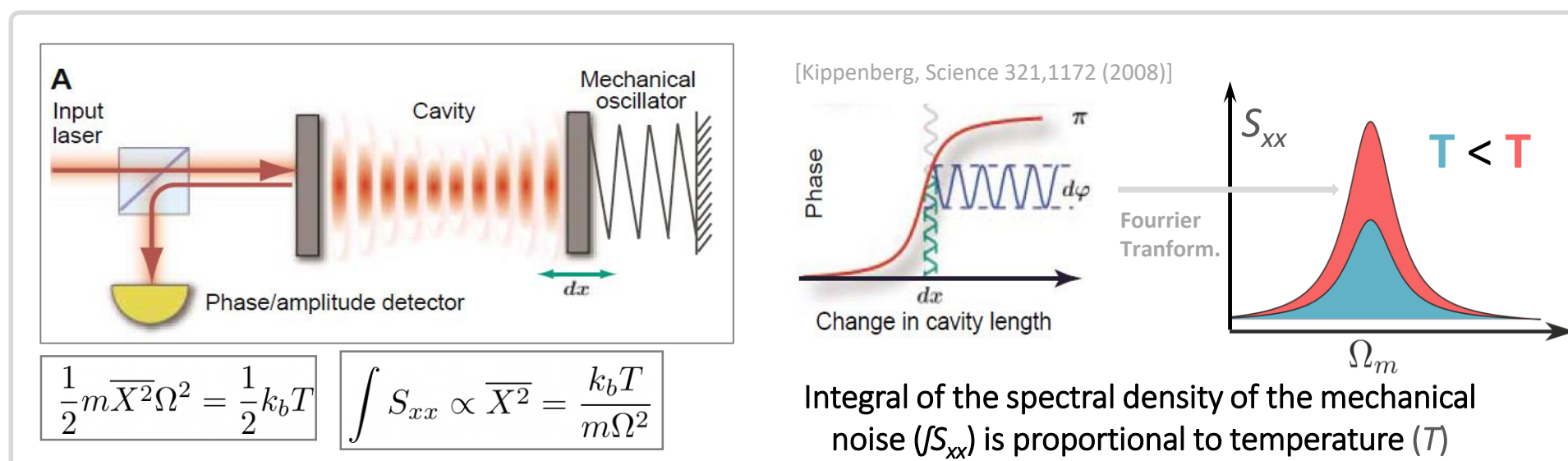
Our ambition is to change paradigm of temperature traceability with a novel small-scale embedded in-situ primary temperature standard. **Our goal** is to develop integrated photonic and optomechanical quantum-based practical primary thermometry from 4 K to 500 K, validated and traceable to best temperature standards.

Integrated photonic and quantum temperature sensors

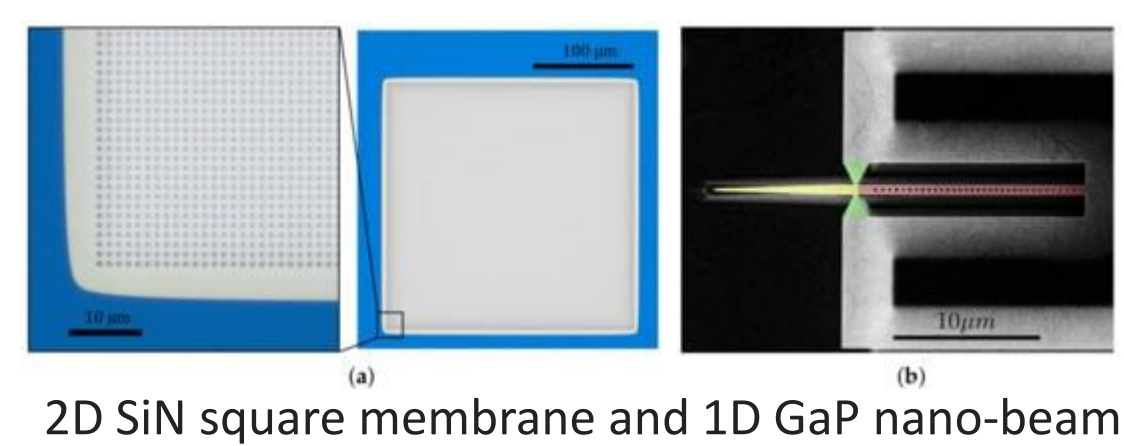
Broad T range: from cryogenics to 500 K
High accuracy: 0.05 K uncertainty
In situ: chipset technology
No drift: primary sensor
Insensitive to EM field: photonic technology

Optomechanics: primary thermometry

Optical measurement of the mechanical displacement of nano-mechanical resonator due to the Brownian motion.

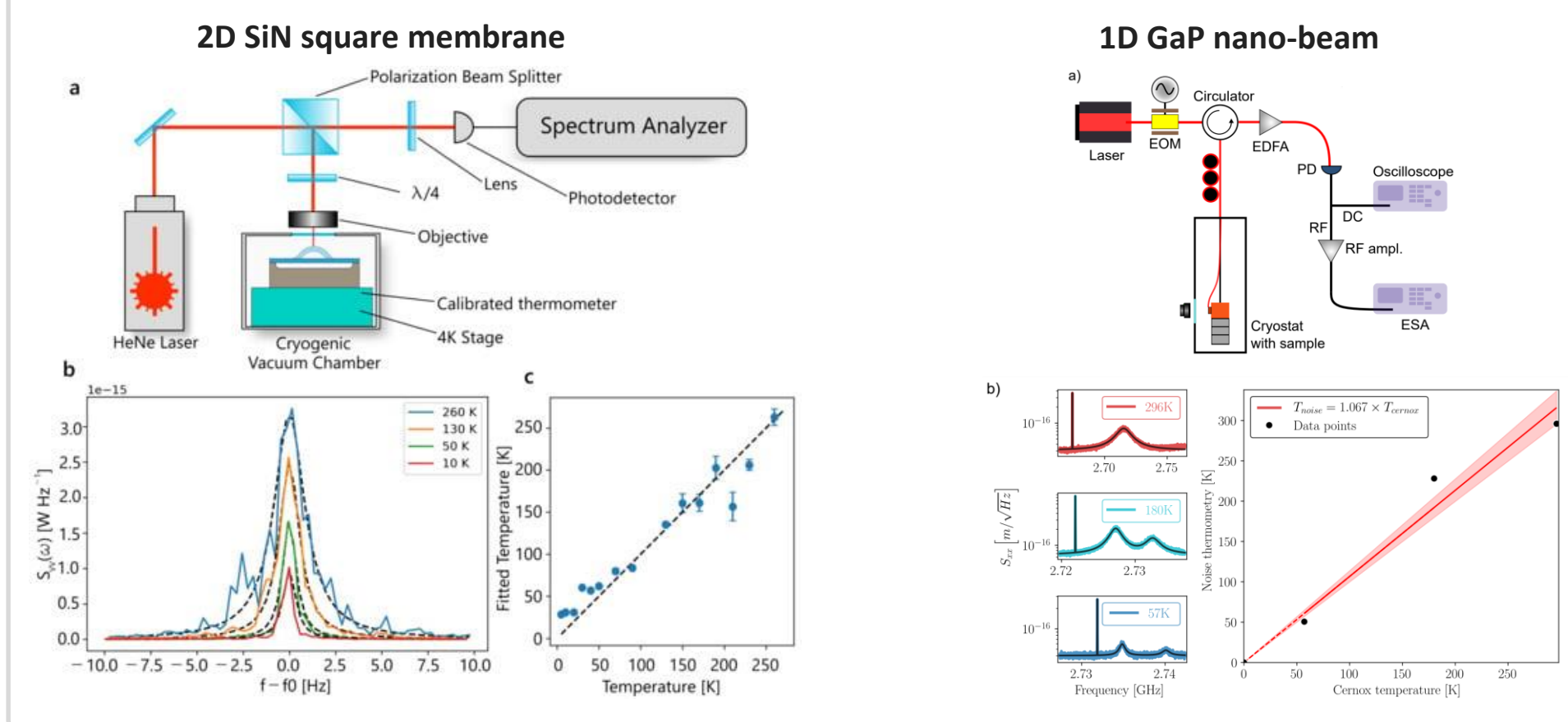


Optomechanical resonator [1]



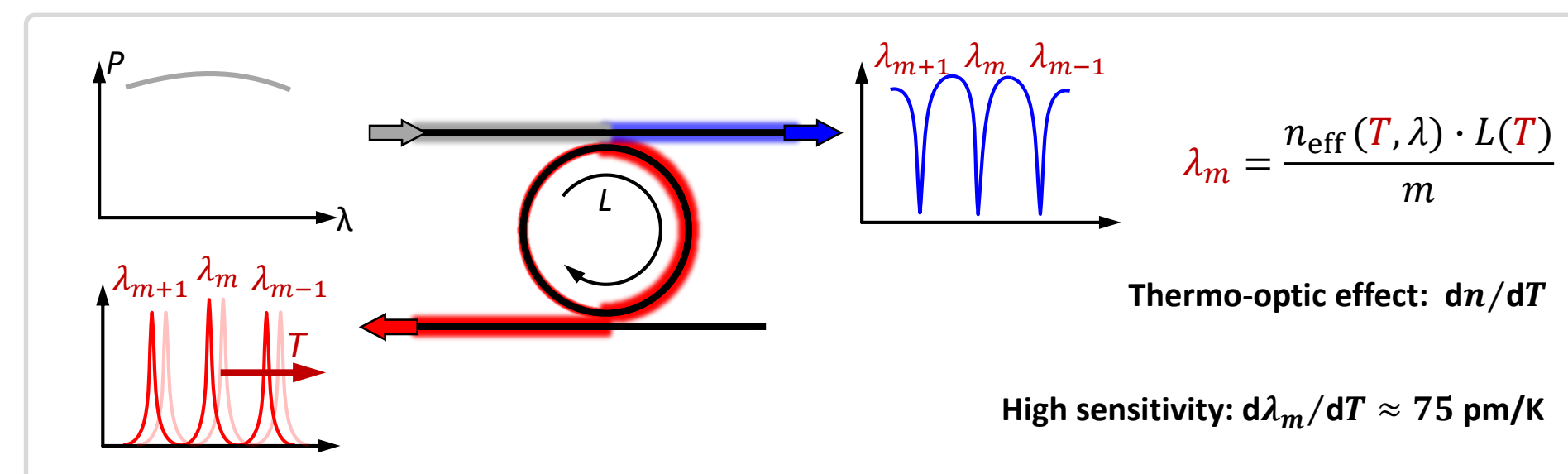
2D SiN square membrane and 1D GaP nano-beam.

Optomechanical thermometry [1]



Photonics: High-resolution thermometry

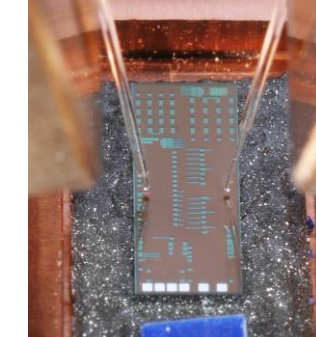
Measurement of the wavelength shift of the optical resonance due to the thermo-optical effect.



High Q factor Photonic Ring Resonator [1]

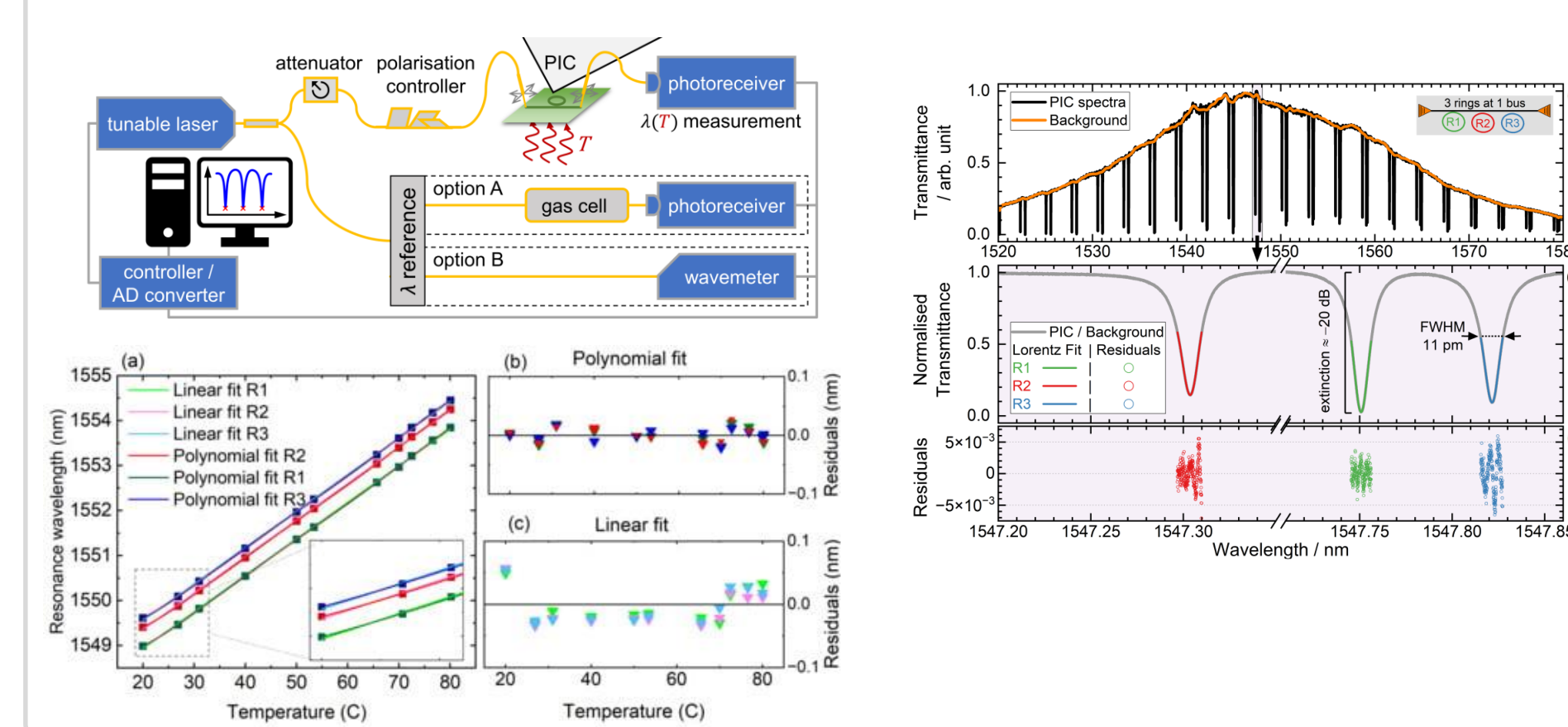


Photonic integrated circuit (PIC) with ring-resonators



Input/output fibers on top of the PIC

Photonic thermometry [1]

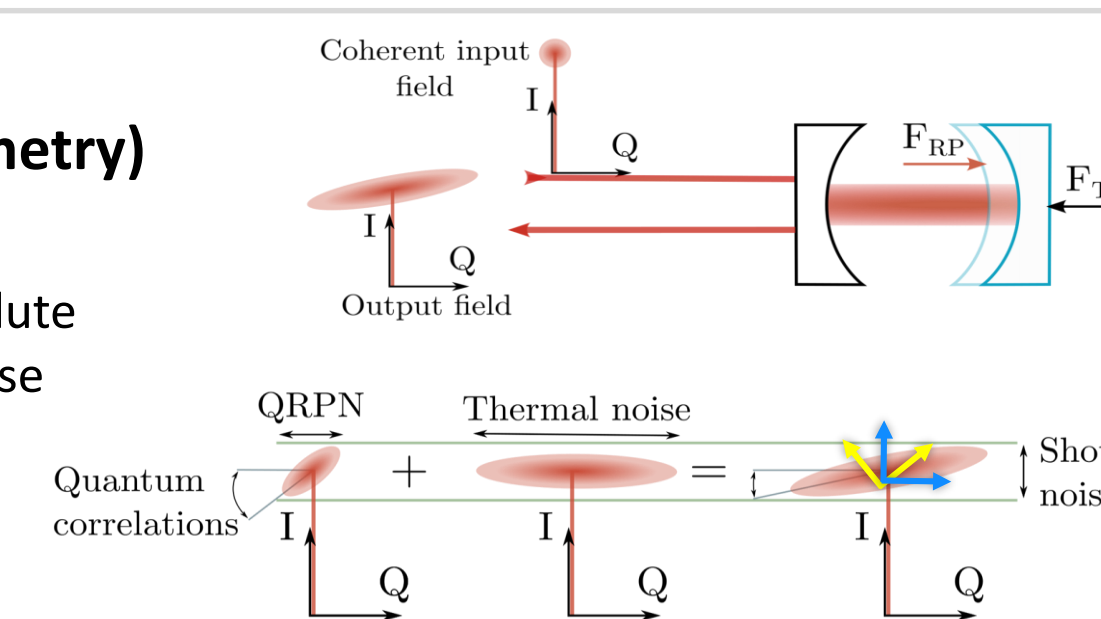


Next steps : Combined wide-operational-range self-calibrated temperature sensor

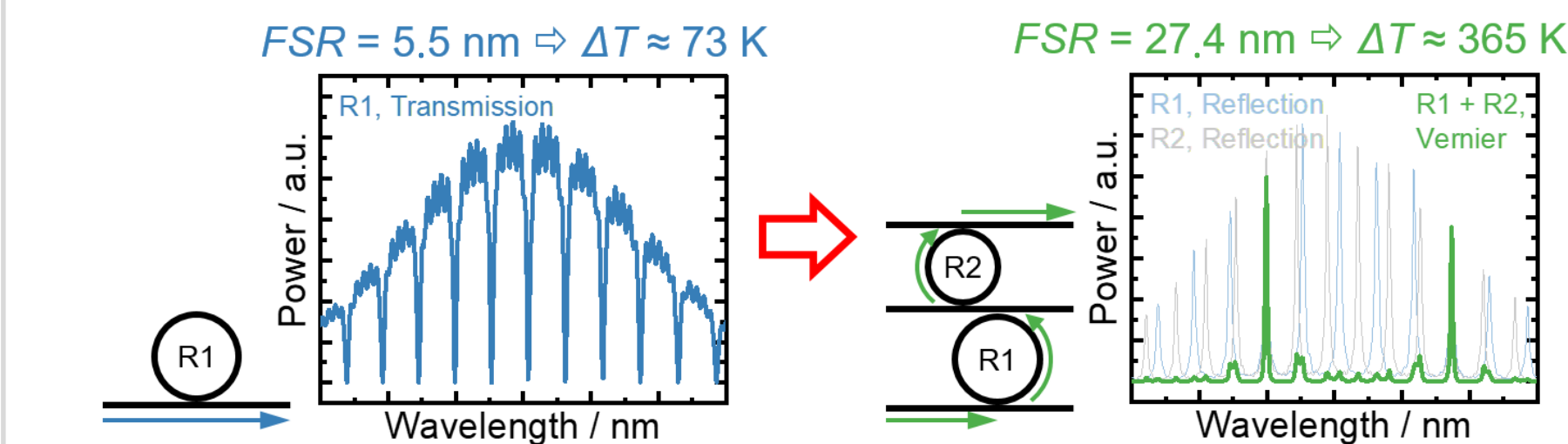
Quantum reference (absolute primary thermometry)

Quantum correlations (radiation pressure noise QRPN) as an absolute scale to calibrate the thermal noise

$$\frac{\text{Thermal correlations}}{\text{Quantum correlations}} \propto \frac{k_B T}{\hbar \Omega_m}$$

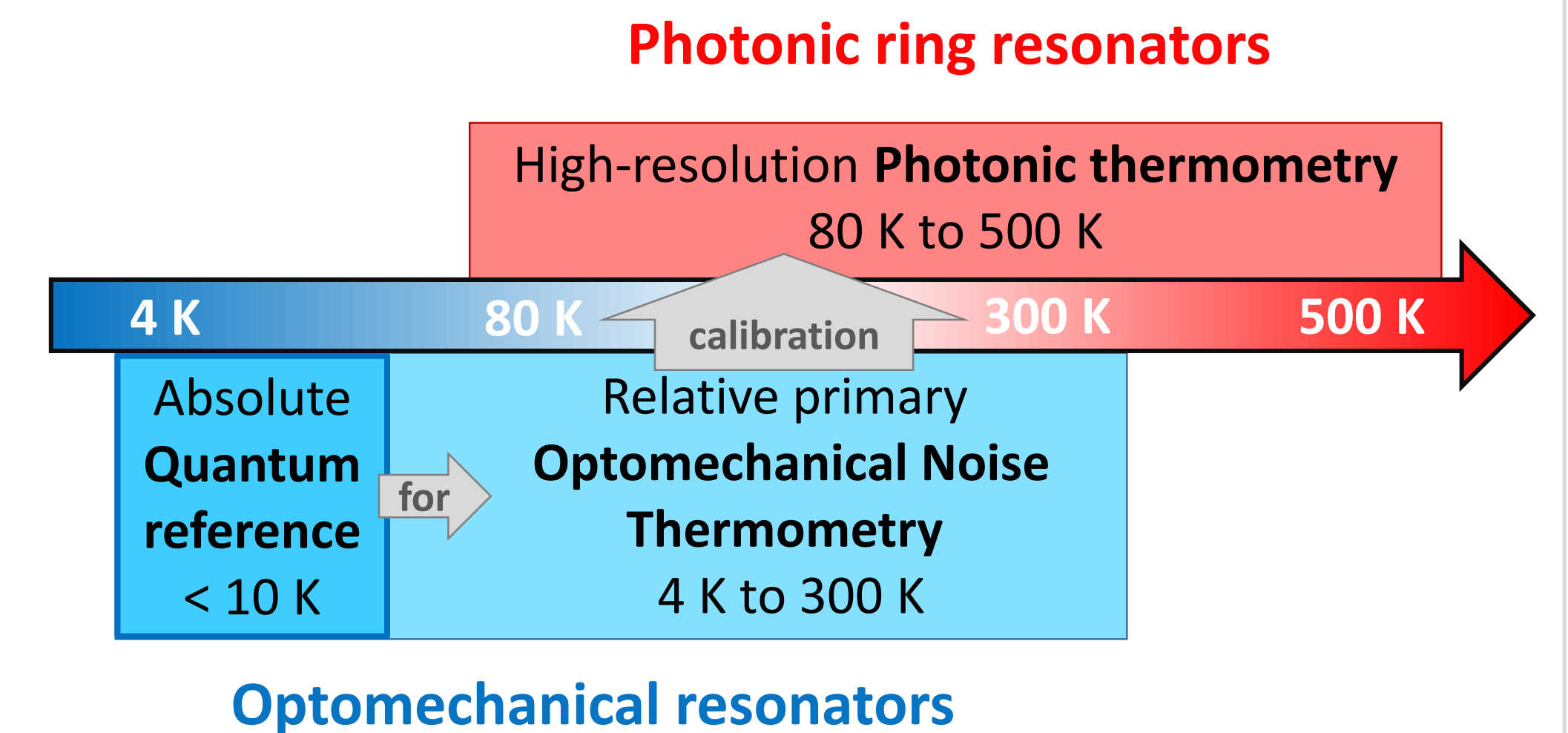


Enhanced temperature range with high resolution (up to 500 K)



We aim to combine optomechanical and photonics ring resonators in a co-packaged sensor which will be self-calibrated and will operate in the large temperature range. Quantum thermometry will provide a quantum reference for the optical noise thermometry operating in the 4 - 300 K range, while sub mK resolution and wide operational range to 500 K provided through photonic thermometry.

Based on the achievements of the **PhotOQuant** project, the **PhoQuS-T** project will develop integrated optical practical primary thermometry from 4 K to 500 K to enable in-situ traceability in further practical applications. This will be reached through a combination of different technical approaches. With the optomechanical sensors the optical noise thermometry will be developed from 4 K to 300 K and the quantum thermometry will be tested below 10 K in order to provide a quantum reference for the optical noise thermometry. The operating temperature range will be extended from 80 K to 500 K with high-resolution photonic sensors based on passive and novel active photonic integrated circuits of micro- and nano-resonators. For further practical applications, the integrated packaging for optomechanical and photonic sensors need to be developed as well as robust fibre to chip coupling over the temperature range from 4 K to 500 K. Finally, the developed sensors will be metrologically validated and their quantum applications will be demonstrated.



✓ "PhotOQuant" progress [1]

❑ Current state of the art [2]

➤ Future "PhoQuS-T" evolution

1) Optomechanical noise thermometry (4 K to 300 K) and quantum thermometry (< 10 K)

- ✓ High Q factor optomechanical resonators (SiN, GaP) fabricated and tested
- ✓ Noise thermometry protocols developed and tested

- ❑ Self-heating is the main systematic effect
- ❑ Noise thermometry is a relative technique
- ❑ Only one demonstration of quantum correlation thermometry by NIST in 2017

- **Absolute quantum thermometry** below 10 K
- **Combined relative & absolute thermometry** (optics/photonics & optomechanics)
- **Reduced self-heating** with new design
- **Array of sensors** for wide T range operation

2) Advanced photonic thermometry (80 K to 500 K)

- ✓ Si ring resonators (RR) fabricated ($Q \approx 10^5$) and tested around room temperature
- ✓ High sensitivity: 75 pm/K, resolution: 10 mK
- ✓ Theoretical study: SiN high potential for RR (transparent in visible range, no two-photon absorption (TPA))

- ❑ Restricted operational range (150 K) due to the free spectral range of single RR
- ❑ Self-heating due to two photon absorption in Si
- ❑ Active photonic thermometry (combining laser + RR on a chip) explored theoretically

- **Broad operational range** from 80 K to 500 K with advanced design (e.g. coupled RR)
- **Reduced self-heating** for RR
 - Thick SOI platform for Si for high $Q \approx 10^7$, low propagation losses (≈ 0.1 dB/cm)
 - New material SiN (no TPA, VIS and IR)
- **Active photonic thermometer** demonstrated (towards fully integrated chip-based devices)

3) Robust fibre-to-chip coupling packaging solutions (4 K to 500 K)

- ✓ Free-space coupled devices with active alignment systems were developed.

- ❑ Low-loss robust fibre-to-chip coupling is needed for further practical applications.
- ❑ Fibre-to-chip coupling solutions exist, but are not tested over temperature range from 4 K to 500 K.

- **Low-loss robust fibre-to-chip coupling** for practical applications from 4 K to 500 K (gluing, welding or mechanical support)
- **Co-packaged solution** for optomechanical and photonic sensors

4) Metrological validation and applications

- ✓ Optomechanical noise thermometry demonstrated over 4 K to 300 K range
- ✓ Photonics thermometry demonstrated from 300 K to 360 K ($u_{\text{stdv}} = 10$ mK)

- ❑ Optomechanics: NIST (2017) demonstration for quantum correlations thermometry ($u = 1$ K at 40 K, $u = 30$ K at 300 K)
- ❑ Photonics: NIST (2018) demonstration with $u = 175$ mK and recent study at NRC (2023) with $u = 10$ mK (296 K to 353 K)
- ❑ No practical application demonstrated

- **Metrological validation**
 - Quantum thermometry (< 10 K): $u_{\text{target}} 10 \%$
 - Noise thermometry (4 K ... 300 K): $u_{\text{target}} 0.1$ K
 - Photonics (80 K ... 500 K): $u_{\text{target}} 5$ mK at 300 K
- **Self-calibration** demonstration
- **SPRT replacement** possibility test
- **Practical applications** demonstration (ion trap and pressure standard)

[1] Briant T. et al., *Optics* 3, 159 (2022)

[2] Purdy T. et al., *Science* 356, 1265 (2017); Klimov N. et al., *Sens Actuators A Phys.* 269, 308 (2018); Dedyulin, S. et al., *Measurement* 221, 113453 (2023)