

1. SUMMARY

Quantum sensing is one of the most promising applications of quantum technologies, offering sensitivities that surpass classical limits. Among the most urgent applications are **high-precision gas sensors** for carbon dioxide (CO_2) and methane (CH_4), which are central to climate monitoring, industrial safety, and environmental regulation. Detecting small concentration changes with high accuracy is essential, yet current (classical) optical sensors are constrained by noise and sensitivity limits.

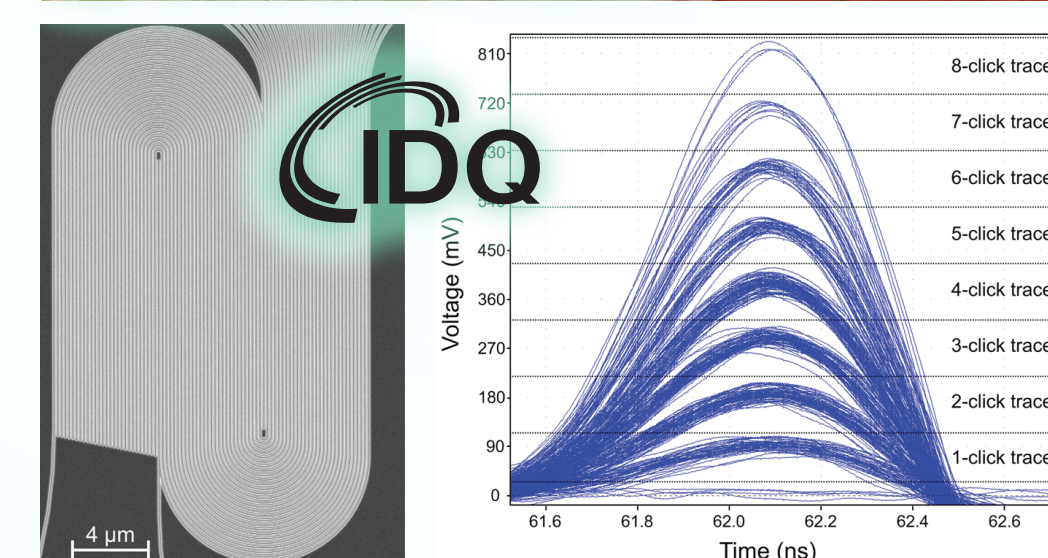
LINQSENS addresses this challenge by developing integrated **quantum photonic non-linear interferometers (NLIs)** [1] capable of phase measurements while remaining **robust to optical loss**—a major obstacle to practical quantum sensing. The approach exploits the non-linear gain of optical parametric amplification to generate and manipulate quantum correlations, enabling superior phase estimation. **Coherent seeding** [2] further amplifies the phase-dependent signal while preserving quantum correlations, improving tolerance to realistic loss and noise. **Photon-number-resolving (PNR) detection** [3] extracts enhanced statistical information from higher-order correlations, enabling phase sensing precision beating the **shot-noise limit (SNL)** even under imperfect conditions [4].

Thin-film lithium niobate (TFLN) [5] provides a compact, low-loss, and scalable platform for NLIs. **LINQSENS** will develop two prototype gas sensors—one for CO_2 and one for CH_4 —where refractive-index-induced phase shifts from gas absorption are measured using the NLI. These prototypes will validate the platform's suitability for practical real-world quantum sensing.

2. PROJECT AIMS

LINQSENS will deliver the following breakthroughs under the QuantERA Applied Quantum Science theme:

- **TFLN integrated quantum photonics devices:** Optimised components, including squeezers and fibre coupling.
- **Loss-tolerant NLIs on chip:** Designs of Integrated SU(1,1) interferometers with coherent seeding and parametric gain control via $\chi^{(2)}$ non-linear effects.
- **PNR readout for enhanced sensitivity:** Exploiting full photon-number correlations to enable practical, noise-resilient quantum sensing beyond the SNL. Measurements to be performed with IDQ's PNR superconducting nanowire single-photon detectors (PNR-SNSPDs)
- **Theoretical framework and analytical tools:** To extract phase information from the complete counting statistics in the presence of imperfections.



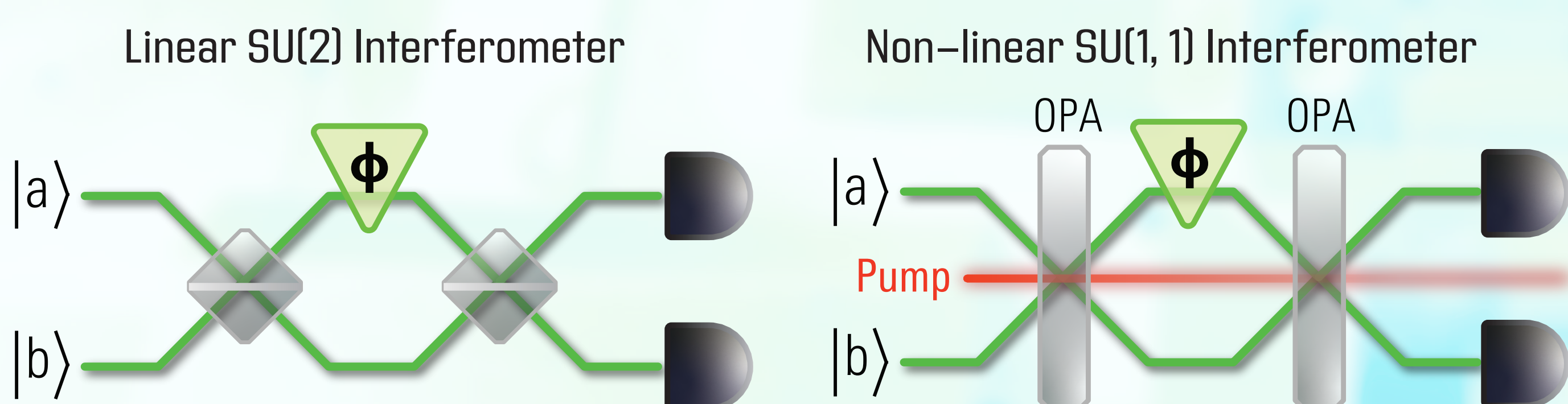
Collectively, these advances establish a robust scientific and technological framework for integrated quantum metrology, combining the empirical methodology and theoretical validation. Consequently, LINQSENS will realise a practical, loss-tolerant photonic architecture that serves as a cornerstone for deployable, quantum-enhanced sensing systems.

3. BACKGROUND

Quantum sensing aims to measure phases—e.g. those induced by refractive index changes due to gas absorption—with precision surpassing classical bounds with a **quantum advantage** in sensitivity.

Traditional optical sensors relying on classical light interfering in linear interferometers (e.g., Mach-Zehnder) are fundamentally constrained by the shot-noise limit (SNL), where $\Delta\phi \geq 1/\sqrt{N}$ and N is the mean photon number [6].

While quantum resources like squeezed states or NOON can theoretically reach the Heisenberg limit, $\Delta\phi \geq 1/N$.



In linear interferometers [7,8], **photon loss** degrades quantum correlations often resulting in only **conditional** sub-shot-noise performance. However, NLIs [1,4] replace beamsplitters with optical parametric amplifiers (OPAs) allowing the **amplification** of squeezed states while retaining enhanced phase sensitivity!

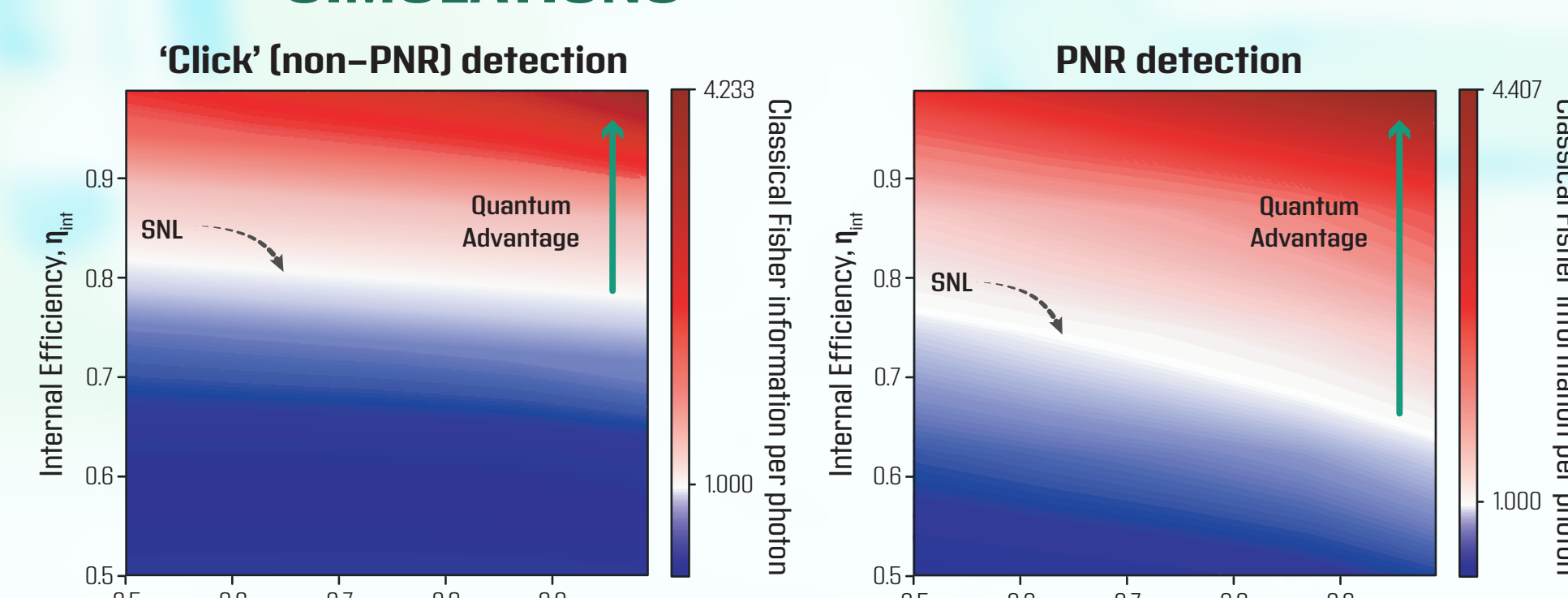
4. METHODOLOGY

Our approach is rooted in our expertise in quantum sensing (IC/ICFO/Ox), state-of-the-art TFLN integrated quantum photonics (ETH-Z) and PNR measurements (IC/IDQ/Ox). IC/Ox team recently performed a bulk-optics demonstration of **unconditional quantum sensing beyond the SNL enabled by PNR detection** [4]:

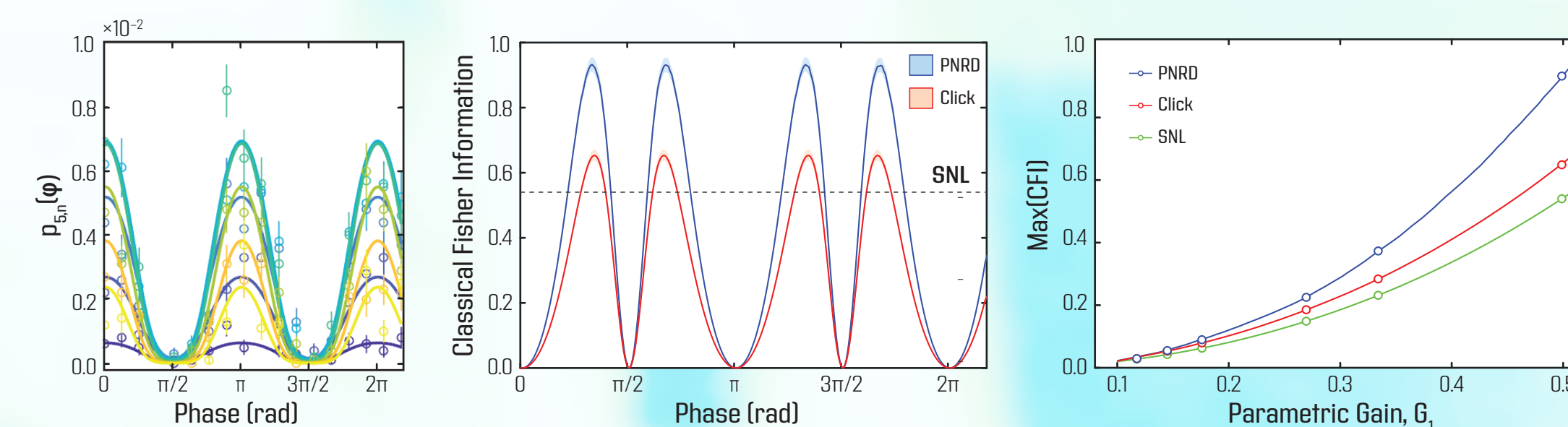
SIMULATIONS

CFI strongly depends on **internal photon loss** between OPAs.

Quantum advantage threshold is **higher** for 'click' detectors compared to PNR detectors.

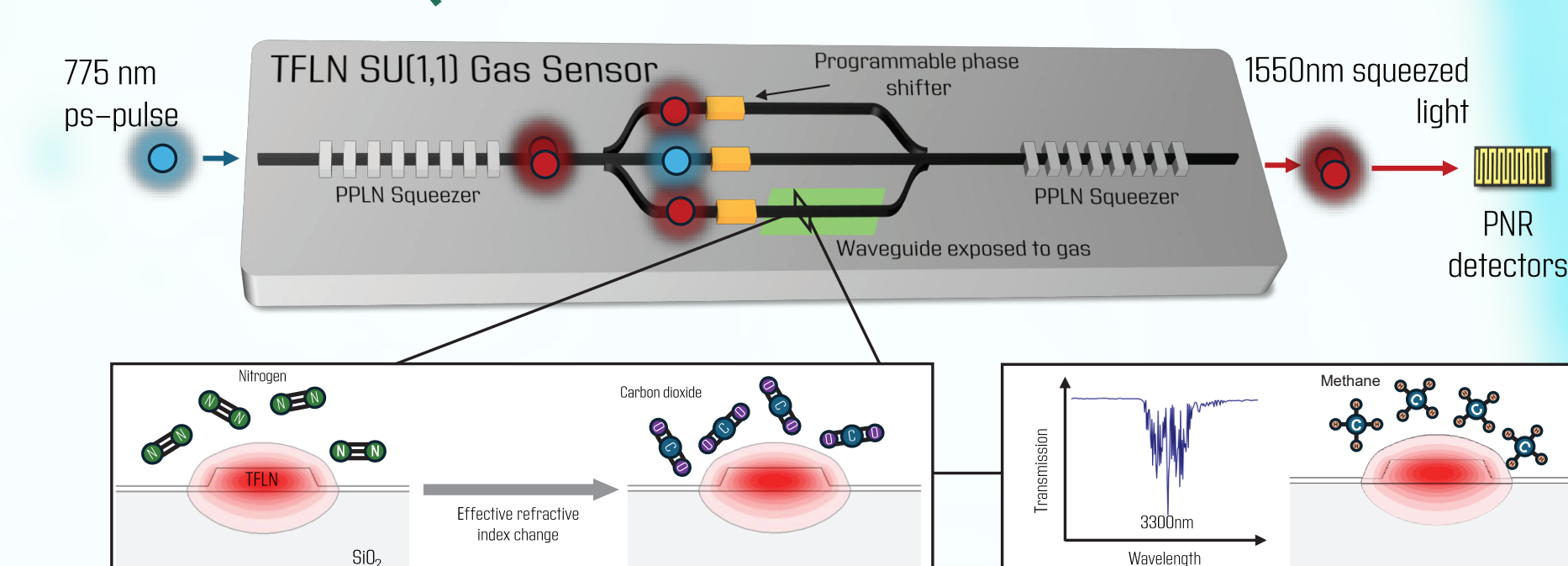


PREVIOUS EXPERIMENTAL RESULTS [GJM]



Joint photon-number probability exhibits fringes up to $m, n = 7$ (only, $m = 5$ case shown). Unconditional violation of the SNL. **PNRDs outperform** click detectors in CFI Advantage of PNRD over click-detection grows monotonically with gain, G .

LINQSENS: TRANSLATING TO TFLN INTEGRATED PHOTONICS



- **Compact, scalable, deployable device**
- **Lower intrinsic losses**
- **Two NLI designs for CO_2 and CH_4**

5. NEXT STEPS

IC's test-bed established. First generation TFLN NLI (Yurke [9], without cladding window) fabricated with characterisation underway.

We will model the effect of seeding combined with PNRD including photon-number dependent efficiencies of IDQ's PNR-SNSPDs.

Over the next six months, second generation chips will be fabricated with cladding window for gas sensing.

