# $^{31}$P Nuclear Spin Qubit in Silicon

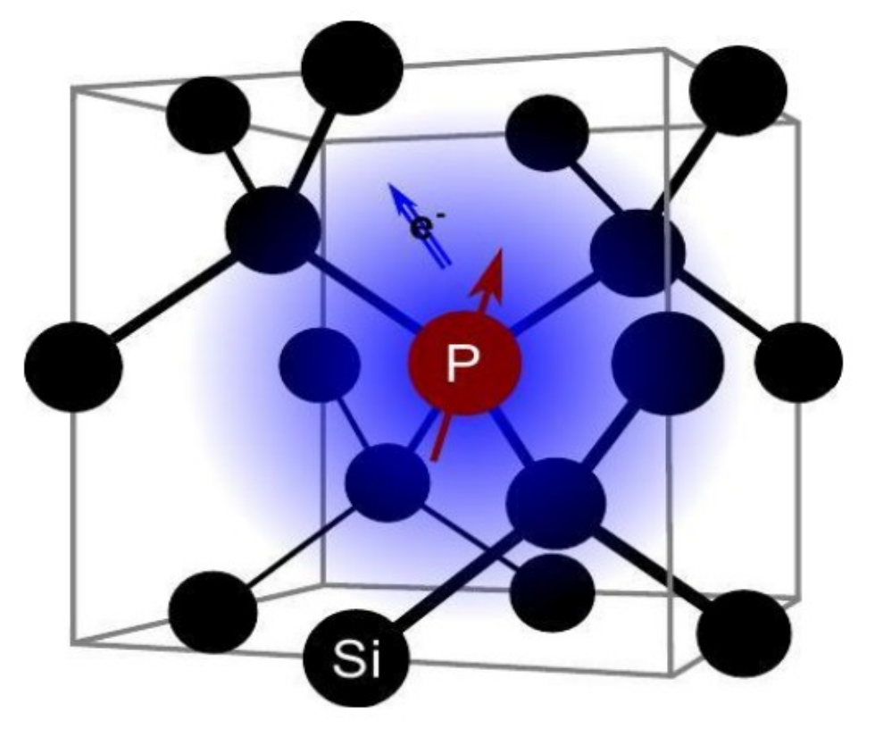
Holger Haas, Thomas Alexander, Rahul Deshpande, David Cory

IQC Institute for Quantum Computing

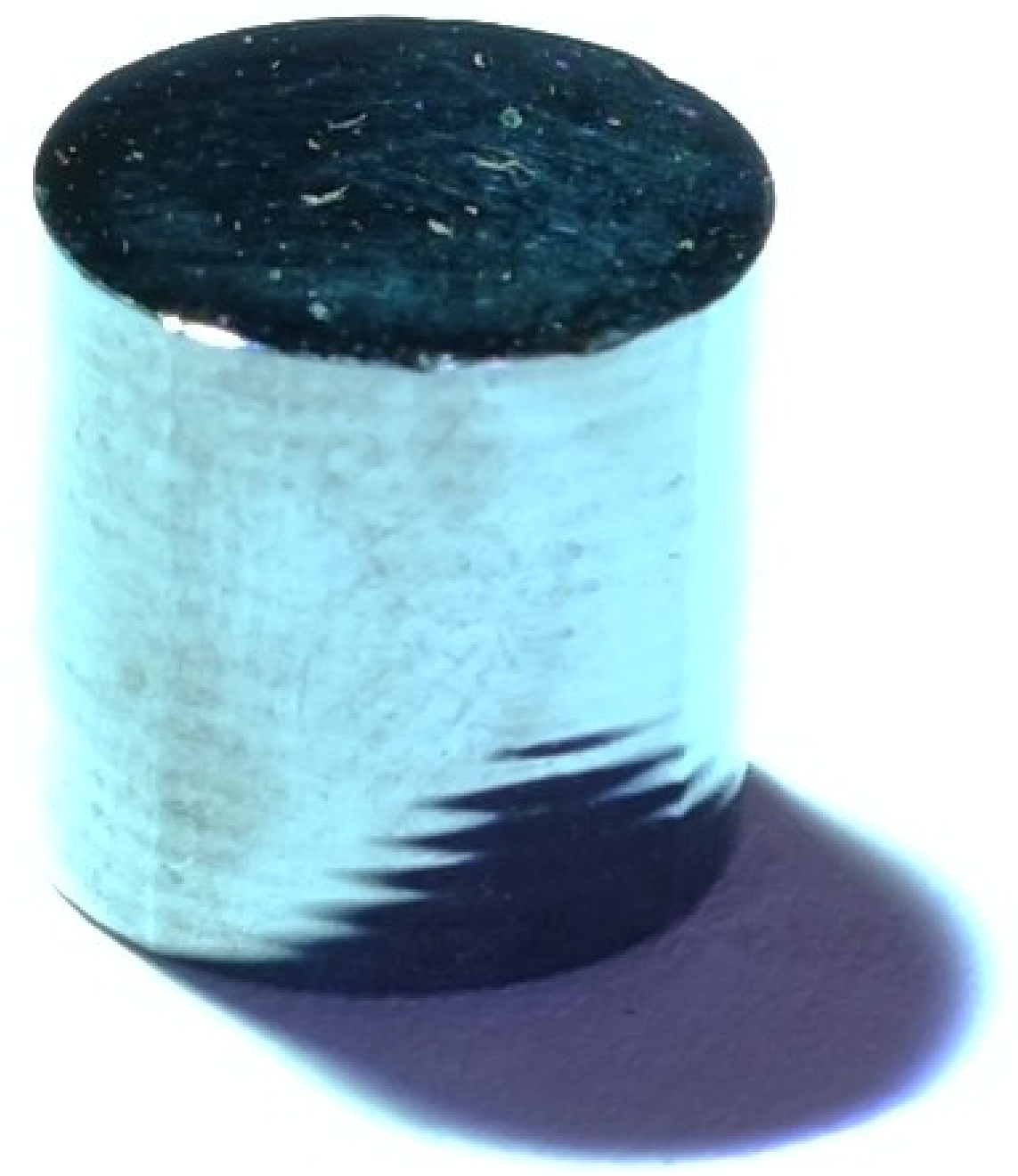
UNIVERSITY OF WATERLOO

## $^{31}$P Defects in Silicon

- Silicon crystals can be grown as one of the purest and defect free materials due to decades of fabrication expertise in the semiconductor industry.
- We use silicon crystals doped with phosphorus at low concentrations (~$10^{15}$ cm$^{-3}$).
- Silicon has 3 naturally occurring isotopes: $^{28}$Si (92%), $^{29}$Si (5%), $^{30}$Si (3%), the Avogadro project has provided us with isotopically purified silicon with $^{28}$Si concentration of 99.9954%.
- Isotopic purification yields an extremely noiseless environment for spin qubits.
- **Phosphorus ($^{31}$P) defect nucleus make for an extremely long-lived qubit, while the associated donor electron provides a source for high spin polarization.**



$^{31}$P defect nucleus with its donor electron in silicon crystal lattice.



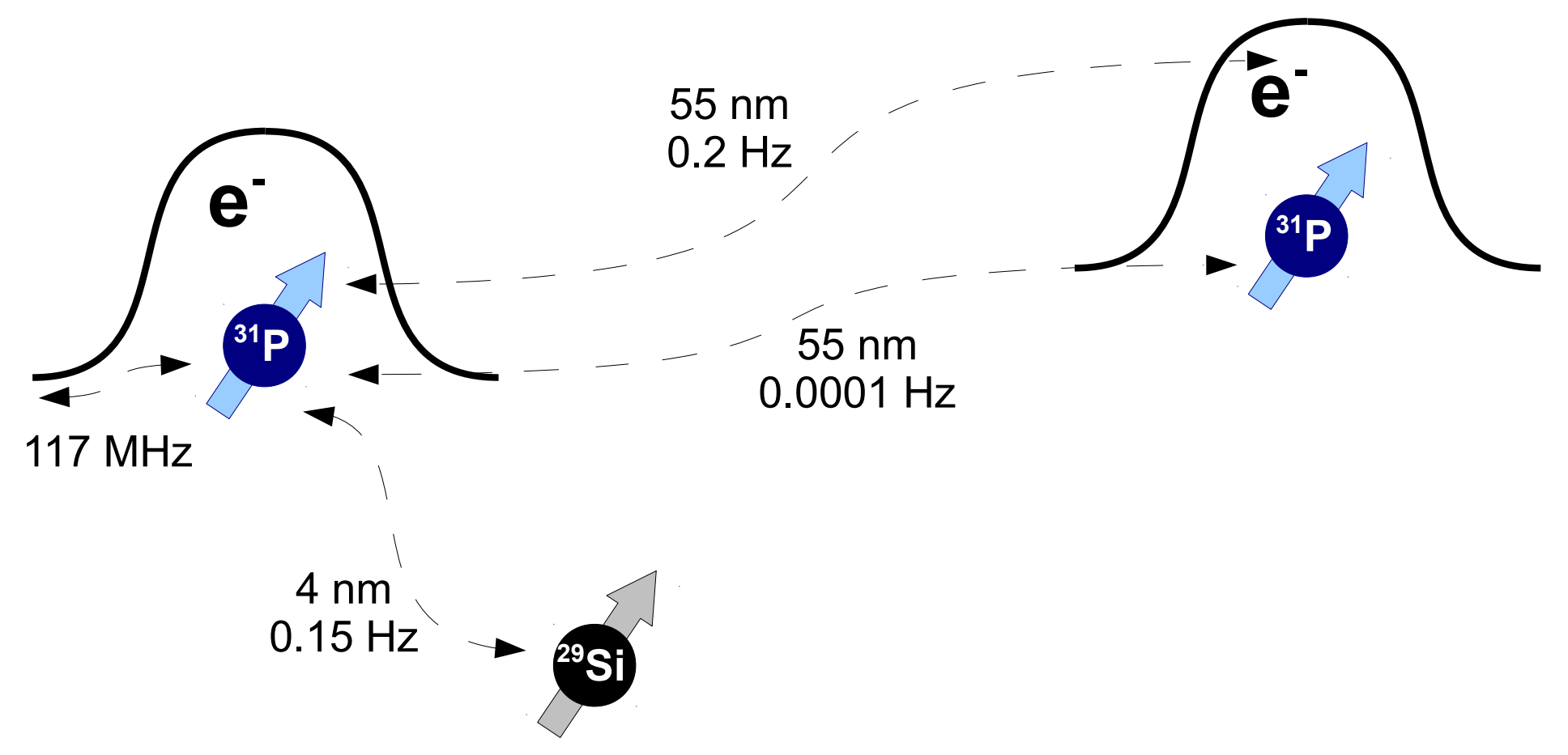
High purity silicon sample.

## Magnetometry

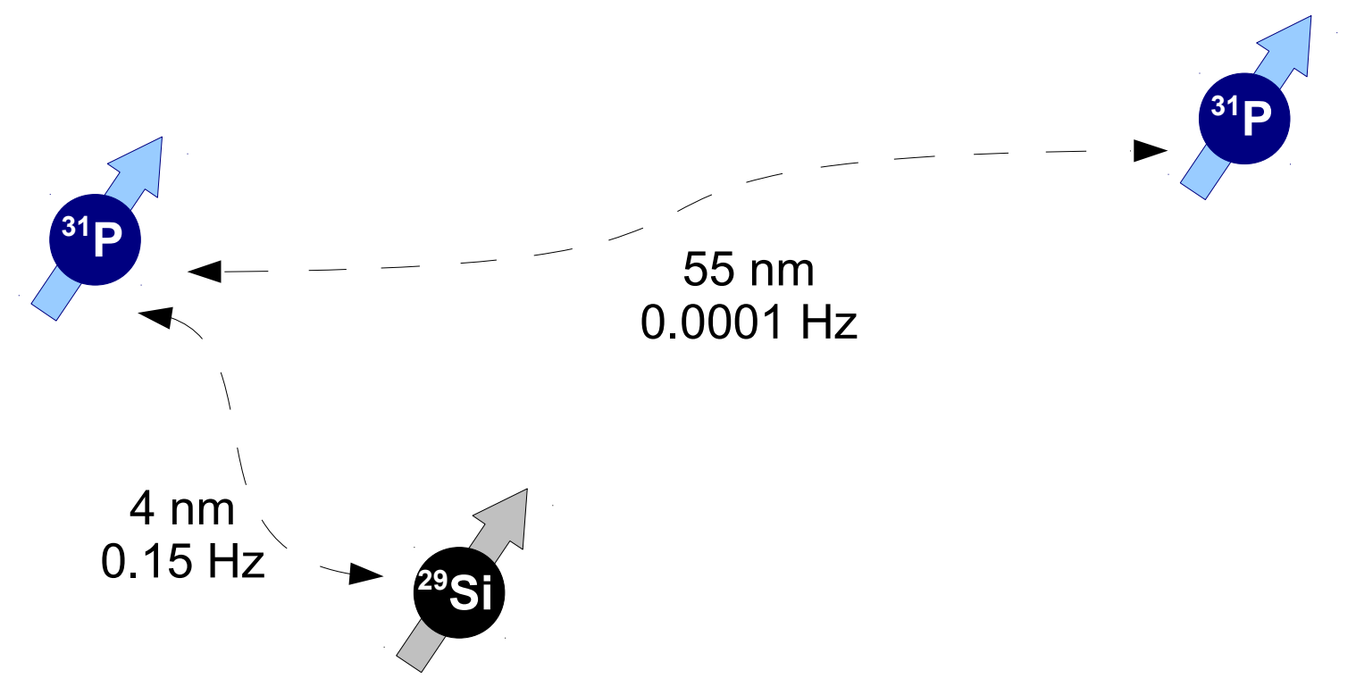
- Efficient, high sensitivity, high accuracy magnetometry requires a system that is polarizable quickly and on-demand, while maintaining very long coherence times.
- $^{31}$P defect nuclei satisfy these demands. Donor electron polarization can be rapidly transferred onto the nuclei via optical, electrical or microwave mediated dynamical nuclear polarization (DNP) methods. Furthermore, removal of the donor electron yields extremely long coherence times [2] for the nuclear spins.

## Decoherence/Sensitivity

- The decoherence rate of $^{31}$P nuclear spins depends predominantly on their interaction strengths with the surrounding magnetic moments (e.g. donor electrons, $^{29}$Si nuclear spins and other defects). The associated time scale determines the effective sensing time for detecting magnetic fields.
- Below are the average nearest neighbour distances to such magnetic moments and the associated interaction strengths for our silicon sample.



- With the donor electrons present in the crystal we have shown [1] the $^{31}$P spin decoherence rate ($T_2$) to be 1.2 s, limited by its interaction with the donor electron.
- Removal of the electrons would retain only the interactions depicted below.

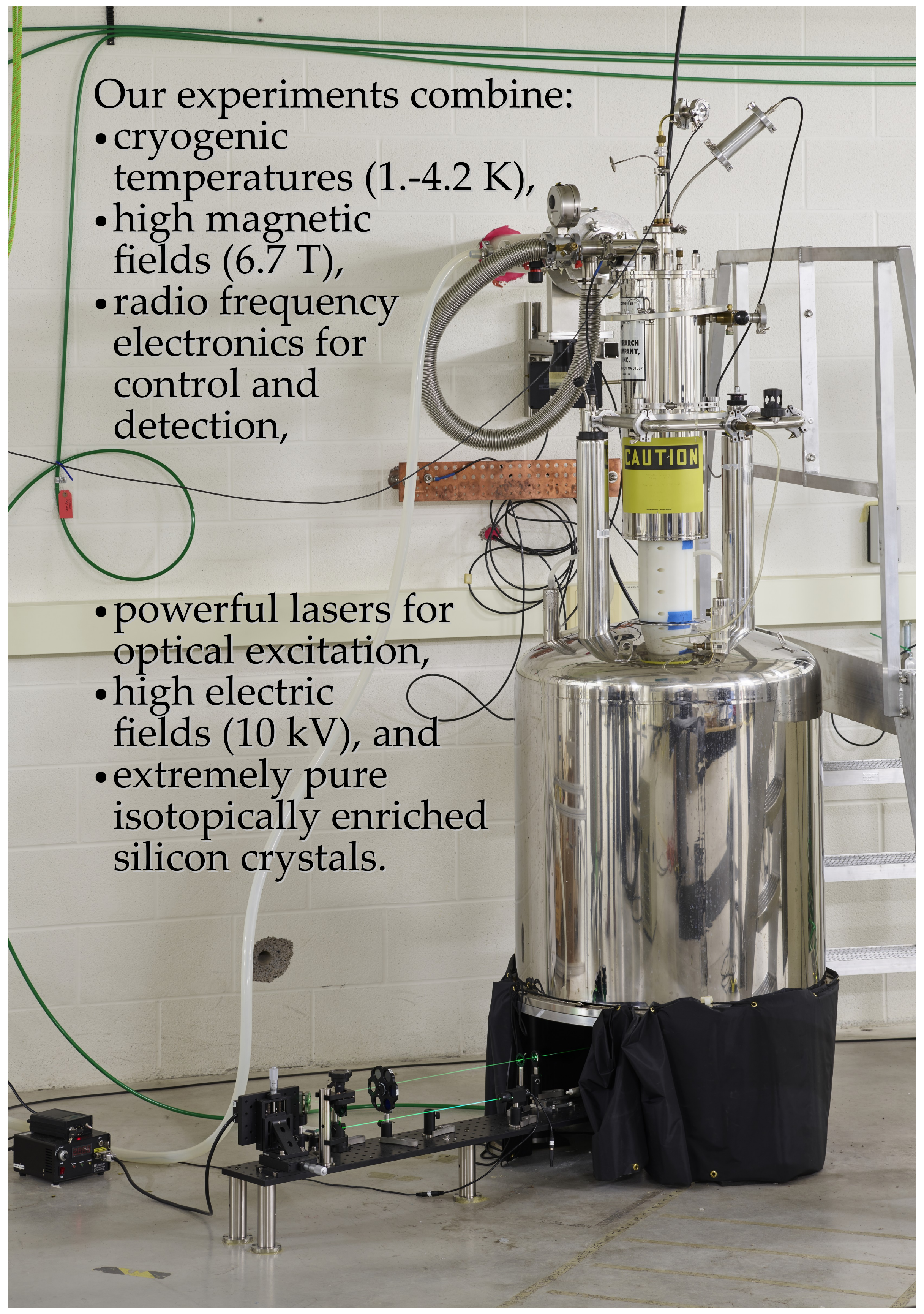


- The interaction with the $^{29}$Si nuclear spins can be further suppressed by using quantum control techniques.
- Ionized $^{31}$P defects have been shown [2] to have coherence times of 2,340 s at room temperature and 10,800 s at cryogenic temperatures.
- Electrical ionization would provide a fast, easy to implement scheme for removing the donor electrons for thin silicon samples.

## Our Research & Results

- In our experiments we use infrared (1047 nm) optical irradiation for polarization transfer along with radio frequency control and inductive readout to manipulate and detect the $^{31}$P spin state.
- Previously we have demonstrated [1] an ability to optically hyperpolarize $^{31}$P nuclei to near unity (>64%) with 578 s time constant.
- Our current research focuses on the optical DNP mechanism and electrical ionization of phosphorus defects. Recently we have shown [3] 10x reduction of the DNP time constant and we have provided [3] first experimental evidence for phononic nature of the DNP mechanism.

## Experimental Setup



Our experiments combine:

- cryogenic temperatures (1.-4.2 K),
- high magnetic fields (6.7 T),
- radio frequency electronics for control and detection,
- powerful lasers for optical excitation,
- high electric fields (10 kV), and
- extremely pure isotopically enriched silicon crystals.

## Outlook

**This research is critical for developing practical devices in three distinct ways.**

- Understanding the optical DNP mechanism and decoherence properties of $^{31}$P defect nuclei enables finding optimal physical conditions for using such nuclei for magnetometry and other applications.
- We are also verifying the demands on silicon fabrication necessary for practical applications.
- Using electric fields for defect ionization helps optimizing the robustness, cost and space efficiency of auxiliary equipment needed for building functional devices.

## Acknowledgements

## References

[1] P. Gumann et al, Phys. Rev. Lett. **113**, 267604 (2014)
[2] K. Saeedi et al, Science **342**, 830 (2013)]
[3] Forthcoming