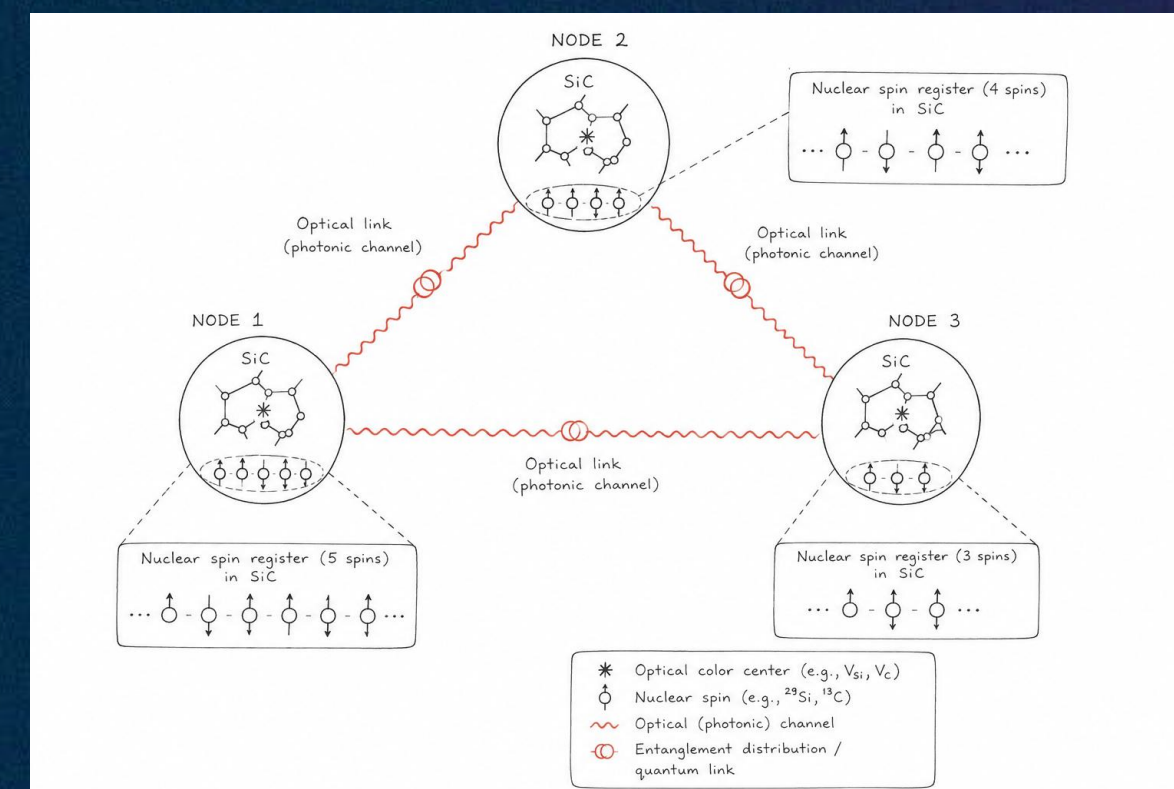


Call 2021
Final Evaluation



InQuRe



Field testing an integrated quantum repeater node
Vadim Vorobyov

COLLABORATION (overview)



GEOGRAPHICAL BREADTH

- **Germany**
- **Sweden**
- **France**
- **Romania (Widening Countries)**

VARIETY OF SECTORS, DISCIPLINES – complementarity of stakeholders (any private sector partners?)

- Attocube AG - Cryostate fiber integration equipment
- Pi3 University of Stuttgart - Quantum Node / Memory.
- Institut de Physique de Nice NSRS, UMR - Dark Fiber Metropolitan Quantum network
- “Alexandru Ioan Cuza” University of Iasi (RAMTECH) - Quantum Frequency Converters

QUALITY OF COOPERATION – effectiveness, coordination, meetings, mobility activities, yearly consortia meeting.

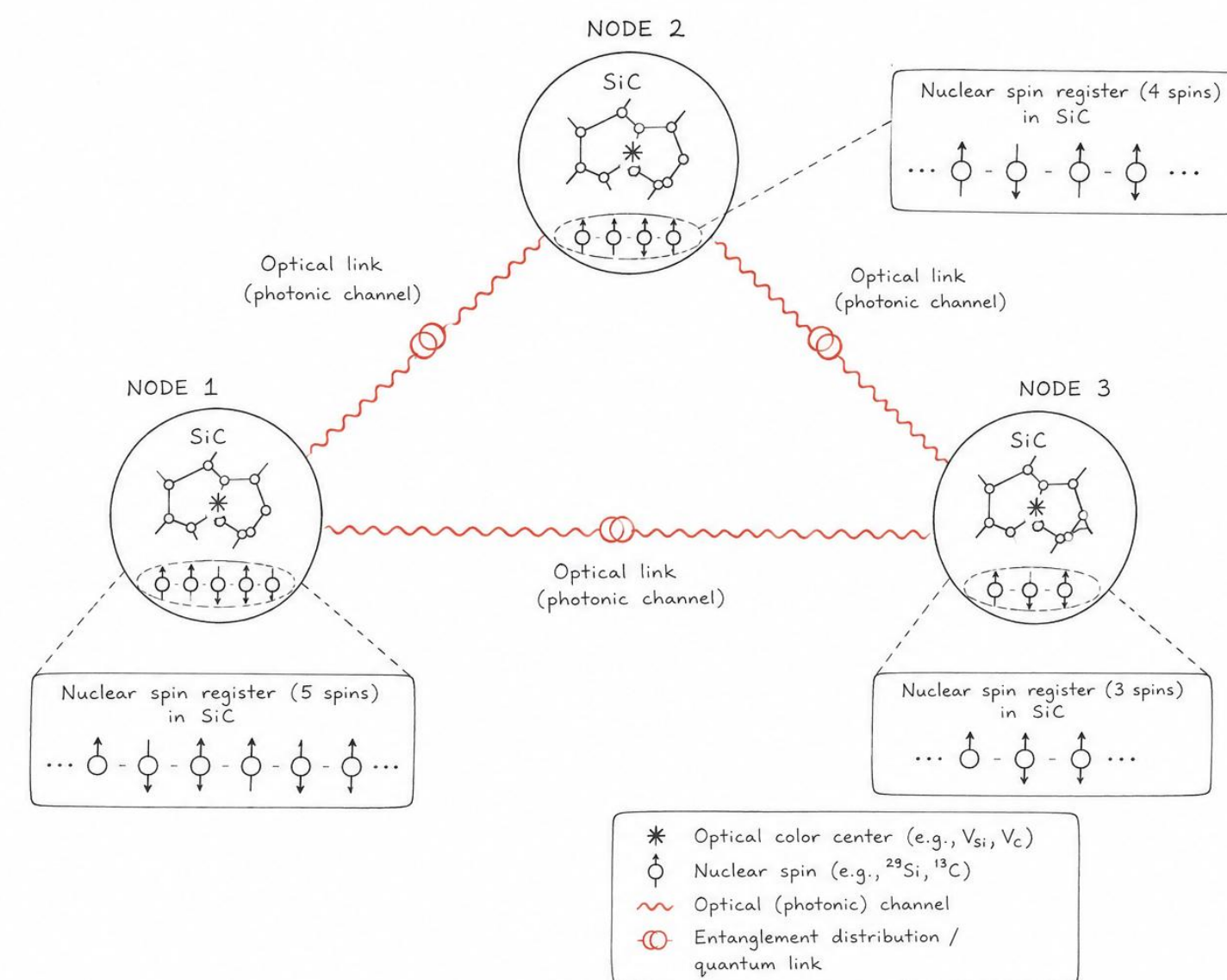
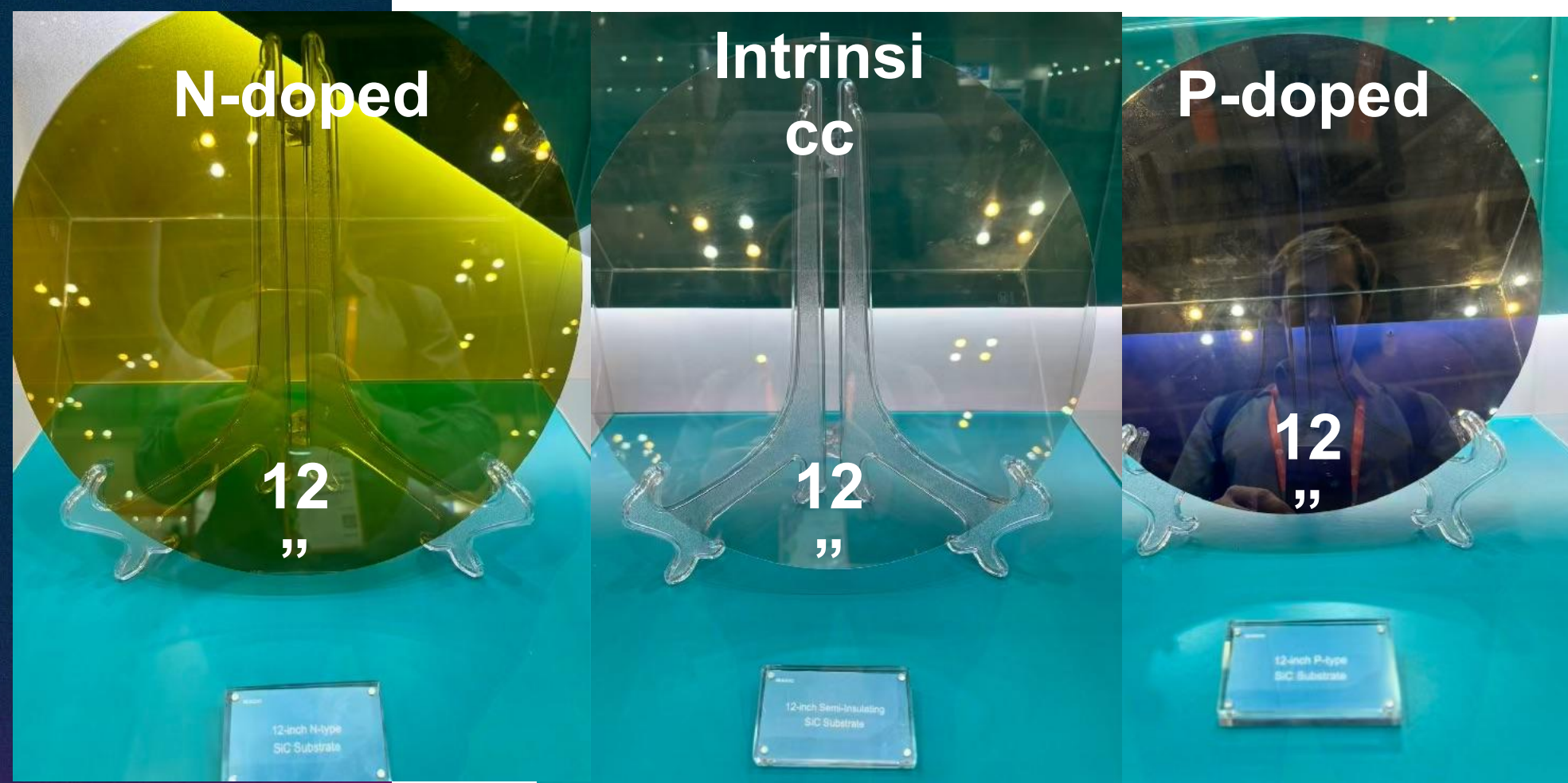
INFRASTRUCTURE SHARING within the project consortium (Attocube/US, RAMTECH/US)





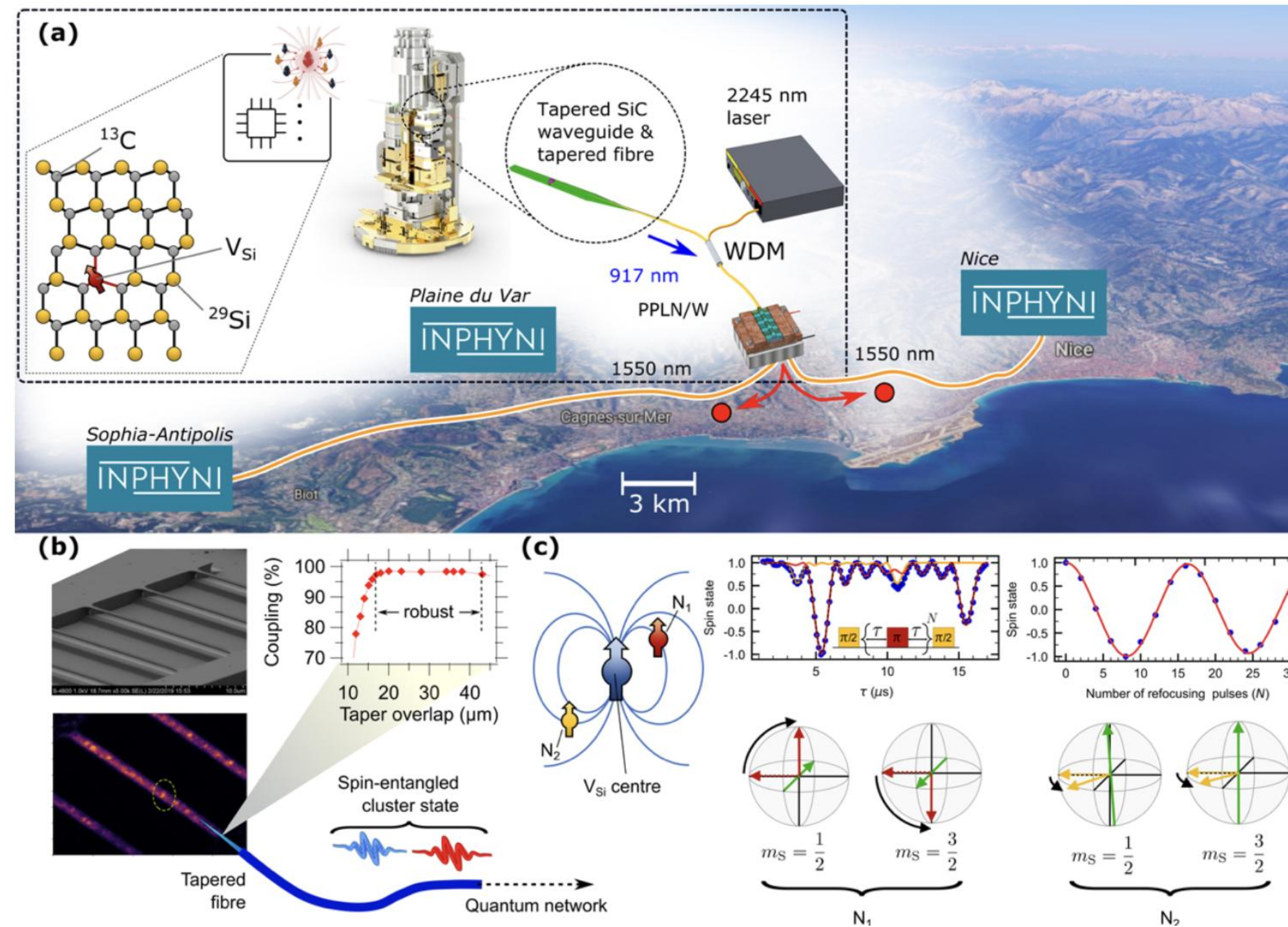
SUCCESS STORY (highlights)

CHALLENGE – scalable technology for quantum repeater nodes made out of Silicon Carbide

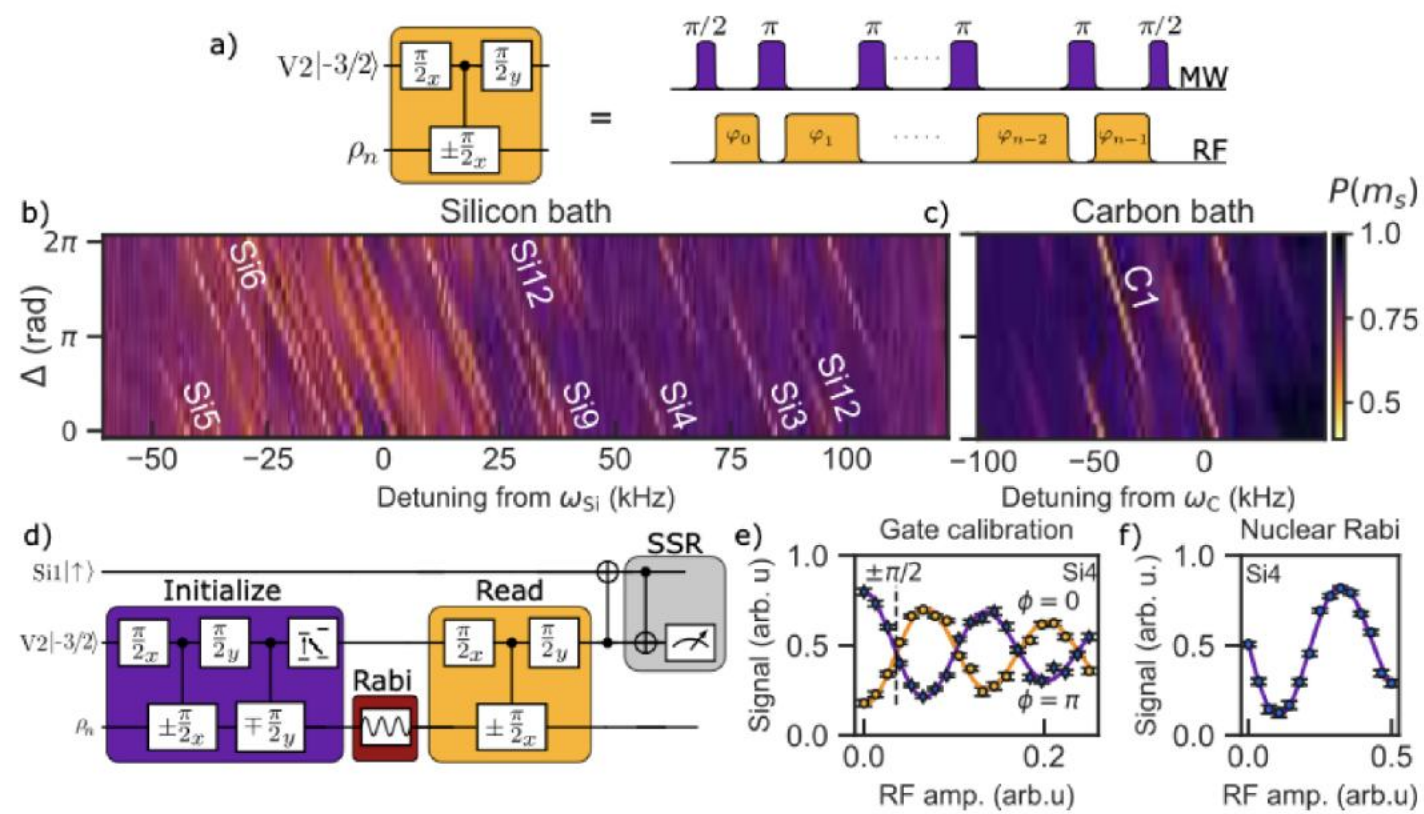
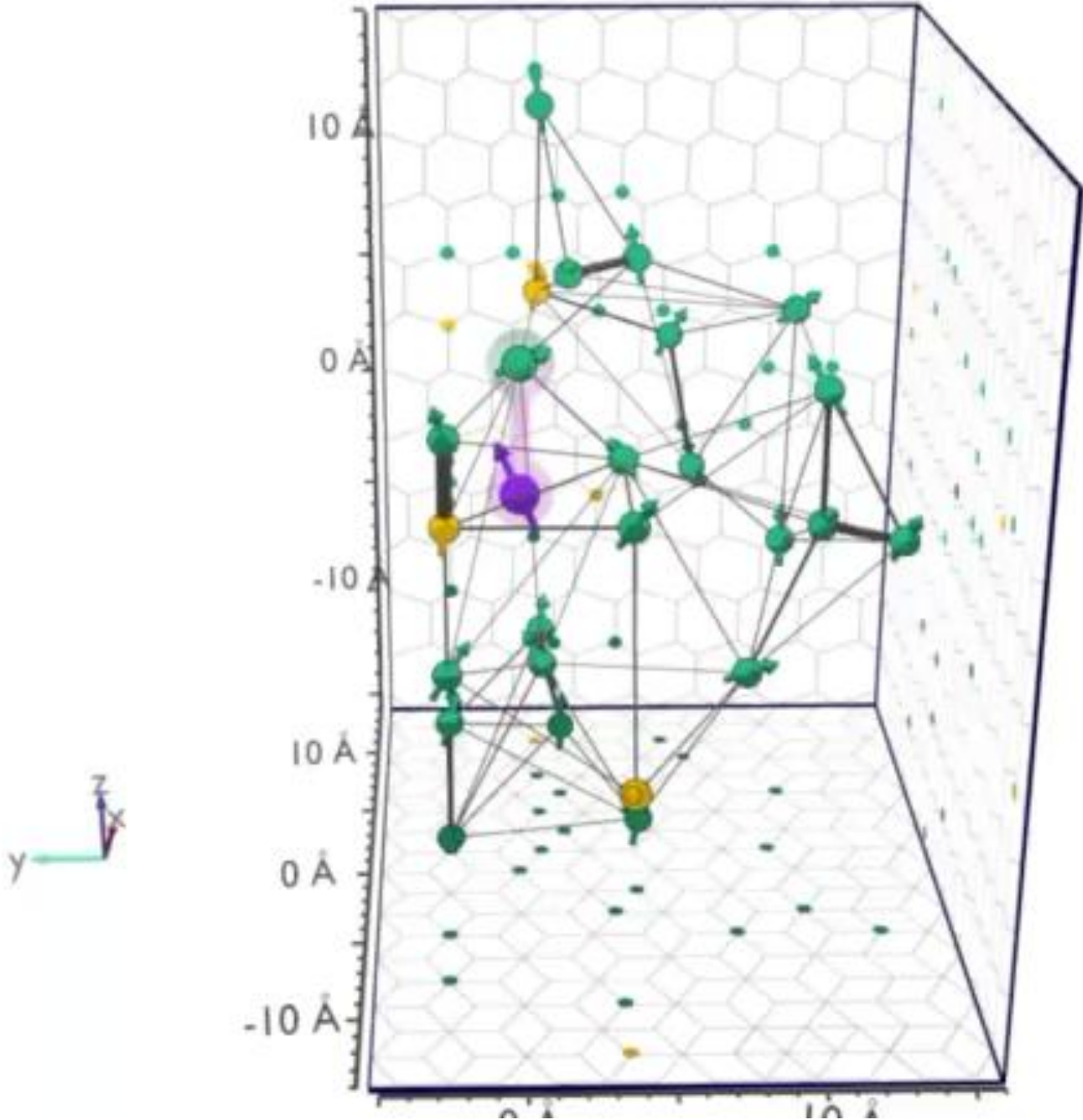


SOLUTION

PLANNED AND SURPRISING/UNPLANNED OUTCOMES

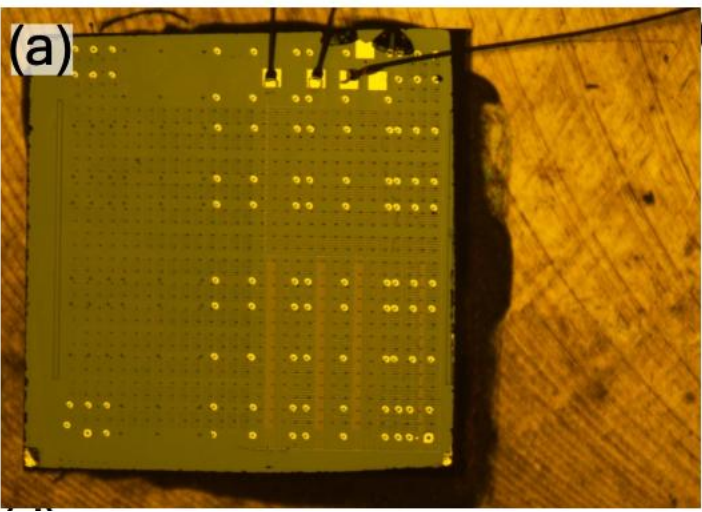


Solutions

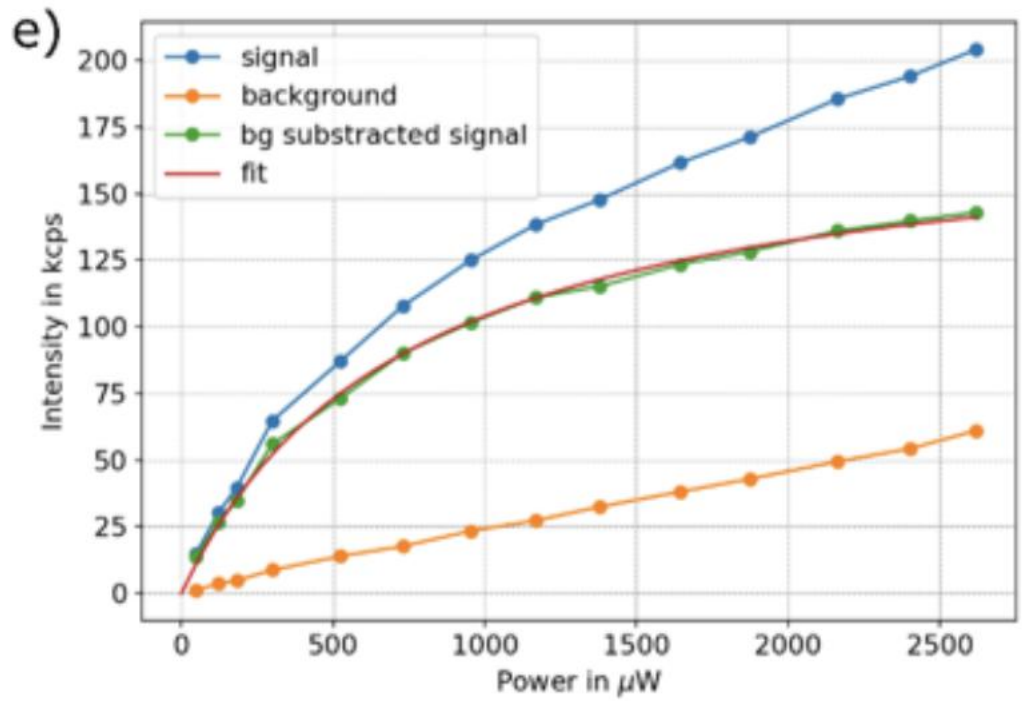
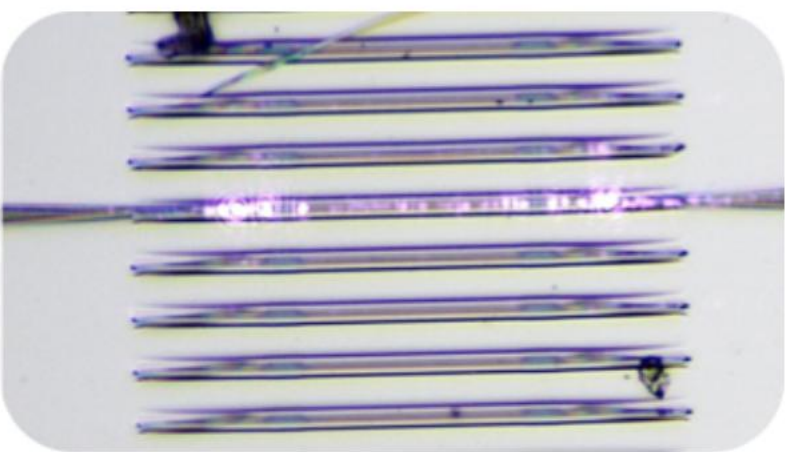


Protocols for coherent nuclear spin control
Quantum register of 25 nuclear spin qubits

Isotopically pure, ultra clean epitaxial 4H- SiC, a-plane.

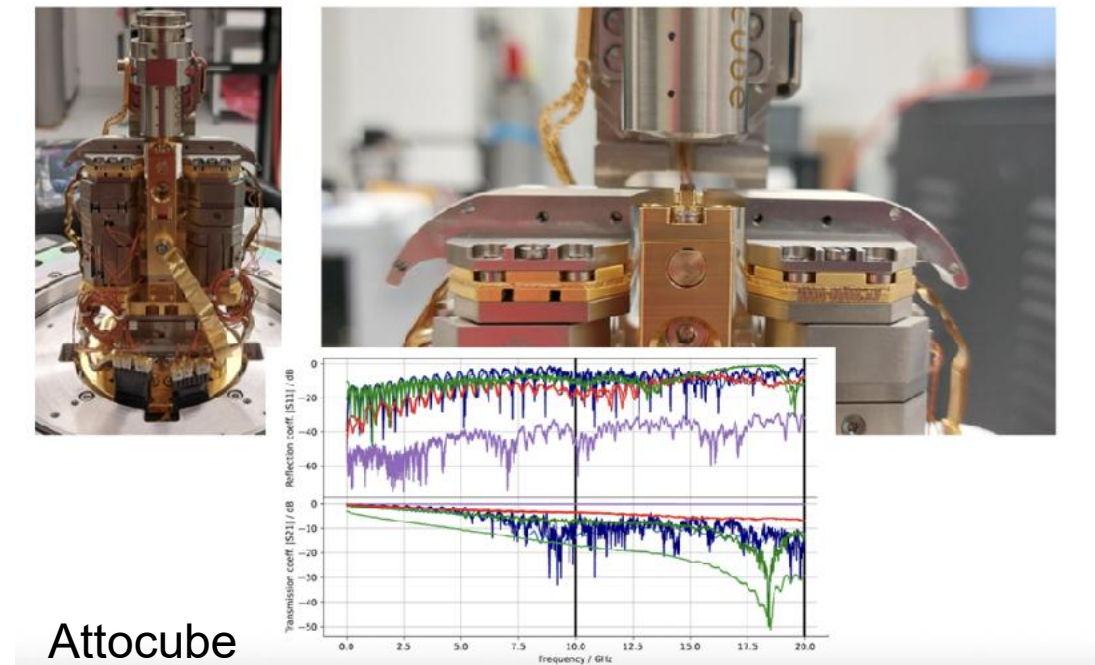
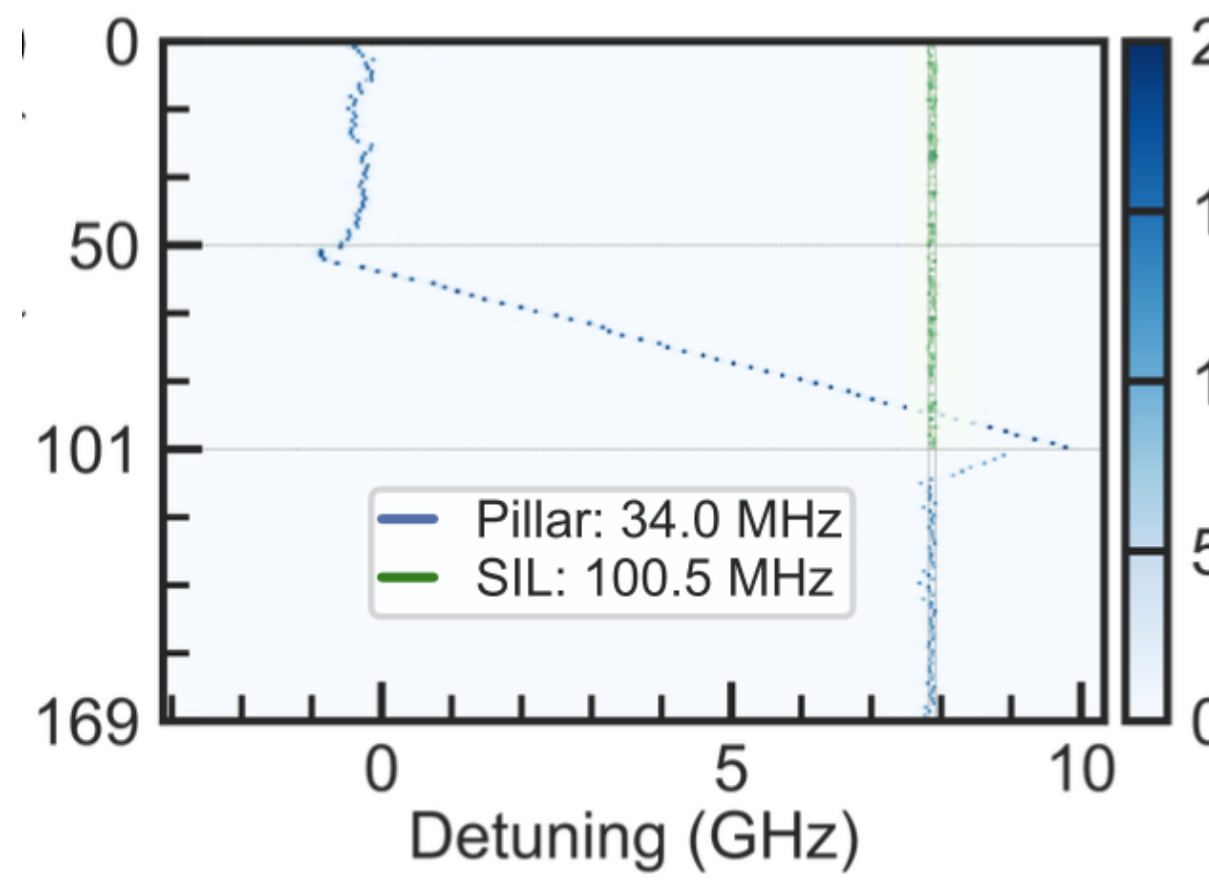
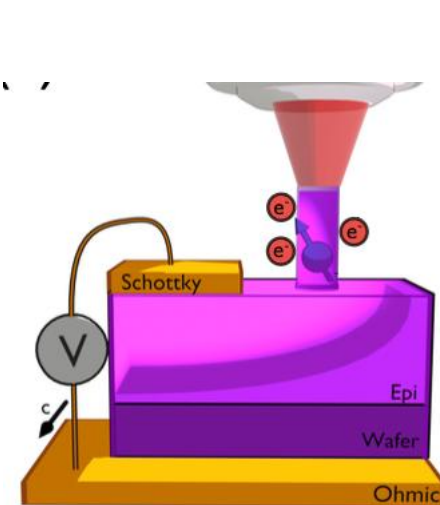
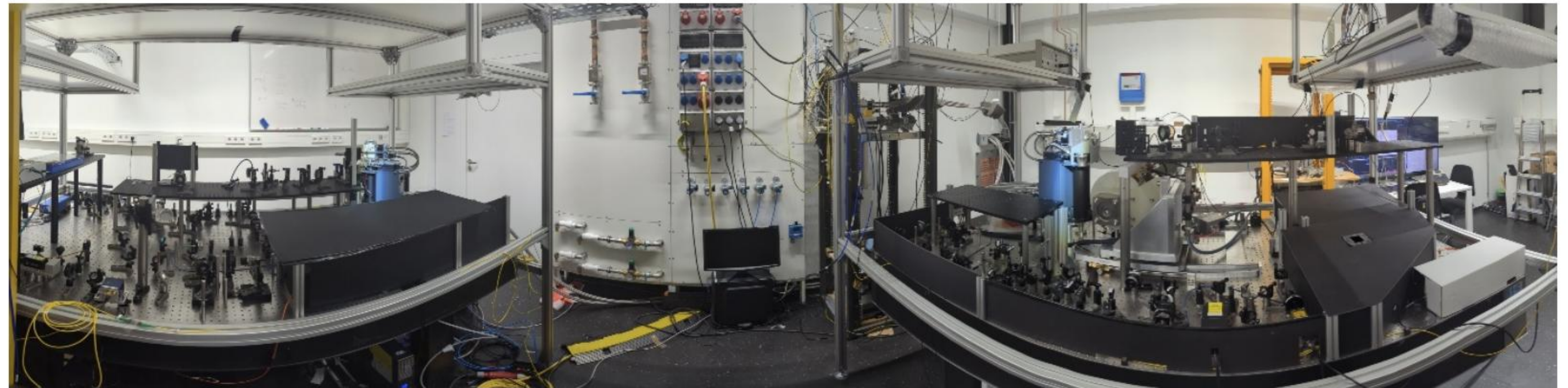


With optical Fiber Interface

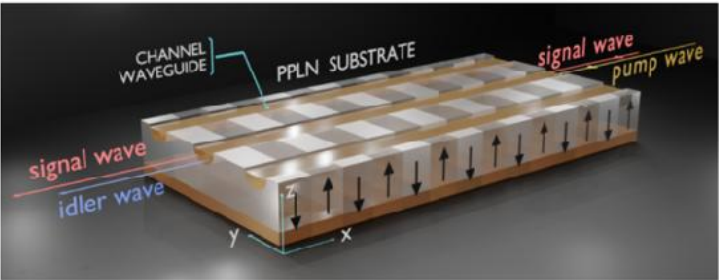
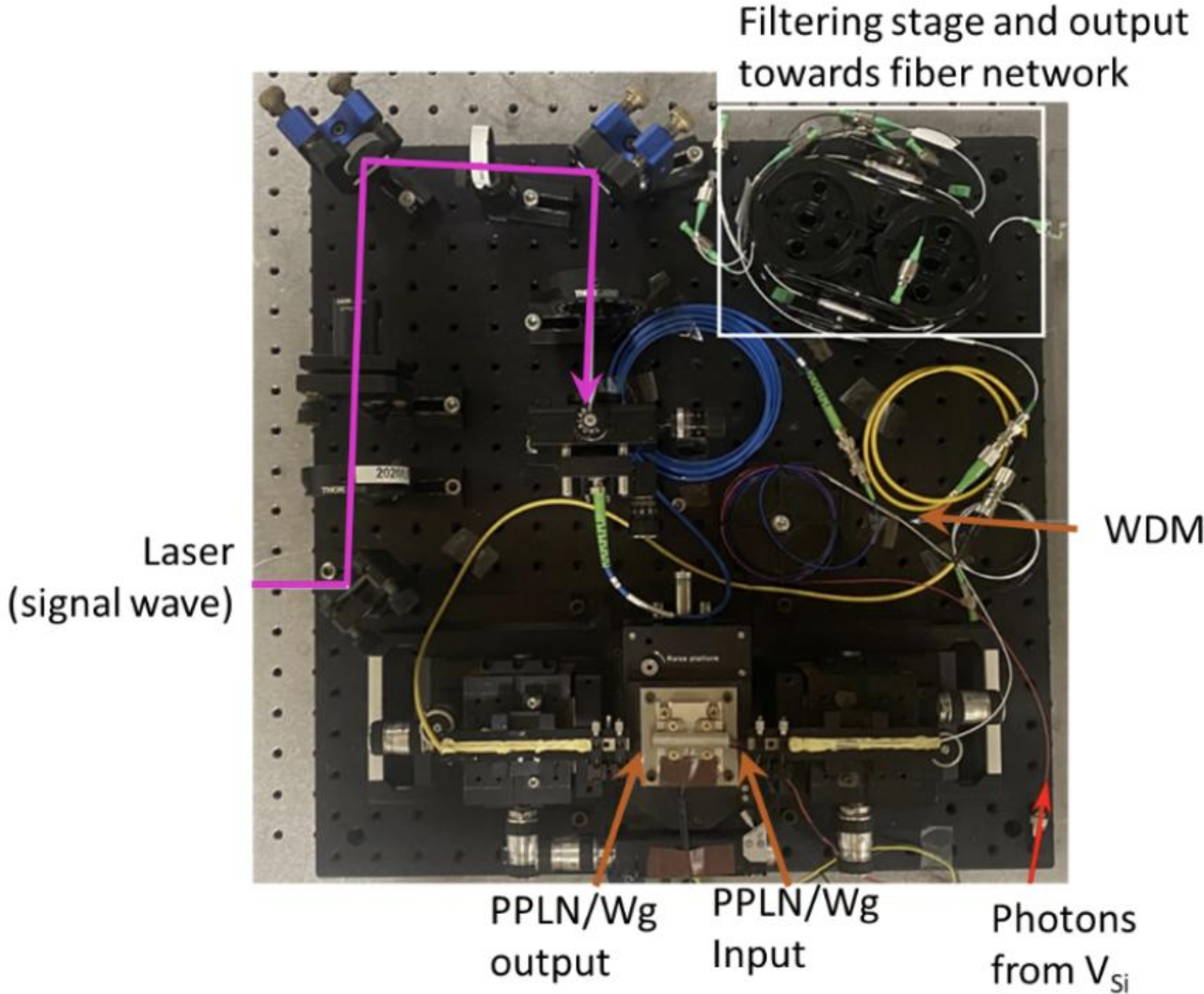
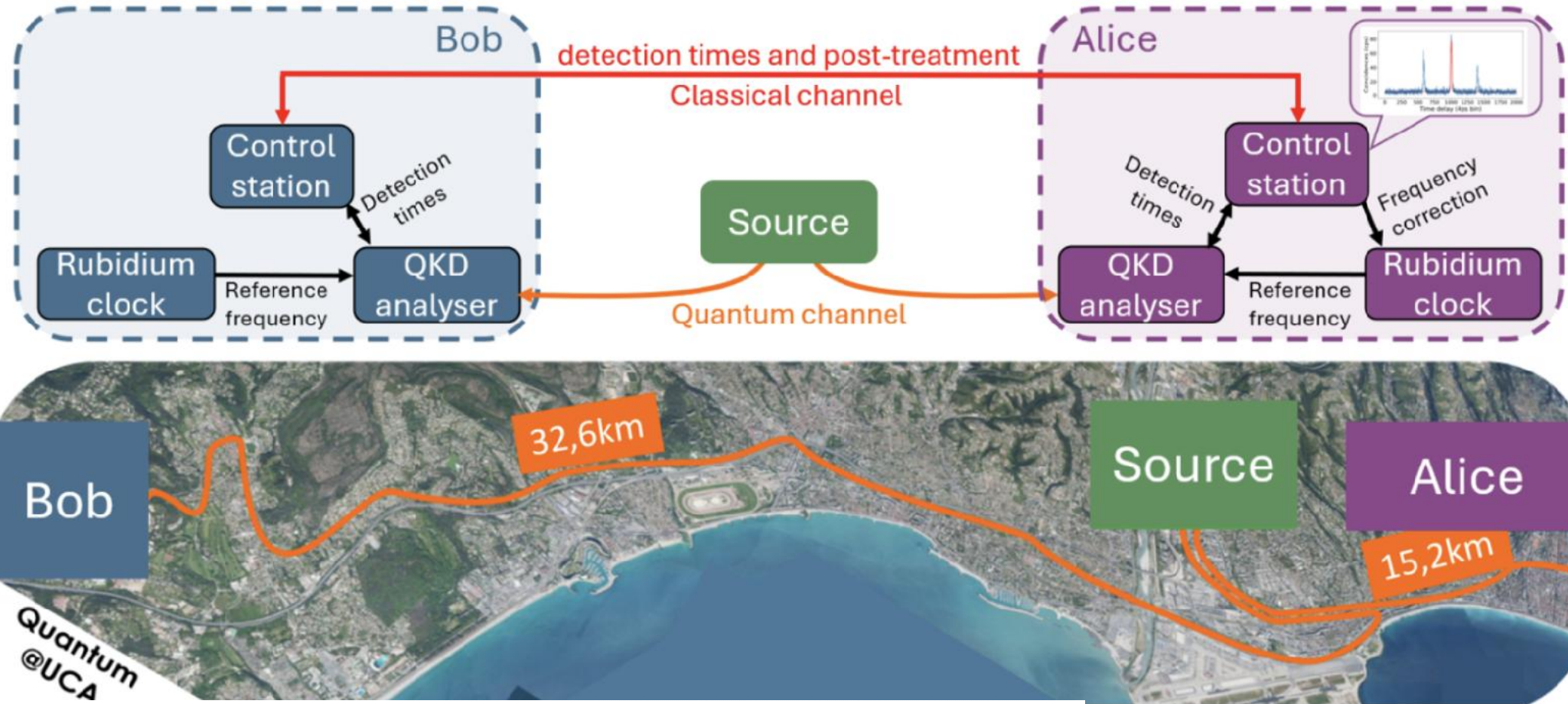


Solutions

Two - node setup



Solutions



SCIENTIFIC OUTPUTS



PUBLICATIONS AND PRESENTATIONS (highlights)

[1] Mathis Cohen, Anthony Martin, Romain Dalidet, Florian Pastier, Marie Billard, Aristide Lemaitre, Valérian Giesz, Niccolo Somaschi, Sarah Thomas, Pascale Senellart-Mardon, Sébastien Tanzilli, Laurent Labonté; Compact and efficient quantum frequency conversion of a fiber-pigtailed single-photon source. *APL Quantum* 1 March 2026; 3 (1): 016101. <https://doi.org/10.1063/5.0292682> Page of 10 15

[2] Pelet, Yoann, Grégory Sauder, Mathis Cohen, et al. ‘Operational Entanglement-Based Quantum Key Distribution over 50 Km of Field-Deployed Optical Fibers’. *Physical Review Applied* 20, no. 4 (2023): 044006. <https://doi.org/10.1103/PhysRevApplied.20.044006>

[3] Heiler, J., Körber, J., Hesselmeier, E., Kuna, P., Stöhr, R., Fuchs, P., Ghezellou, M., Ul-Hassan, J., Knolle, W., Becher, C., Kaiser, F., & Wrachtrup, J. Spectral Stability of V2 Centers in Sub-Micron 4H-SiC Membranes. *npj Quantum Information* 10, 2024. DOI: 10.1038/s41535-024-00644-4. Demonstrates stable optical transitions of V2 centres in nanophotonic SiC membranes, enabling scalable quantum network nodes.

[4] Hesselmeier, E., Takács, I., Ivády, V., Kuna, P., Knolle, W., Son, N. T., Ghezellou, M., Ul- Hassan, J., Dasari, D. B. R., Kaiser, F., Vorobyov, V., & Wrachtrup, J. Qudit-Based Spectroscopy for Measurement and Control of Nuclear-Spin Qubits in Silicon Carbide. *Physical Review Letters* 132, 090601 (2024). DOI: 10.1103/PhysRevLett.132.090601. Demonstrates coherent control and characterization of individual nuclear-spin qubits surrounding V2 centres in SiC, including dynamic nuclear-spin polarization approaching 98%.

[5] Hesselmeier, E., von Berg, O., Kuna, P., Knolle, W., Kaiser, F., Son, N. T., Ghezellou, M., Ul-Hassan, J., Vorobyov, V., & Wrachtrup, J. High Fidelity Optical Readout of a Nuclear Spin Qubit in Silicon Carbide. *arXiv:2401.04465* (2024). Demonstrates nuclear-spin readout fidelities up to 99.5% and state-preparation fidelities of 99%, establishing a key building block for quantum memories and repeater architectures.

[6] Körber, J., Heiler, J., Fuchs, P., Flad, P., Hesselmeier, E., Kuna, P., Ul-Hassan, J., Knolle, W., Becher, C., Kaiser, F., & Wrachtrup, J. Fluorescence Enhancement of Single V2 Centers in a 4H-SiC Cavity Antenna. *Nano Letters* 24 (2024). DOI: 10.1021/acs.nanolett.4c02162. Demonstrates nanophotonic enhancement of photon collection from single V2 centres, improving spin-photon interface performance for quantum networking.

[7] Steidl, T., Kuna, P., Hesselmeier-Hüttmann, E., Liu, D., Stöhr, R., Knolle, W., Ghezellou, M., Ul-Hassan, J., Schober, M., Bockstedte, M., Gali, A., Vorobyov, V., & Wrachtrup, J. Single V2 Defect in 4H Silicon Carbide Schottky Diode at Low Temperature. *Nature Communications* 16, 4669 (2025). DOI: 10.1038/s41467-025-59647-9. Demonstrates electrically integrated V2 colour centres in SiC Schottky devices, an important step toward scalable quantum-network hardware.

[8] Kuna, P., Hesselmeier-Hüttmann, E., Schillinger, P., Gloistein, F., Takács, I., Ivády, V., Knolle, W., Ul-Hassan, J., Wrachtrup, J., & Vorobyov, V. Localization and Coherent Control of 25 Nuclear Spins in Silicon Carbide. *arXiv:2512.20281* (2025). Page of 11 15 This work reports Ångström-level three-dimensional localization and coherent control of 25 nuclear spins surrounding a single V2 centre in 4H-SiC, representing one of the largest solid-state nuclear-spin quantum registers demonstrated to date.

[9]. J. Javadzade, M. Zahedian, F. Kaiser, V. Vorobyov, and J. Wrachtrup, Efficient nuclear spin–photon entanglement with optical routing, *Physical Review Applied* 24, 024059 (2025). DOI: 10.1103/xlmc-x4xg. The work demonstrates an efficient scheme for generating and detecting nuclear-spin–photon entanglement in diamond using optical routing, significantly improving entanglement generation rates relevant for quantum networking.

[10]. V. Bushmakina, O. von Berg, C. Sauerzapf, S. Jayaram, A. Denisenko, C. Tarín, J. Anders, V. Vorobyov, I. Gerhardt, D. Liu, and J. Wrachtrup, Two-Photon Interference of Photons from Remote Tin-Vacancy Centers in Diamond, *arXiv:2412.17539* (2025). The authors report remote two-photon interference between separate SnV centers in diamond, achieving up to 80% interference visibility without post-processing and demonstrating the suitability of SnV centers for future quantum network nodes

Conference Contributions

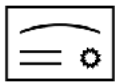
[1] Florian Kaiser et al. High-coherence integrated nanophotonic multi-spin-photon interface based on silicon vacancies in silicon carbide, *Bulletin of the American Physical Society*, 2022.

[2] Charles Babin et al. Nanofabricated and integrated colour centres in silicon carbide with high-coherence spin-optical properties, *Frontiers in Optics, OSA*, 2021.

Invited Talks

[1] Jörg Wrachtrup: Scaling quantum hardware with color centers in SiC, DPG Spring meeting, March 2026, Dresden, Germany

[2] Optically addressable nuclear spin register in silicon carbide, DPG Spring meeting, March 2024, Freiburg, Germany



PATENTS (obtained and pending)



NUMBER OF BACHELOR, MASTER AND PhD THESES prepared under the QuantERA Project

4 PhD (Pierre Kuna, Marcel Krumrein, Raoul Sandu, Ioan Caunic)



IMPACT (potential users)



RELEVANT **INDUSTRY BRANCH**



EXISTING/POTENTIAL **END USERS**



COOPERATION WITH THE **QUANTUM FLAGSHIP** OR OTHER QUANTUM INITIATIVES (if applicable)



The project has a strong overlap with QF projects of QIA.

The local national level initiatives, e.g. German QR.N (BMFTIR) and telekom industry are relevant in the context of the project.

Commercial relevant applications: Single photon sources, frequency converters, stable quantum networks, and fiber probe stations.

Availability of SiC samples with required purity and isotopic content was still noted as a potential interest for high power and chip industry sector.



IMPACT (RRI aspects)



GENDER: 2 out of 8 female researchers involved.



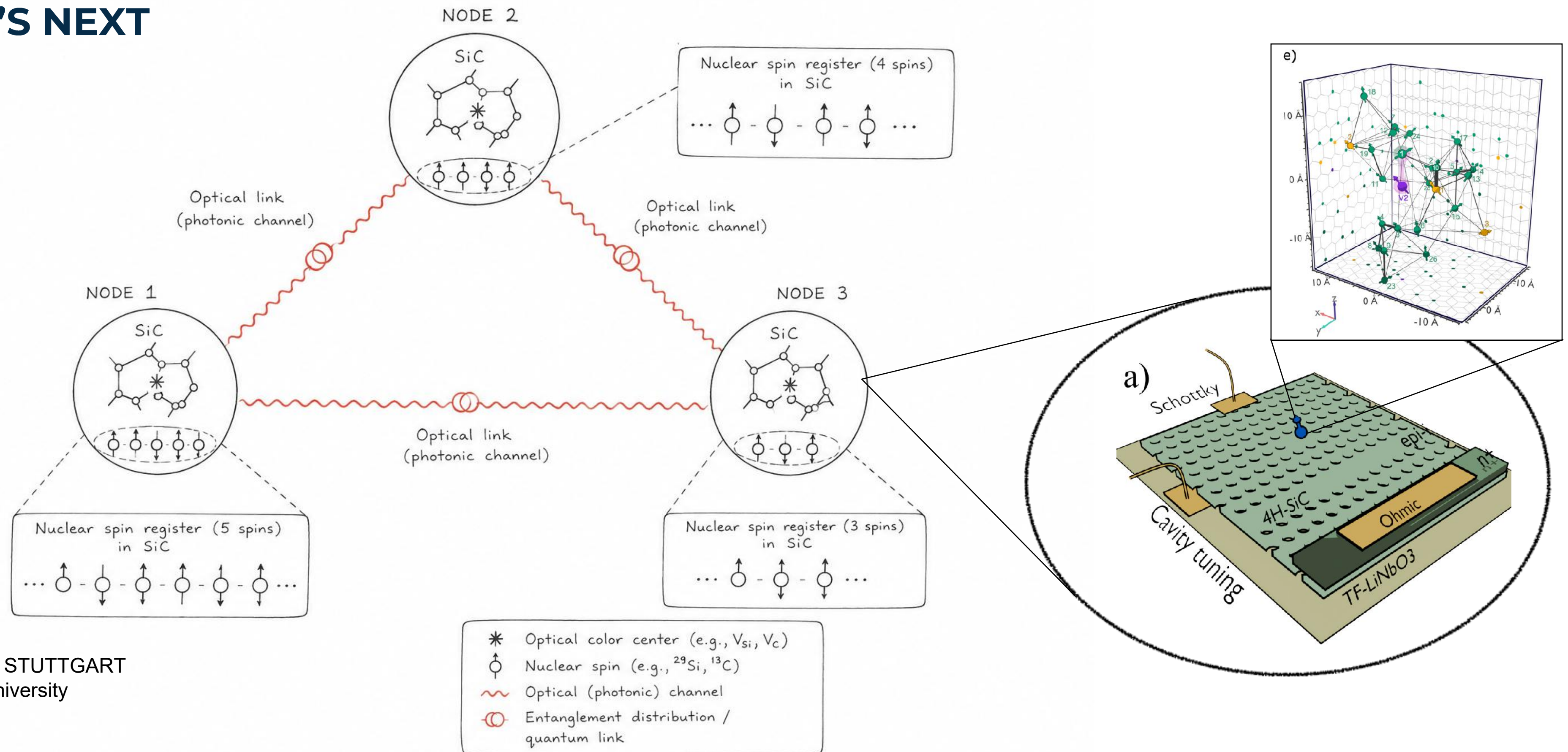
OPEN SCIENCE: Data is published alongside the publications (Open Access), DARUS, available.



SCIENCE EDUCATION: Project attracted many young scientists, in particular 4 BSc, 2 out of them continued in Quantum Science with their MSc, and PhD.



WHAT'S NEXT



- University of STUTTGART
- Linköping University
- Attocube

In collaboration with

HZDR, G. Astakhov Group

SiC for quantum sensors and scanning probe.

