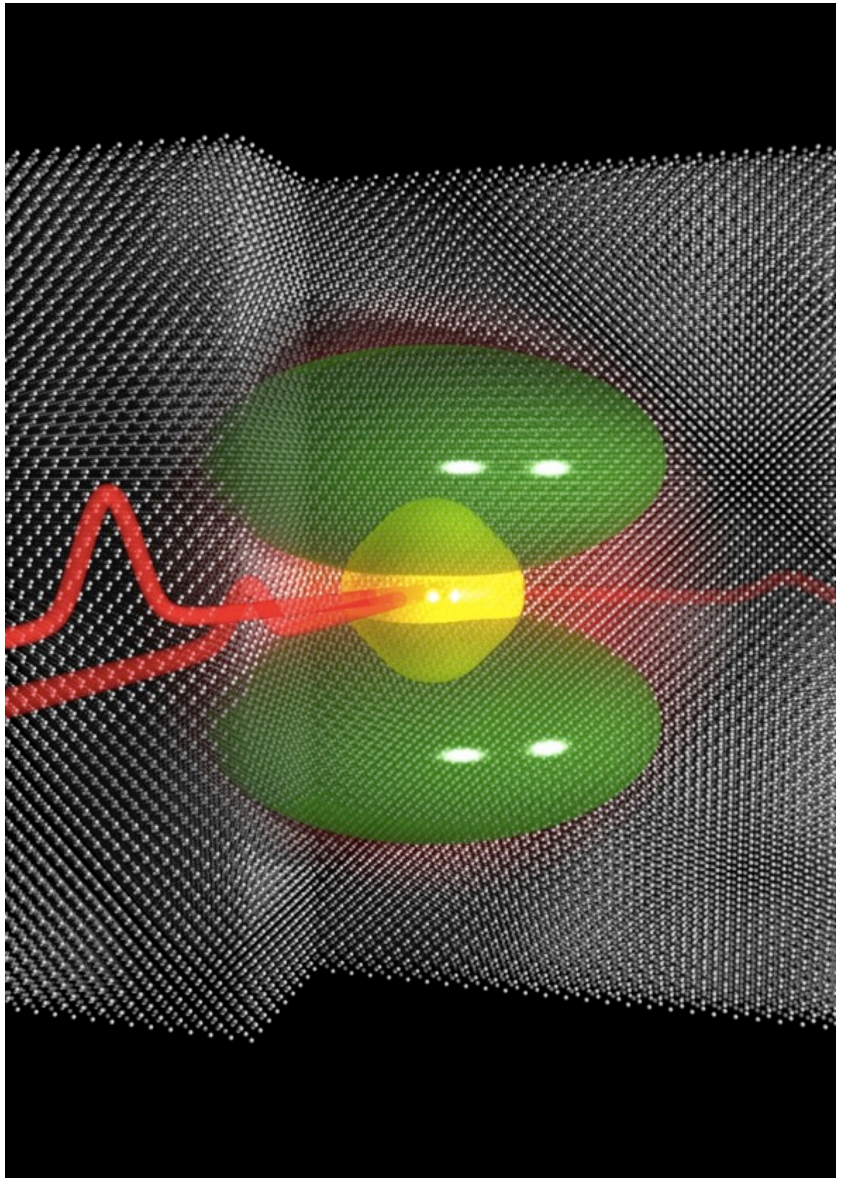


Donor impurities in silicon as a platform for few-body problems:

Donor excitation and donor-donor interactions

Ben Murdin,
Advanced Technology Institute,
University of Surrey, Guildford, UK

www.addrfss.net

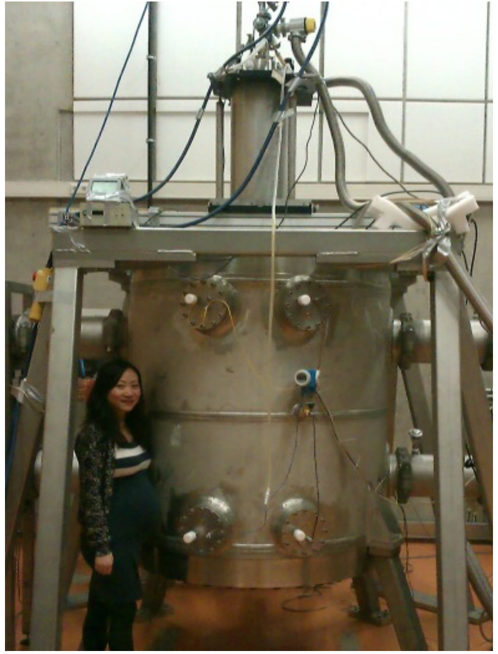
www.compasss.net

Gemma Chapman, Nguyen Le, Steve Chick,
Konstantin Litvinenko, Steve Clowes
James Ingham, Jessica Smith,
Nathan Cassidy, Dave Cox, Roger Webb
University of Surrey, Guildford, England

Britta Redlich, Lex van der Meer, Hans Engelkamp, Peter
Chistianen, Kamy Saeedi, Nils Dessman, Viktoria Eless
Radboud University Nijmegen, The Netherlands

Neil Curson, Andrew Fisher
London Centre for Nanotechnology,UCL

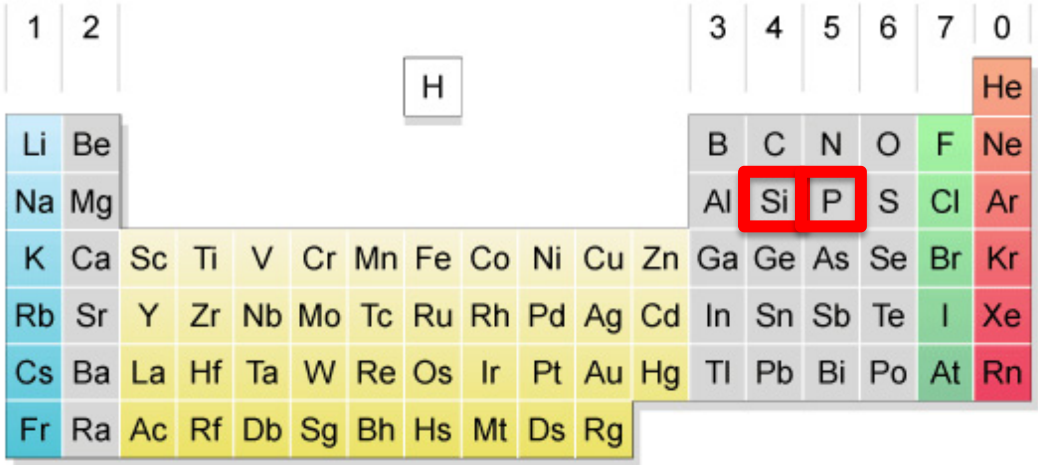
Carl Pidgeon,
Heriot Watt University, Edinburgh, Scotland



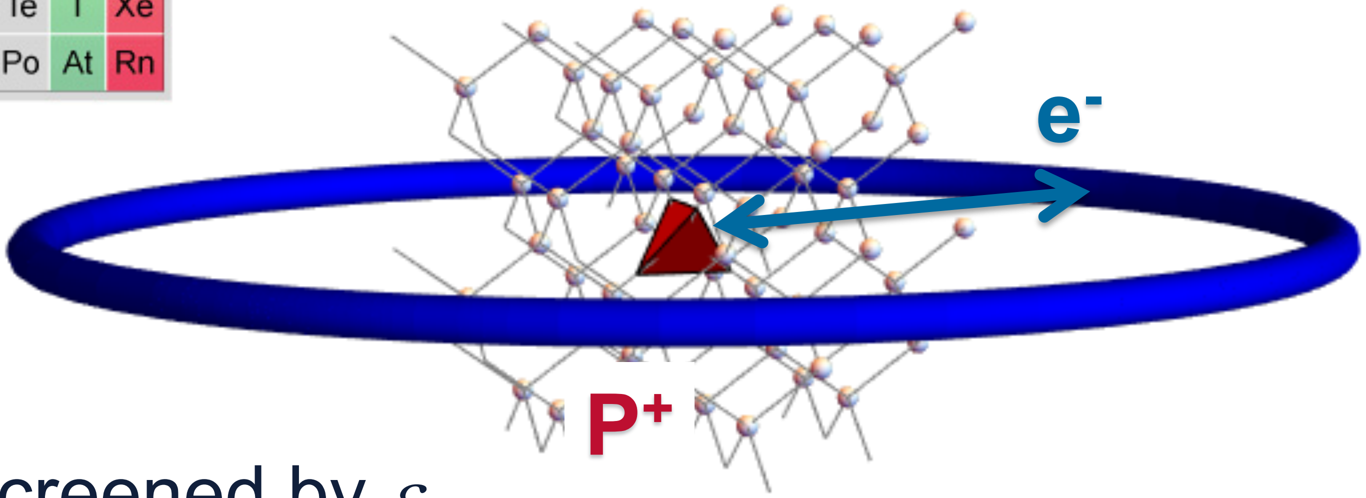
Physics of isolated single donors

Experiments with large ensembles

A hydrogen-like atom in a silicon chip: The Group 5 impurity



1	2											3	4	5	6	7	0
					H												He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg							



P looks like Si with

- an extra +ve charge in the ion
- an extra electron orbiting

The electron-ion attraction is screened by ε_r

The mass is reduced by m^*

Scaling from hydrogen to donor

- **Binding energy:**

$$E_R = \frac{1}{2}\left(\frac{e^2}{4\pi\hbar}\right)^2 \frac{m_e}{\varepsilon^2}$$

- **Bohr radius**

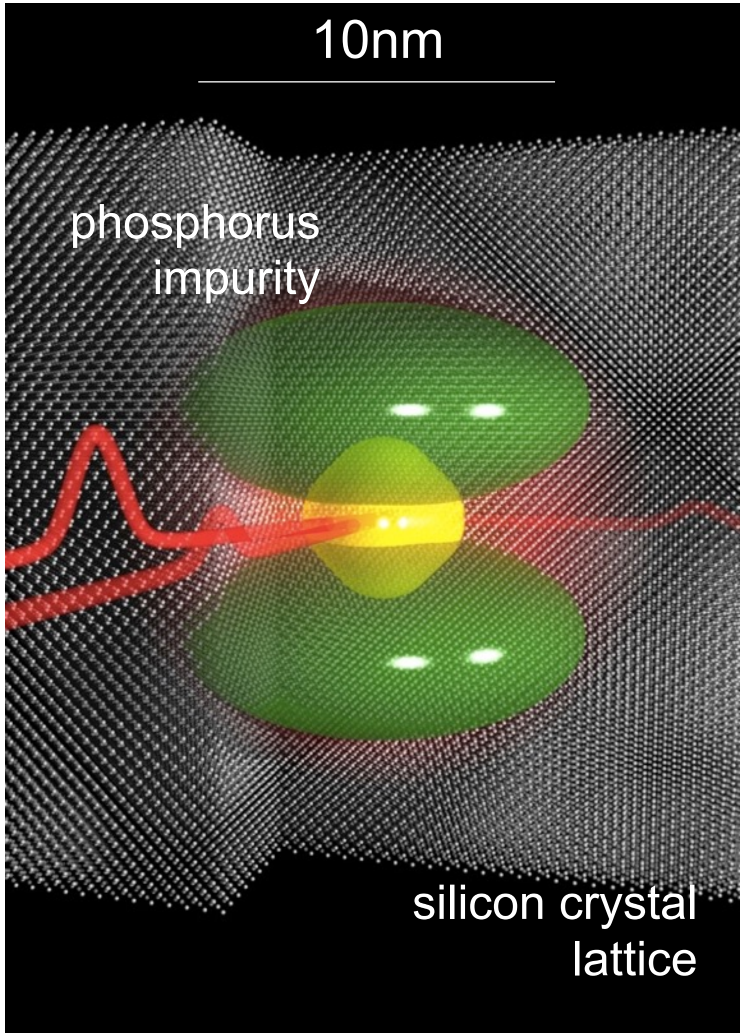
$$a_B = \frac{4\pi\hbar^2}{e^2}\frac{\varepsilon}{m_e}$$

	H	**Si:P**
ε_r	1	11.4
m_e	1	0.19
E_R	13.6 eV	0.020 eV
a_B	0.056 nm	3.2 nm

$$\lambda_0 = hc/E_R$$

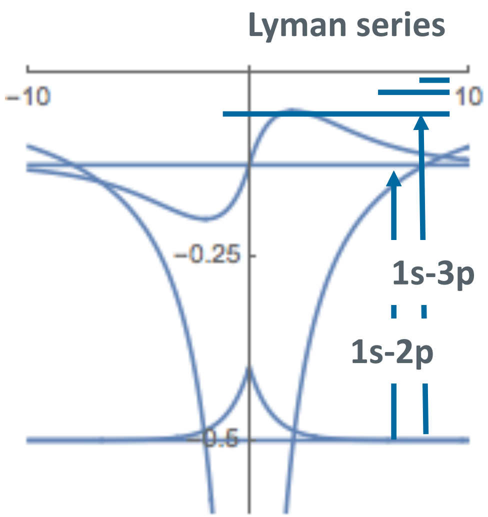
=71μm

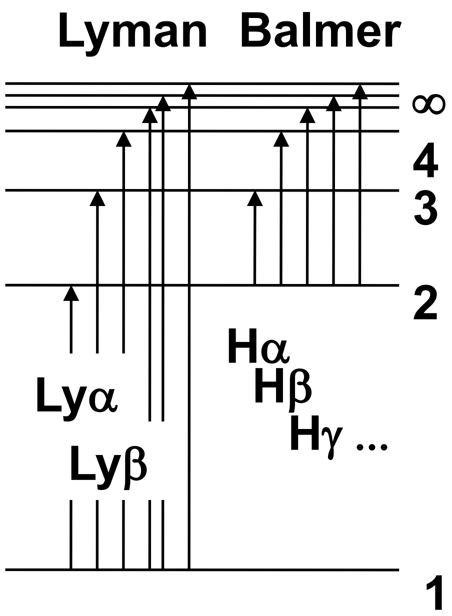
At room temperature the valence electron is donated to conduction, but at low temperature it is bound to the ion, just like hydrogen
The Coulomb attraction is reduced by the dielectric constant, so the binding energy is very small, and the state radius is very large

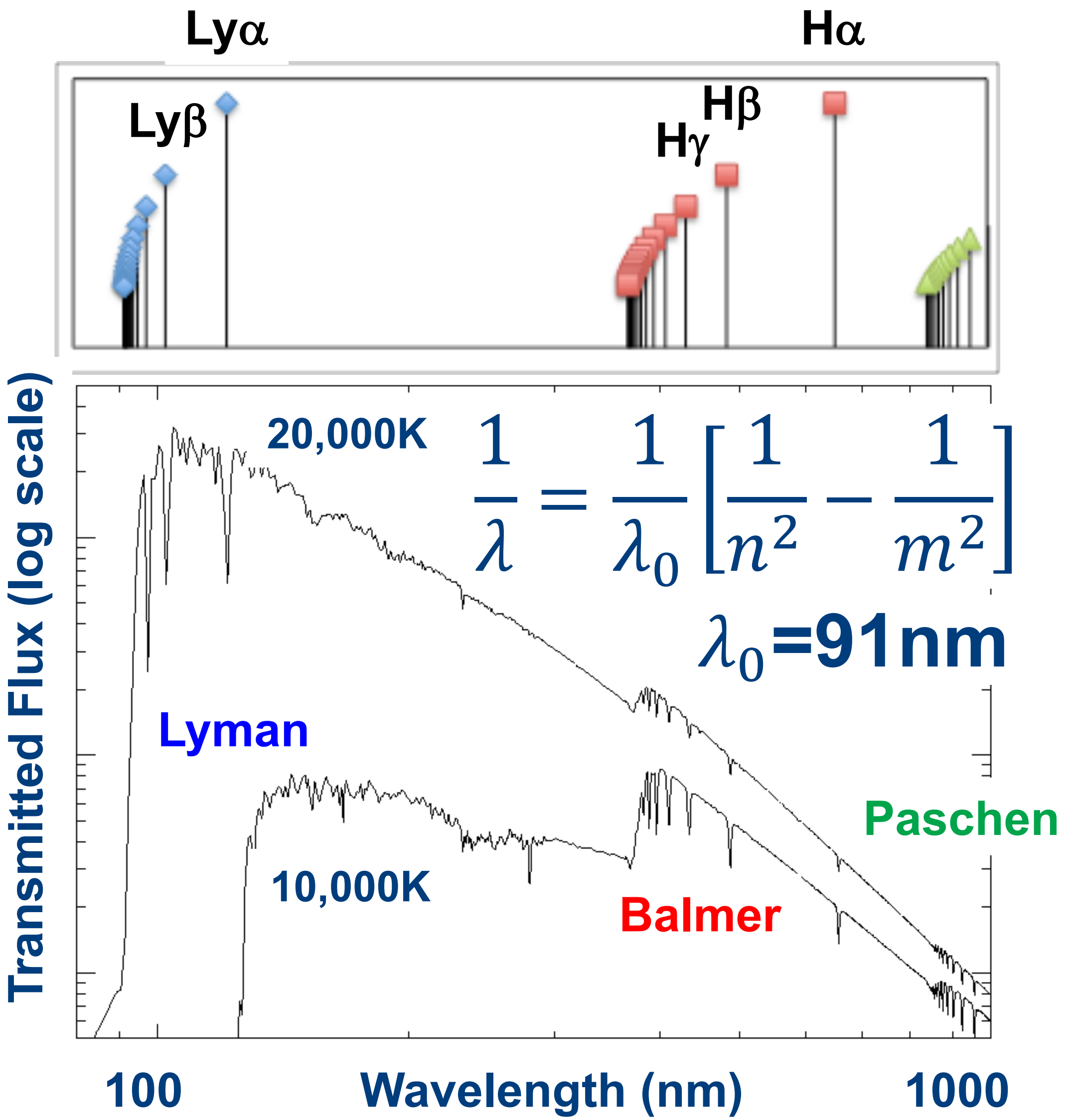


Rydberg spectrum of hydrogen

Hydrogen absorption spectrum seen superimposed on the emission from a very hot black body (a star)







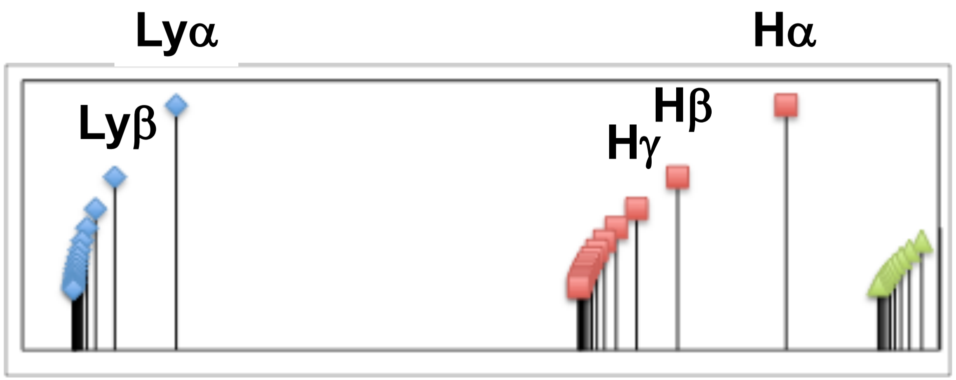
$$\frac{1}{\lambda} = \frac{1}{\lambda_0}\left[\frac{1}{n^2} - \frac{1}{m^2}\right]$$

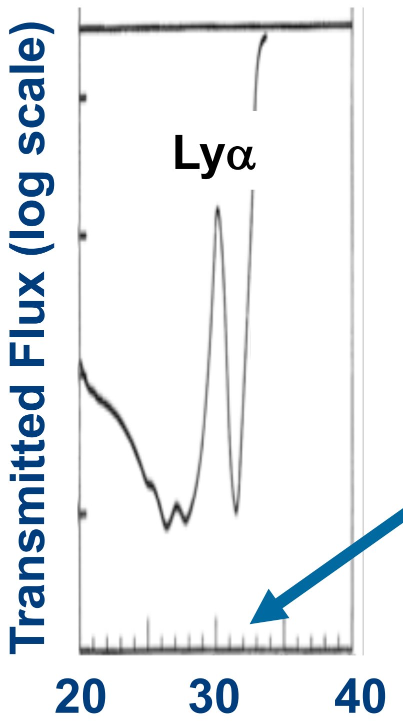
λ_0=91nm

Rydberg spectrum of Si:P

Picus, Burstein and Henvis (1956)

First transmission spectrum of Si:P

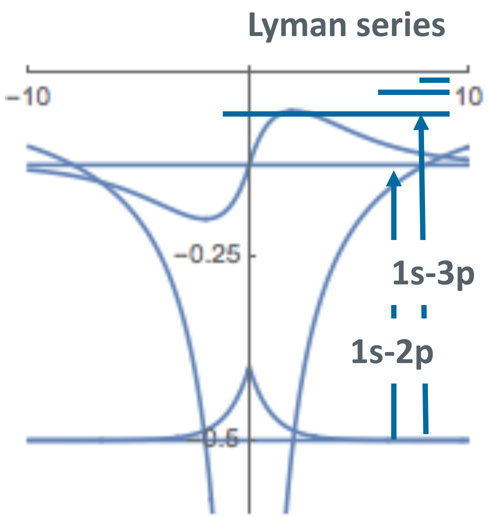


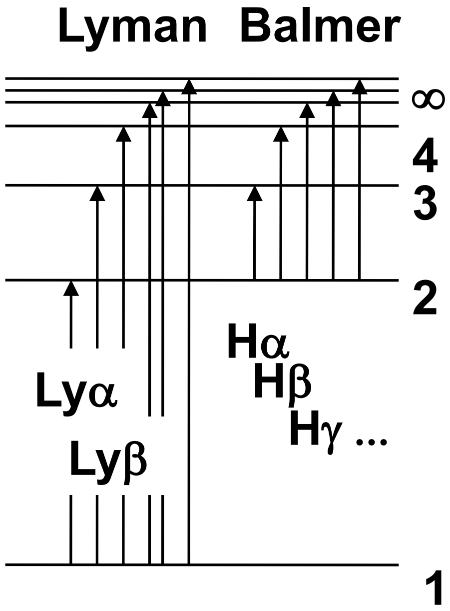


$$\frac{1}{\lambda} = \frac{1}{\lambda_0}\left[\frac{1}{n^2} - \frac{1}{m^2}\right]$$

$$\lambda_0 = 71\mu\text{m}$$

λ is somewhat larger than λ_0, just because of quantum defect (ground state is deeper than expected)

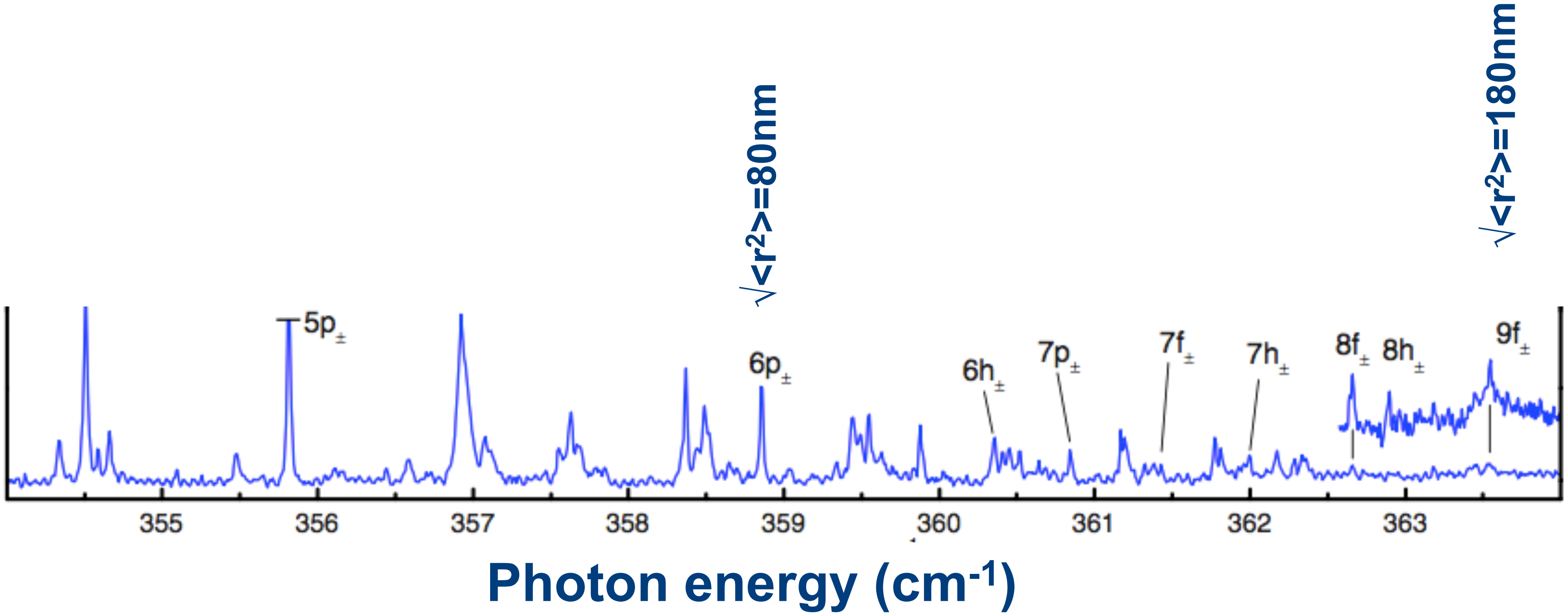




Lyman series spectrum of ^{28}Si:P

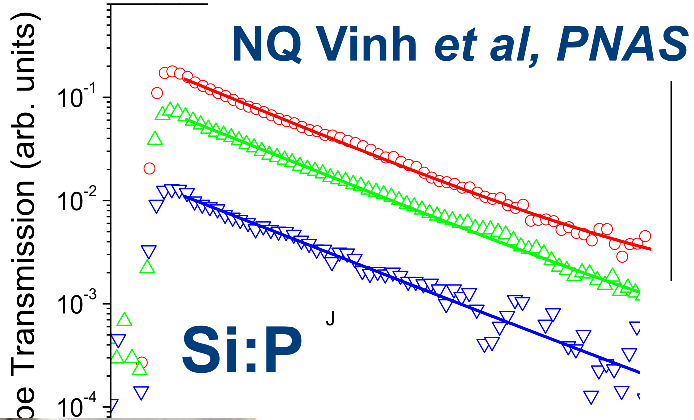
Steger PhysRevB.79.205210 (2009)

The cleanest solid material in the universe?



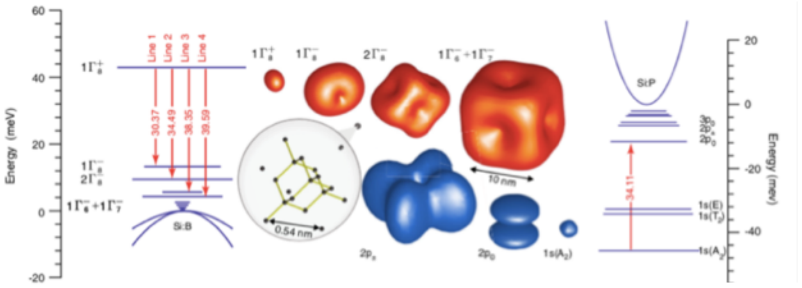
The THz Lyman lines are very sharp, so the lifetimes are very long

INCOHERENT dynamics – orbitals are long lived

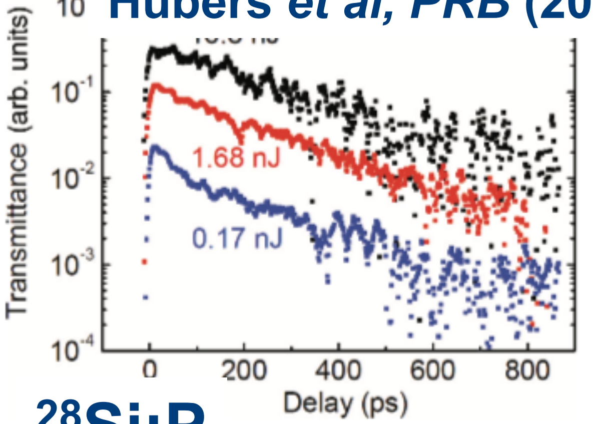


NQ Vinh *et al, PNAS* (2008)

Si:P

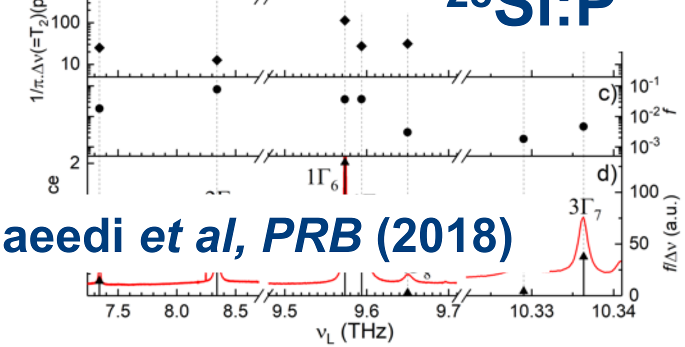


NQ Vinh *et al, PRX* (2013)



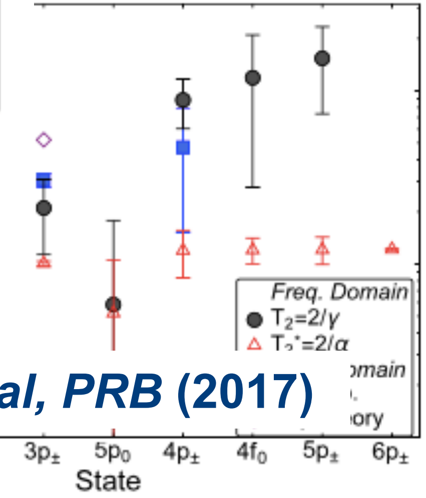
Hubers *et al, PRB* (2013)

Si:Bi



^{28}Si:P

Saeedi *et al, PRB* (2018)



Stavrias *et al, PRB* (2017)

The silicon environment is very clean, so the excitations are coherent

Coherent dynamics – orbitals can be controlled coherently

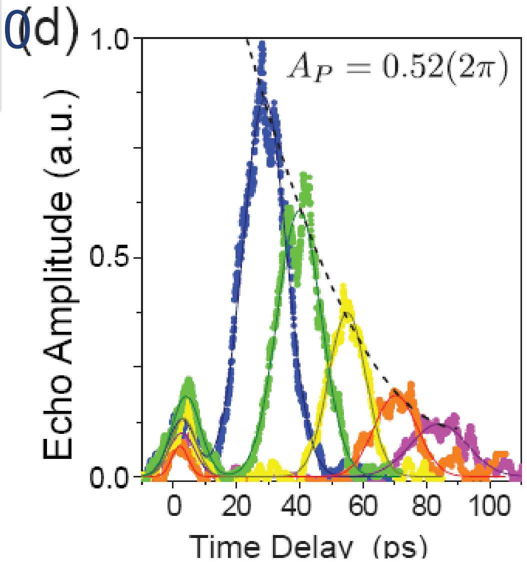
The Economist

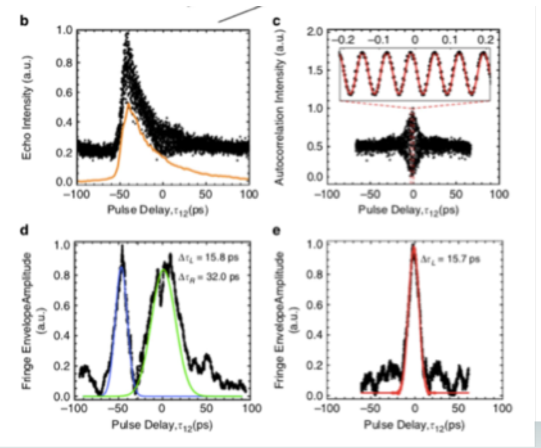
Quantum computing

A quantum hop

Greenland et al, (2010)

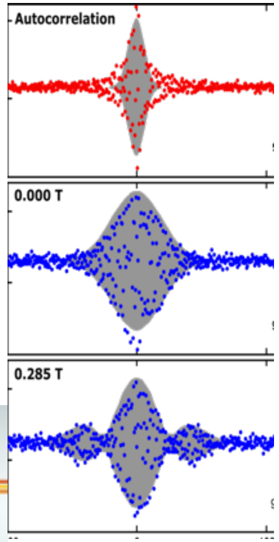
nature International weekly journal of science

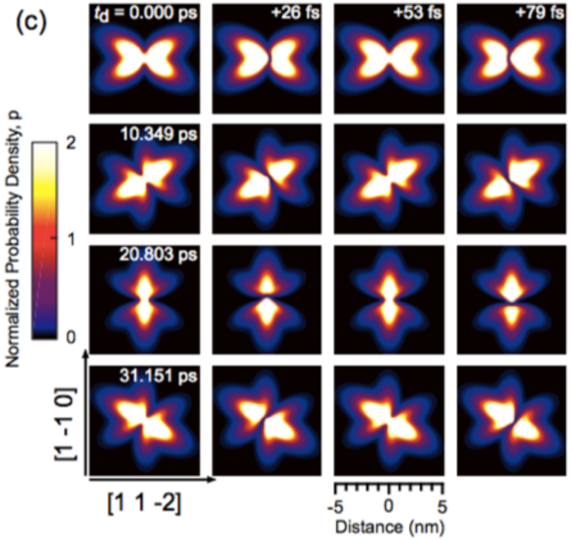




Litvinenko et al (2017)

nature COMMUNICATIONS





Chick et al (2017)

nature COMMUNICATIONS

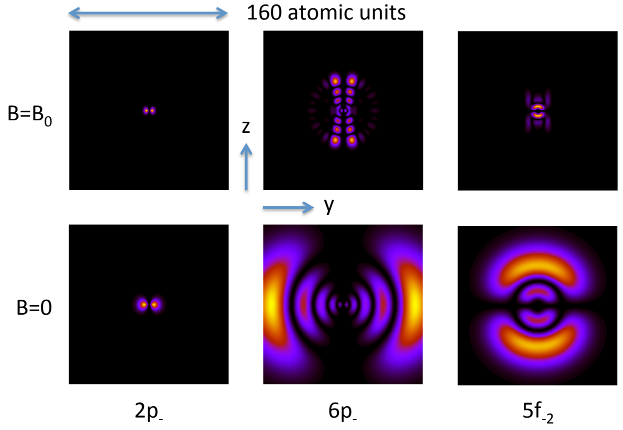
Extreme diamagnetic response to magnetic fields

Murdin et al, (2013) Nature Communications 4, 1469

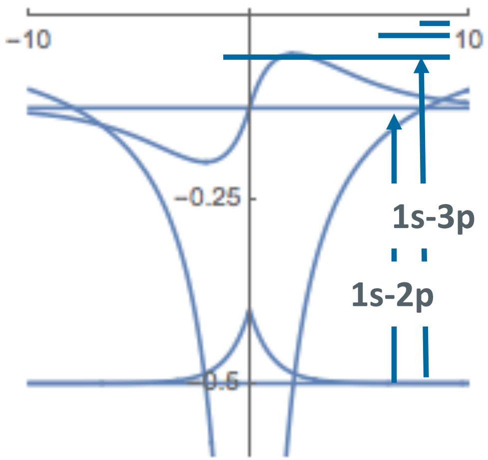
- **The atomic unit of magnetic field**

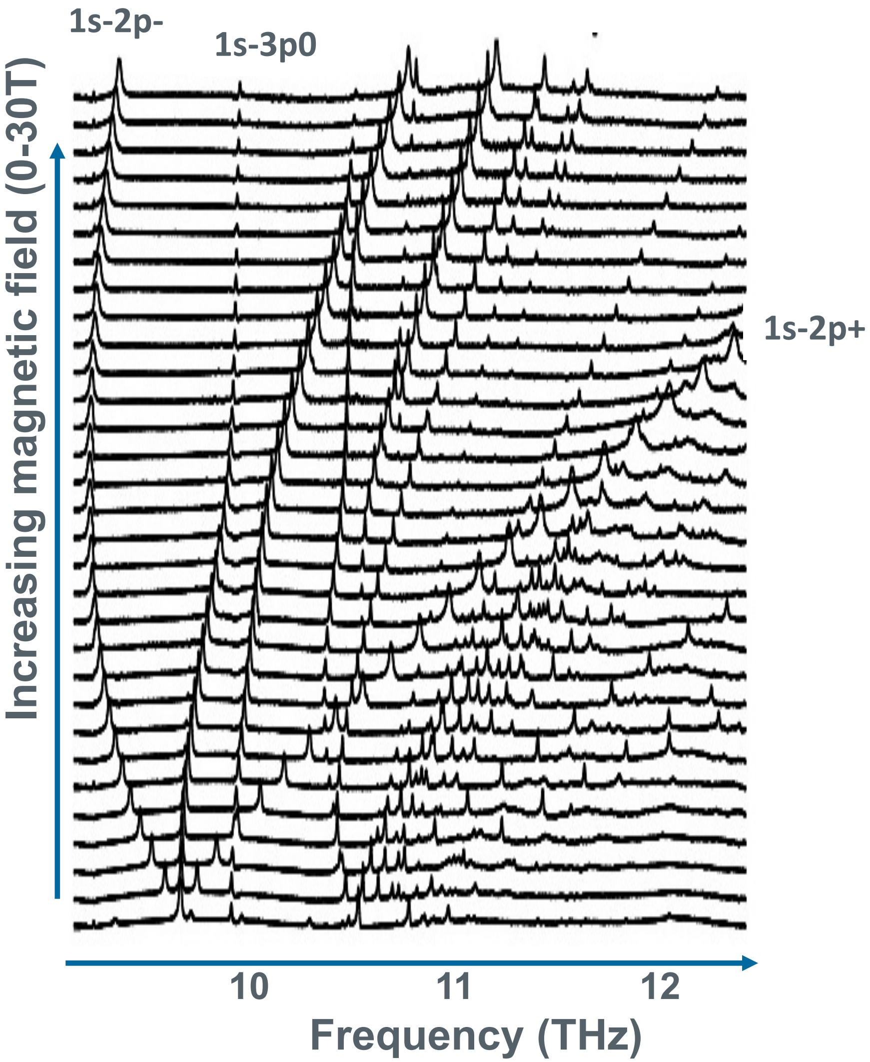
$$B_a = \hbar/(e a_B)^2$$

	H	Si:P
ε_r	1	11.4
m_e	1	0.19
E_R	13.6 eV	0.020 eV
a_B	0.056 nm	3.2 nm
B_a	235,000 T	64 T



Lyman series





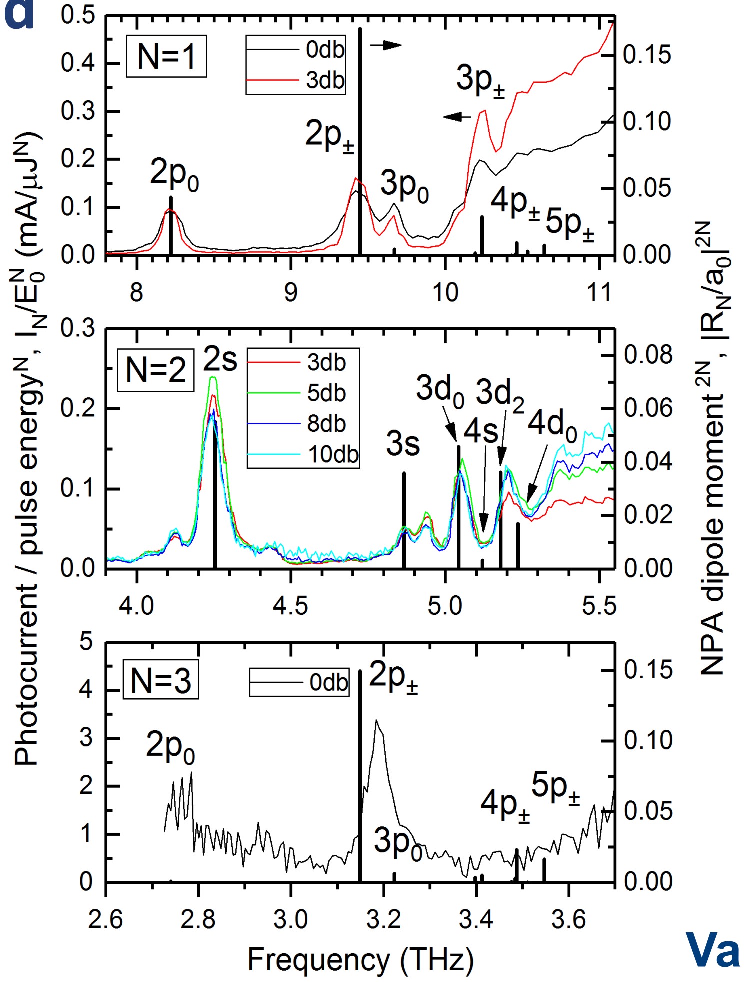
The donor THz dipole moments are very large

The absorption cross-sections of donors are very large (few nm² for silicon, many nm² for germanium)

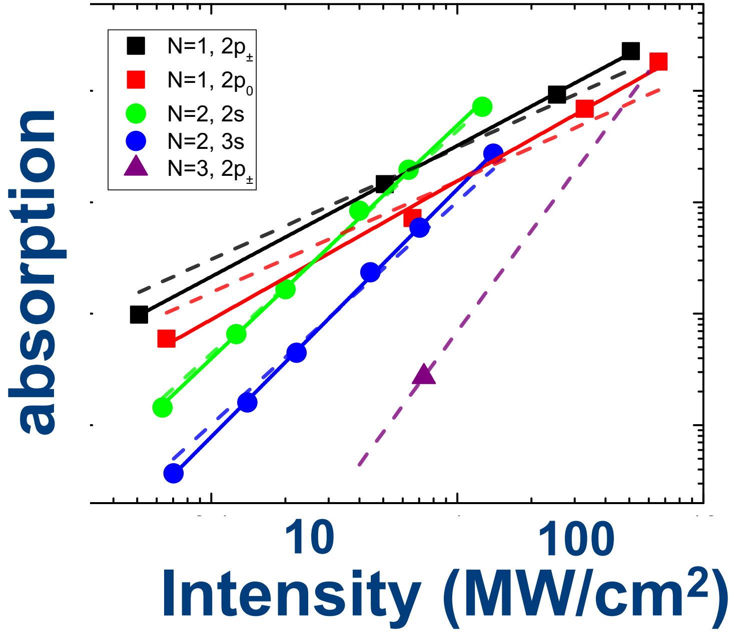
- **The atomic unit of electric field**

$$F_a = E_H/\hbar a_B$$

	H	Si:P
ε_r	1	11.4
m_e	1	0.19
E_R	13.6 eV	0.020 eV
a_B	0.056 nm	3.2 nm
B_a	235,000 T	64 T
F_a	5.1 GVcm^{-1}	130 kVcm^{-1}



1PA∝Intensity
2PA∝Intensity^2
3PA∝Intensity^3



Van Loon et al (2018)

nature photonics

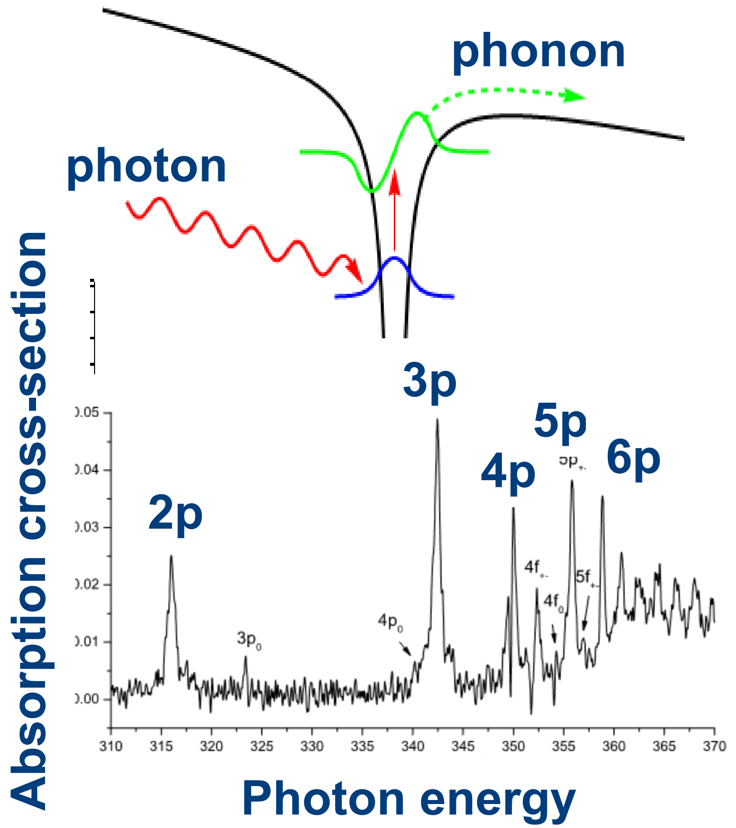
Scaling down to the single/few atom limit

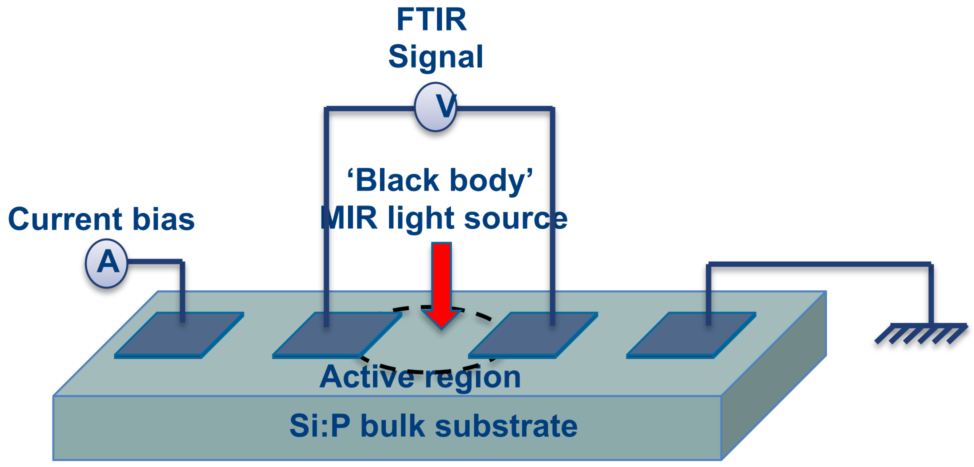
Achievements and problems

Atomic Physics in the solid state – take advantage of microelectronics!

Donors have benefit over atoms in vacuum that they can be electrically read-out (with some violence) without the atom being kicked to kingdom come!

Electrical detection of donor Lyman lines through photoconductivity
[=Photo-thermal Ionization Spectroscopy (PTIS)]

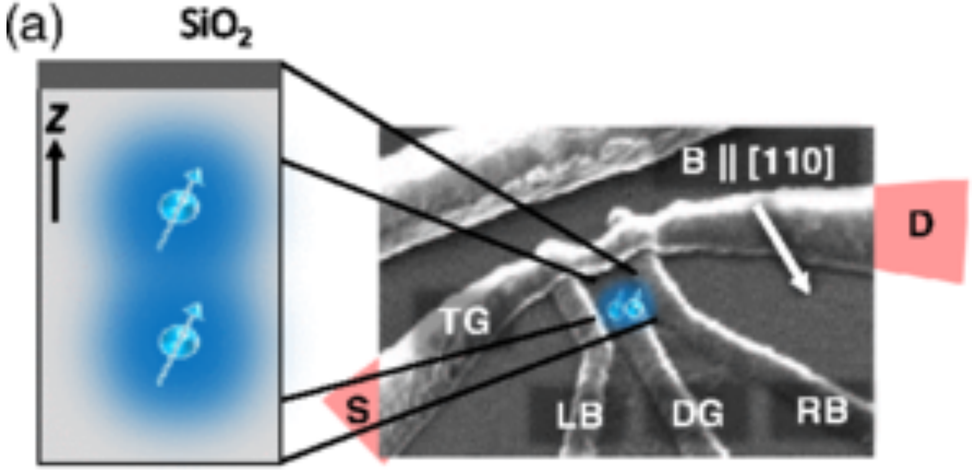


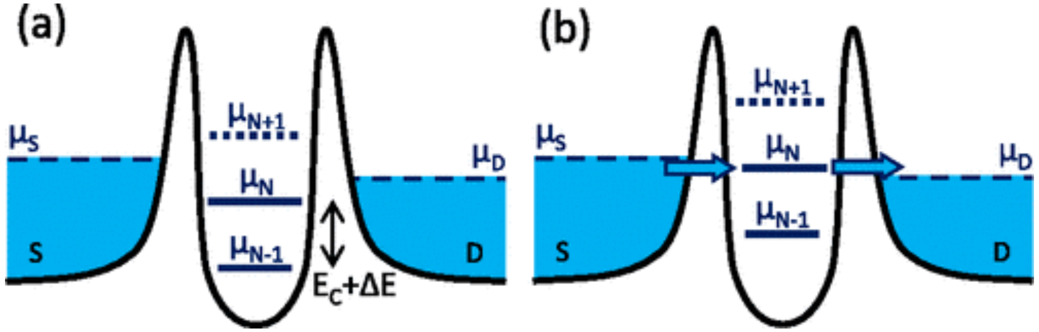


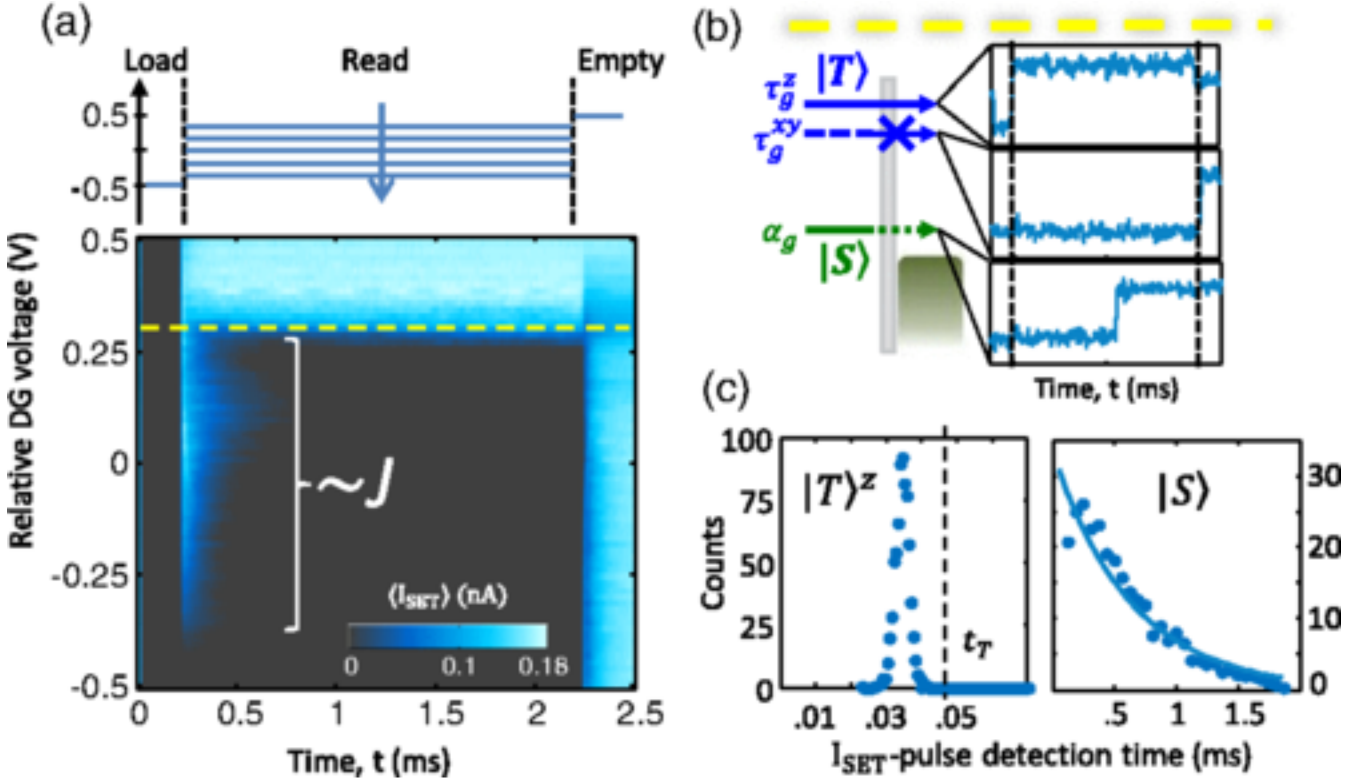
We have detected as few as 10^4 donors …

Scaling down detection/readout to single atoms

Single-Shot Readout and Relaxation of Singlet and Triplet States in Exchange-Coupled 31P Electron Spins in Silicon
Andrew S. Dzurak, and Andrea Morello group UNSW
Phys. Rev. Lett. **112**, 236801 (2014)

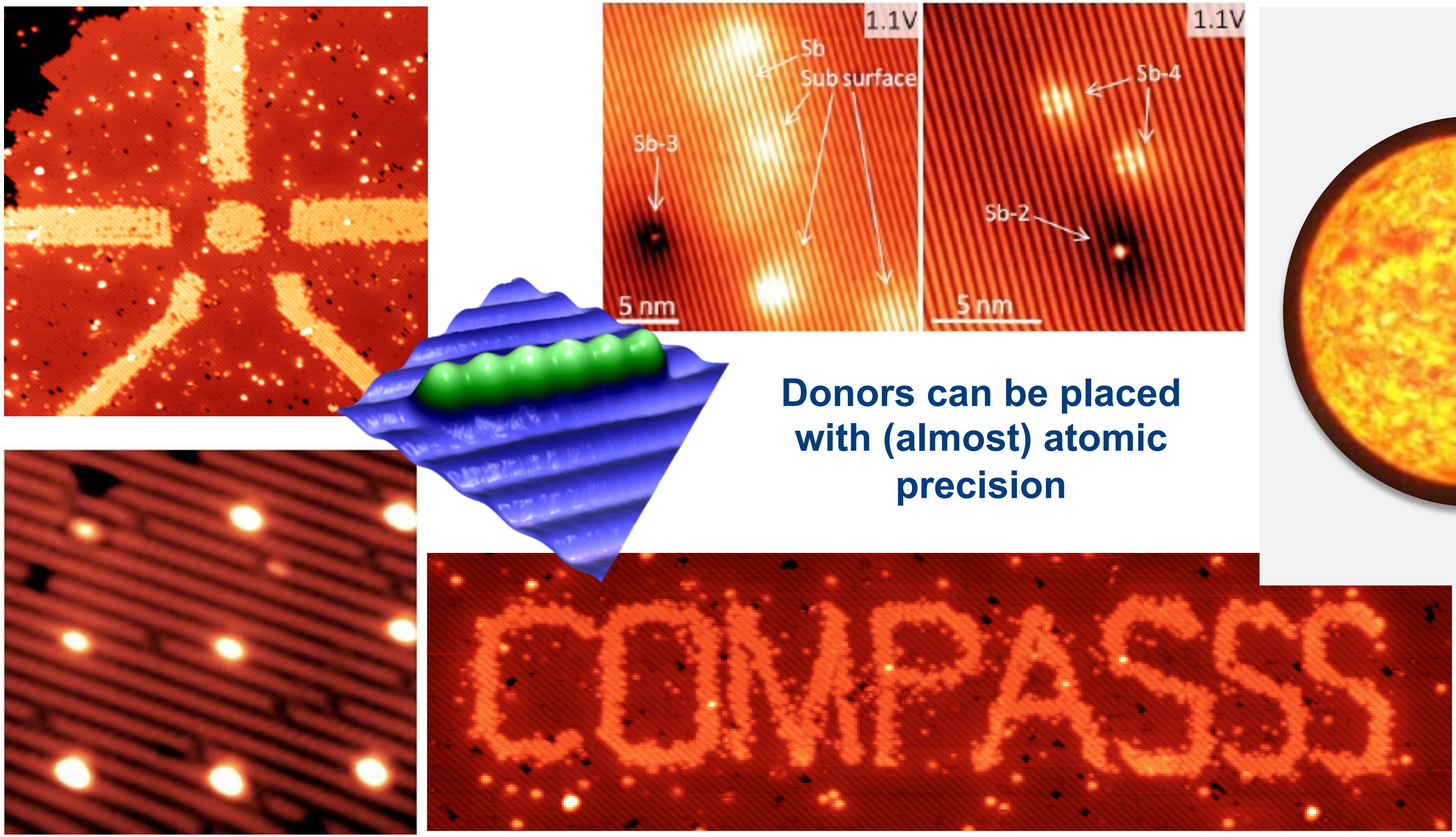




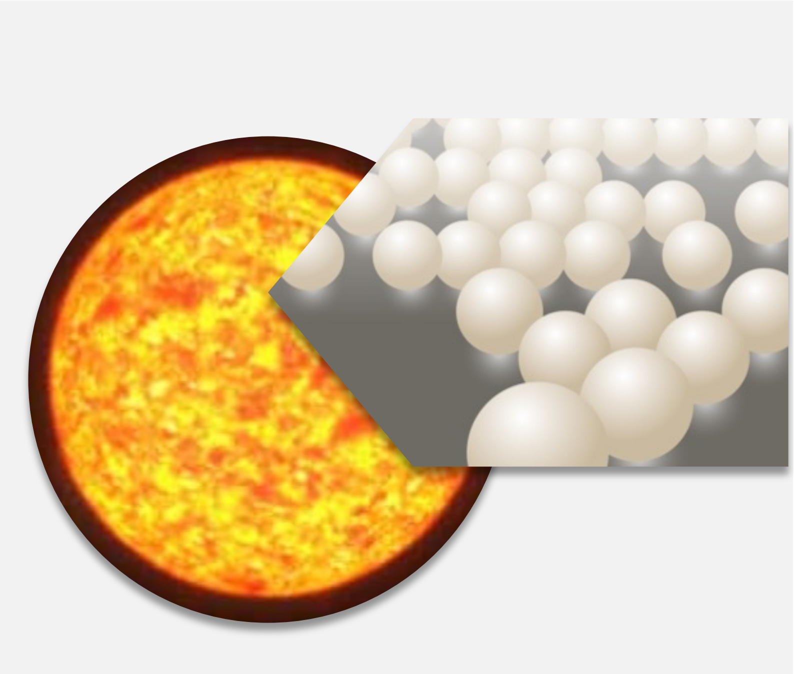


Single atom P positioning with H lithography in Si [collaborators at UCL]

SR Schofield et al, Nature Commun 4, 1649 (2013)

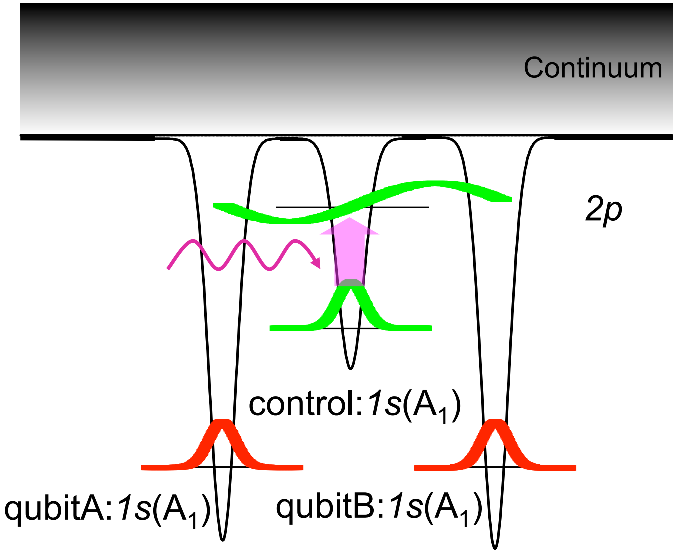


Donors can be placed with (almost) atomic precision



Importance of Si:P QIP

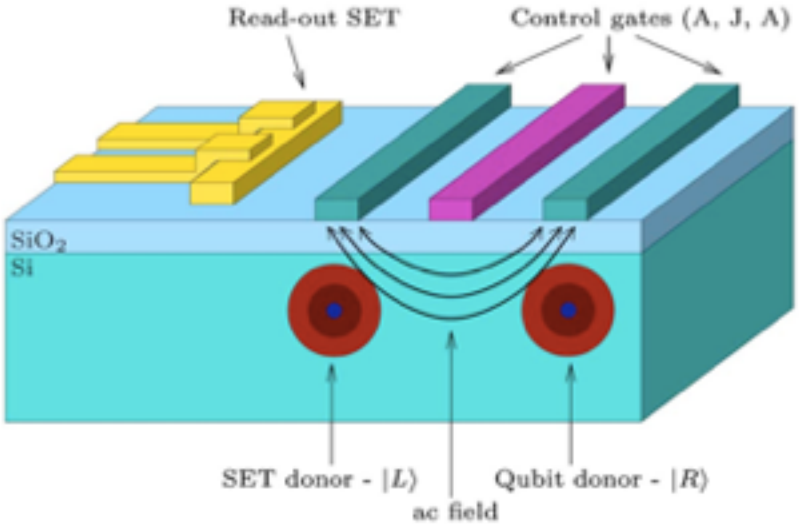
Stoneham-Fisher-Greenland scheme: THz gated entanglement/ control/gating between qubits



e.g. Bi e.g. P

A. M. Stoneham *et al*, *J. Phys. C*, *15, L447, 2003.*

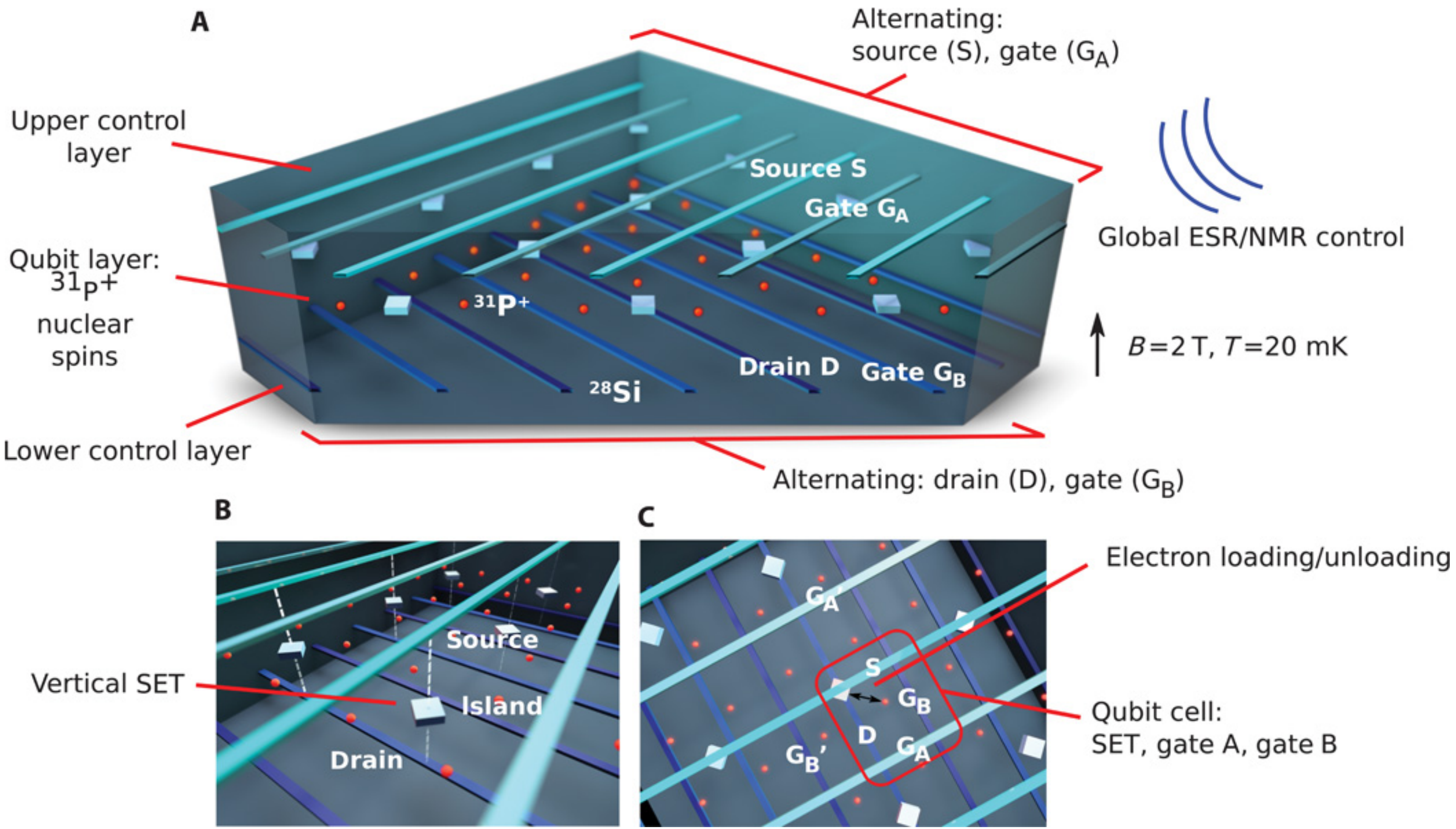
Kane/Hollenberg scheme: THz induced spin-to-charge conversion between qubit and SET donors

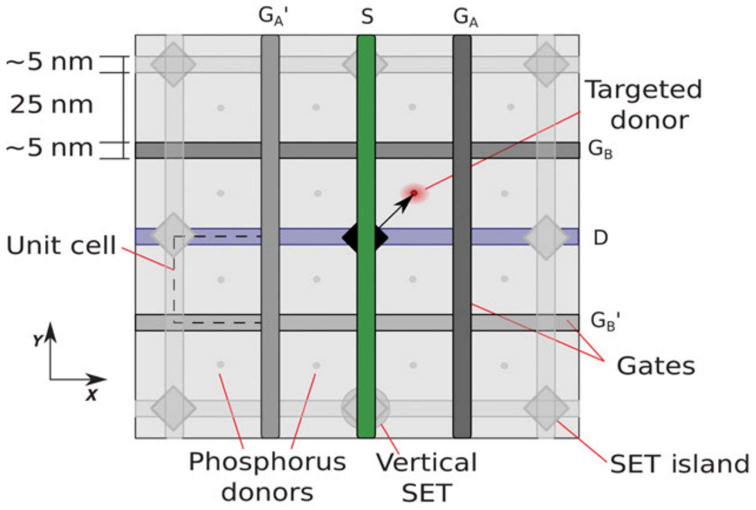


L.C.L.Hollenberg et al
***Phys.Rev.B* 69, 233301 (2004)**

Large scale silicon quantum computer architectures (I)

Some donor quantum computer architectures need very precise placement of atoms (few nm here)

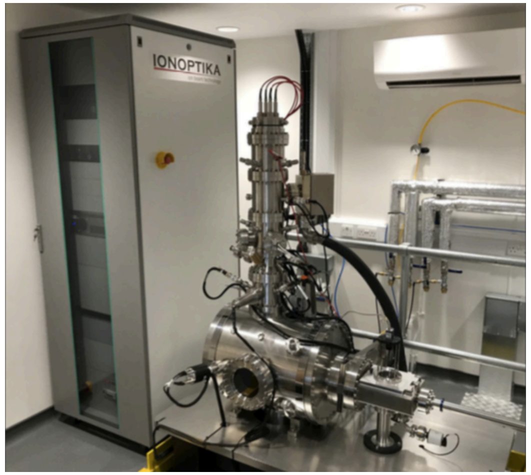




Melbourne/U NSW (Simmons group) [C. D. Hill et al *Science Advances* 2015: 1, e1500707]

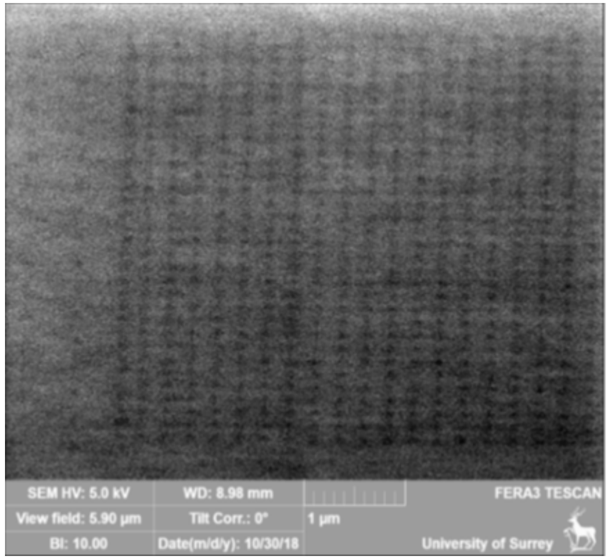
SIMPLE Single Ion Multispecies Positionig at Low Energy

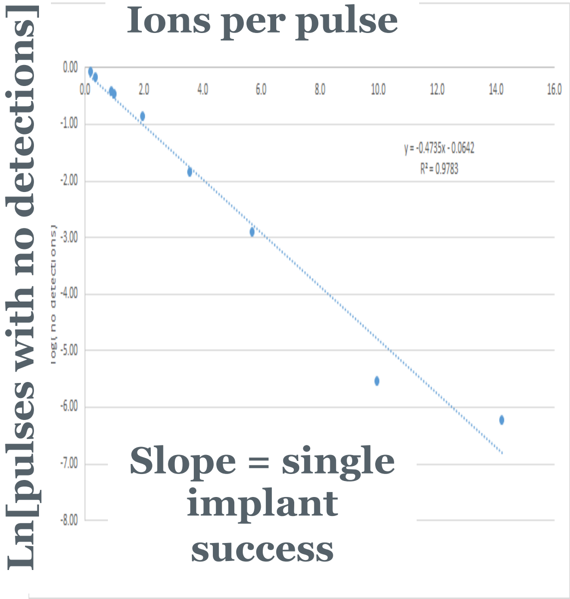
Ion beam implantation – Surrey Ion Beam Centre, Ionoptika Ltd and Manchester



- SIMPLE is a high precision single ion implantation tool specifically targeted at supporting solid-state quantum technologies.
- The aim is for the tool to be a scalable and repeatable manufacturing method for arrays of qubits for quantum processors.
- This is a system developed around a liquid metal ion gun (LMIG) designed to produce sub 20nm spatial resolution, and fire with absolute certainty of the number of ions implanted.

- Species available for Implantation: Au, Ge, Bi. In future, available species: Se, Si, B, In
- The tool has measured beam spotsizes below 20nm – which along with implant straggle, determine the uncertainty of ion positioning.
- Ions can be implanted with energies ranging from 15-25keV.



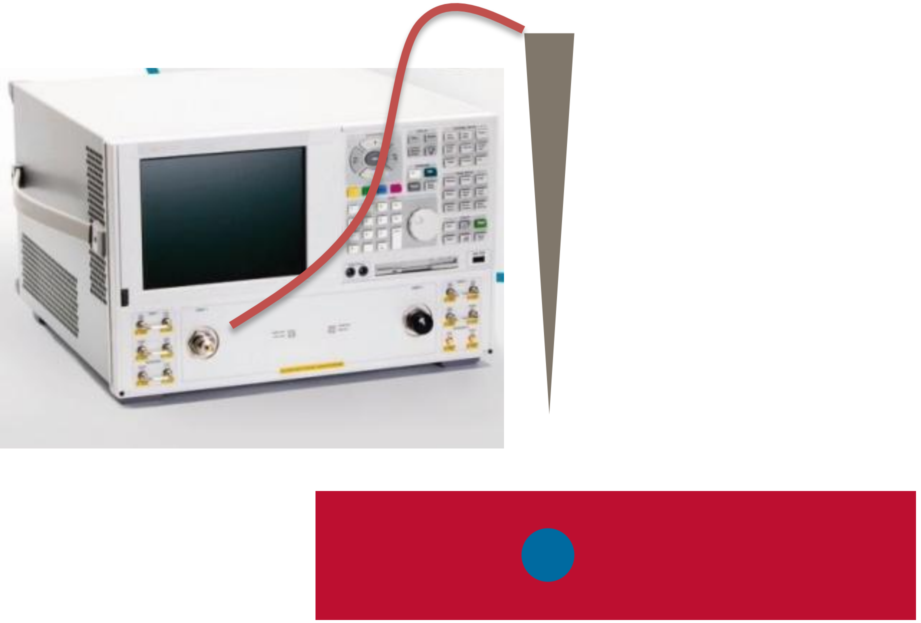


How do we see what we have made?

Scanning probe microscopy

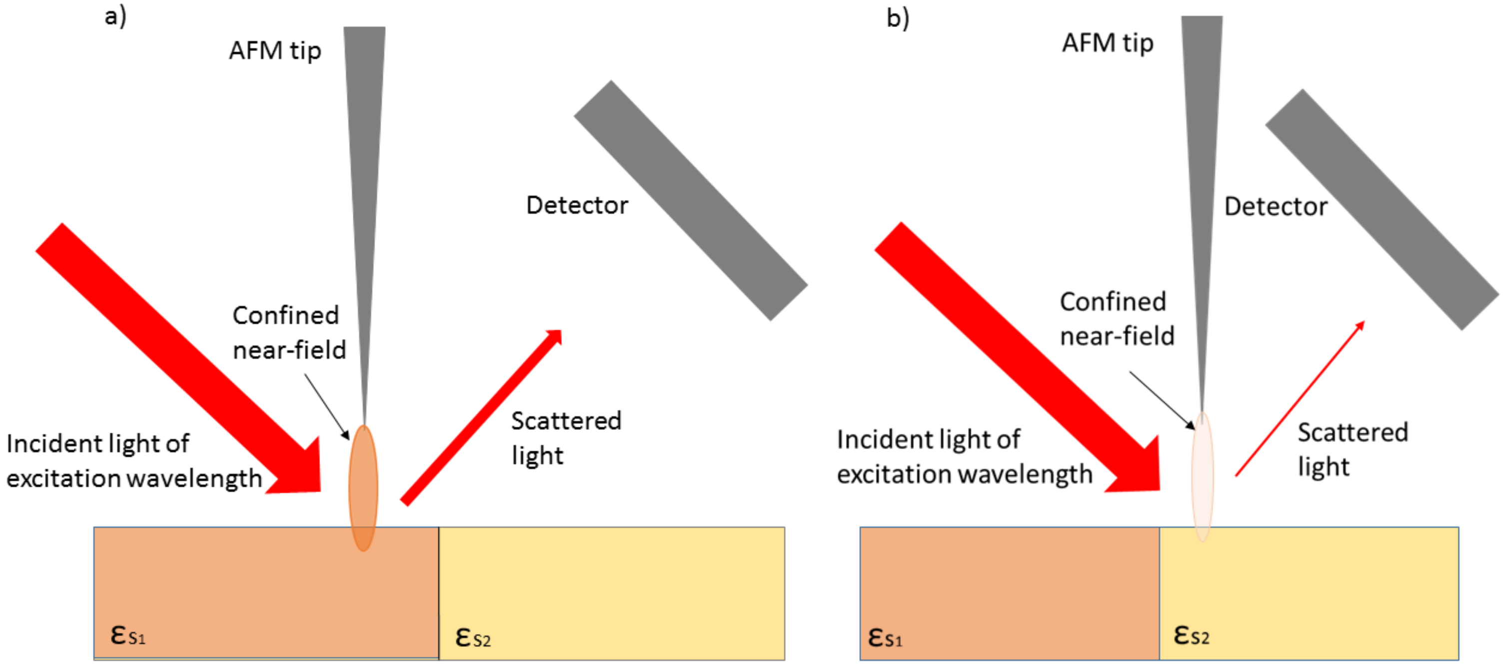
An AFM tip as a microwave antenna

Scanning Microwave microscopy (SMM)



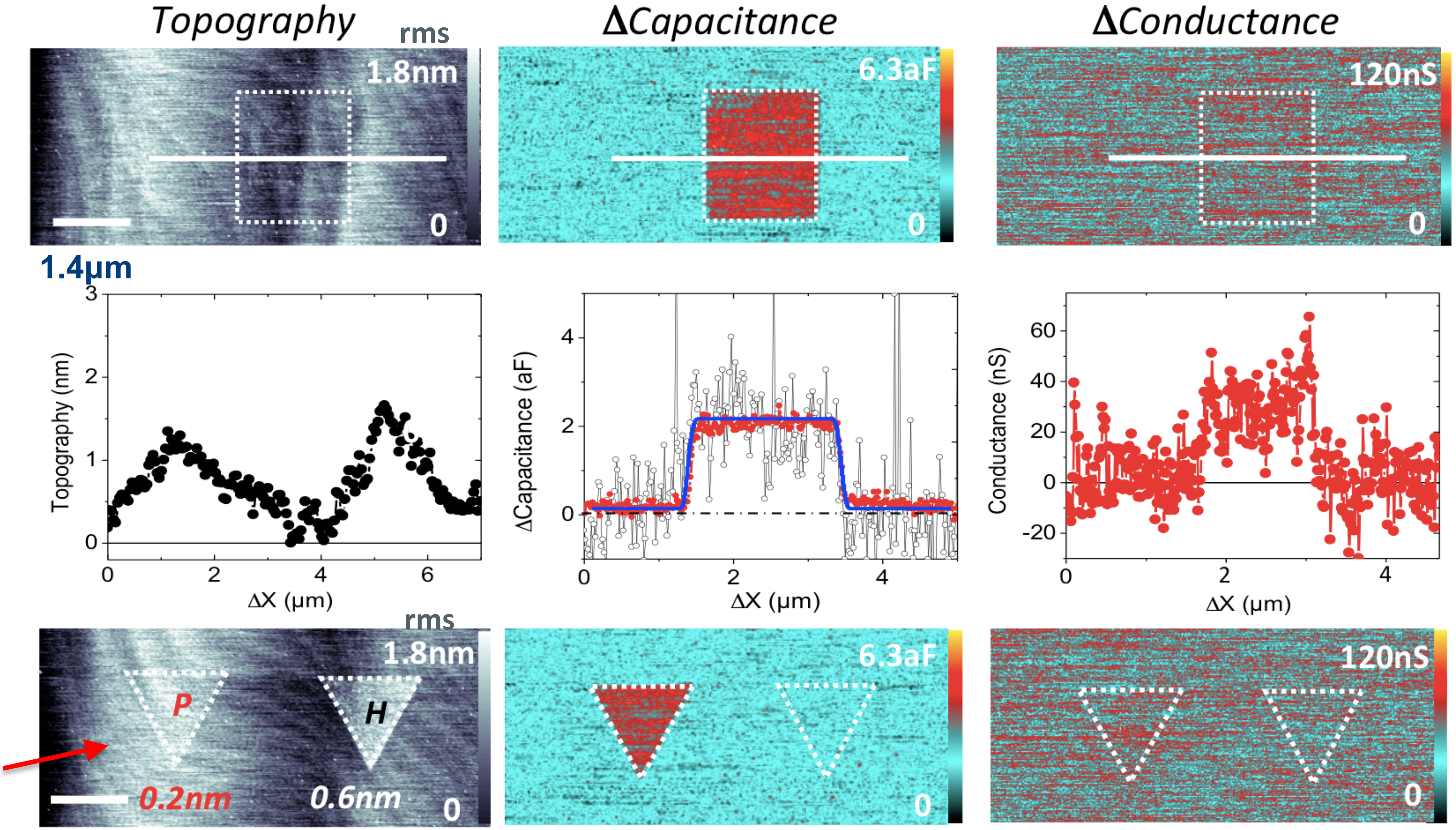
An AFM tip as a near-field scatterer

Scattering-Scanning Near-field Optical Microscopy (s-SNOM)



SMM measurements of buried P resonators and ribbons/wires

G. Gramse, et al Science Advances (Jun 2017) 10.1126/sciadv.1602586



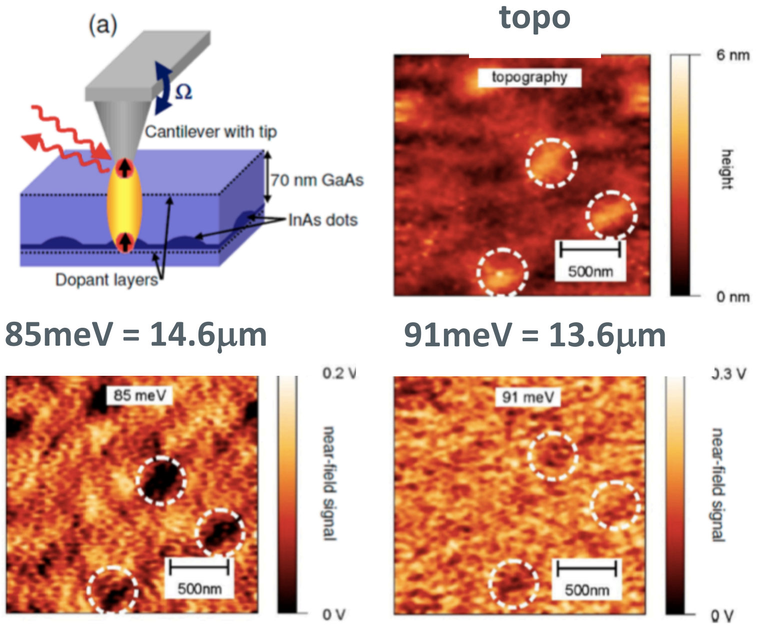
Scale bar = 1.4μm

After lithography and 15nm Si encapsulation. P triangle has incorporated phosphorus; H does not

SMM is good for large conductors, but NOT single qubit level

Single InAs quantum dots have been observed with THz SNOM

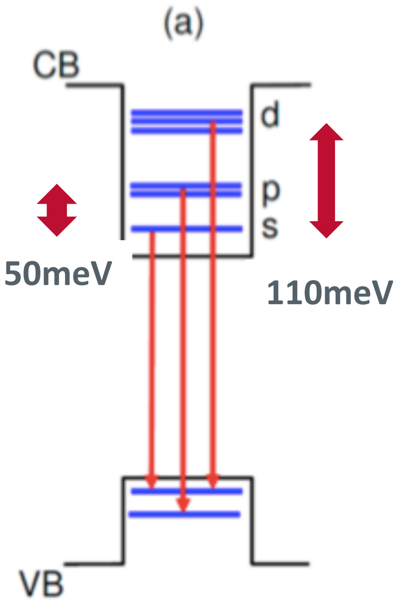
The dipole moment of the s-p inter-sub-level transition in c.b. of a dot is about the same as for a donor



topo

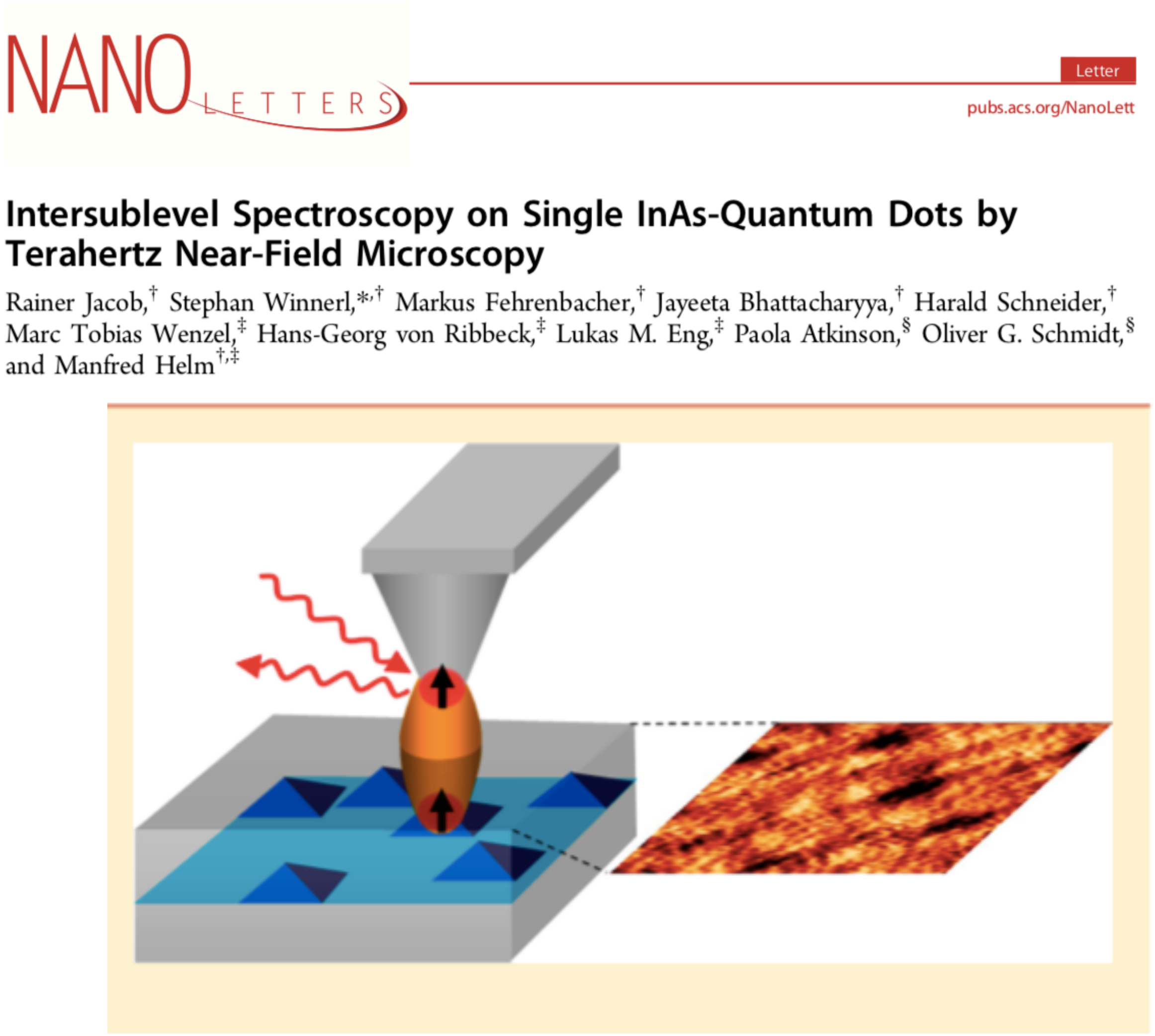
85meV = 14.6µm

91meV = 13.6µm



50meV

110meV

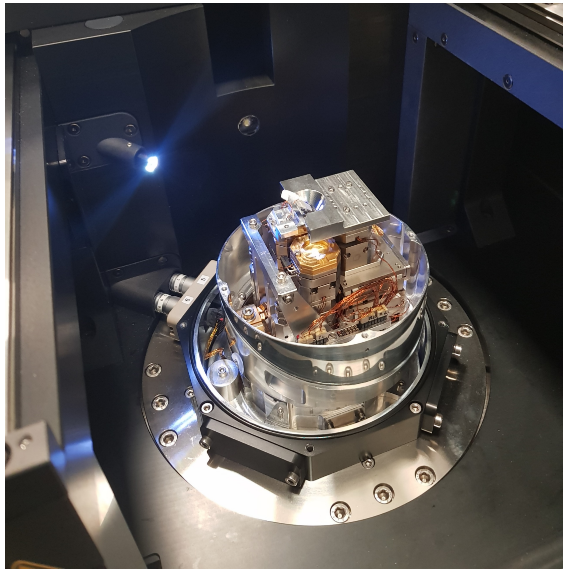

NANO LETTERS
Letter
pubs.acs.org/NanoLett

Intersublevel Spectroscopy on Single InAs-Quantum Dots by Terahertz Near-Field Microscopy

Rainer Jacob,[†] Stephan Winnerl,[*,†] Markus Fehrenbacher,[†] Jayeeta Bhattacharyya,[†] Harald Schneider,[†] Marc Tobias Wenzel,[‡] Hans-Georg von Ribbeck,[‡] Lukas M. Eng,[‡] Paola Atkinson,[§] Oliver G. Schmidt,[§] and Manfred Helm[†,‡]

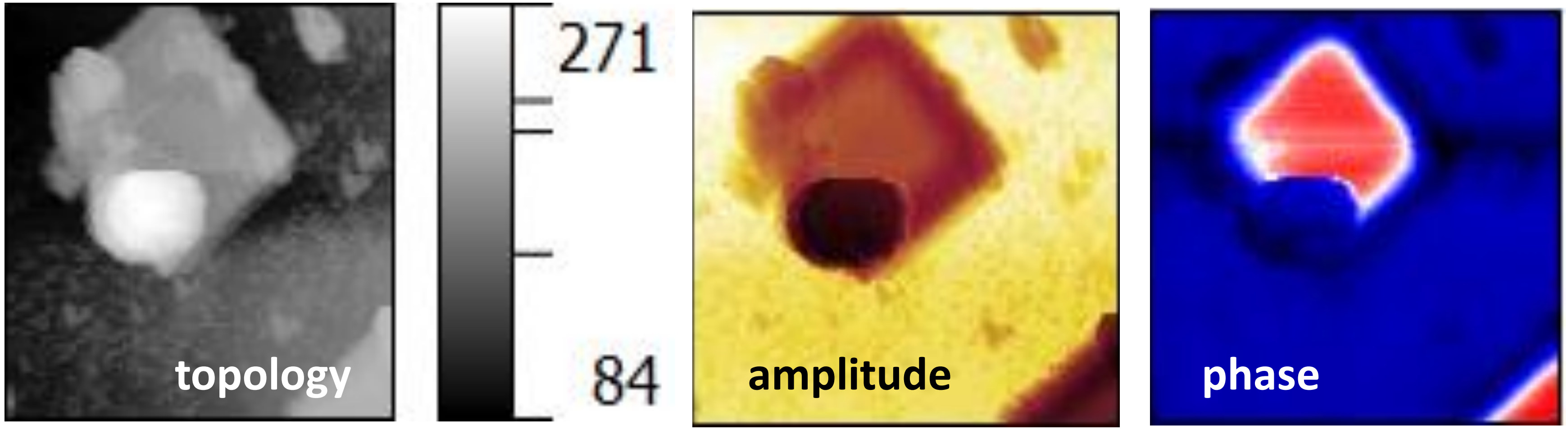
Low temperature (10K) THz scanning SNOM Neaspec at Surrey

- 8 um QCL light source
- Base temperature 5.5K
- Best resolution so far 30nm (tip dependent)
- Interferometric detection (sample/tip is one arm of Michelson) gives amplitude and phase (related to real/imaginary parts)



Test with Si/SiO2 grid with dust speck

Note different contrast with topography/amplitude/phase indicates real SNOM effect



Outlook

- Silicon donors have interesting (extreme) properties (giant diamagnetism, giant non-linearities etc)
- Silicon donors are promising candidates for qubits
- Donors can be placed in designer clusters, so the interactions can be controlled
- Mid-IR to THz transitions control the orbital motion (and provide a means to control interactions between qubits)
- SNOM provides a way to characterize qubit sample structures
- The combination of THz pulses with SNOM might provide a way to address single qubits
- A route to designer few-body physics problems