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Coherent control and electrical detection of charge excitations in hydrogenic silicon impurities with a Free Electron Laser

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Coherent Optical and Microwave Physics for Atomic Scale Spintronics in Silicon

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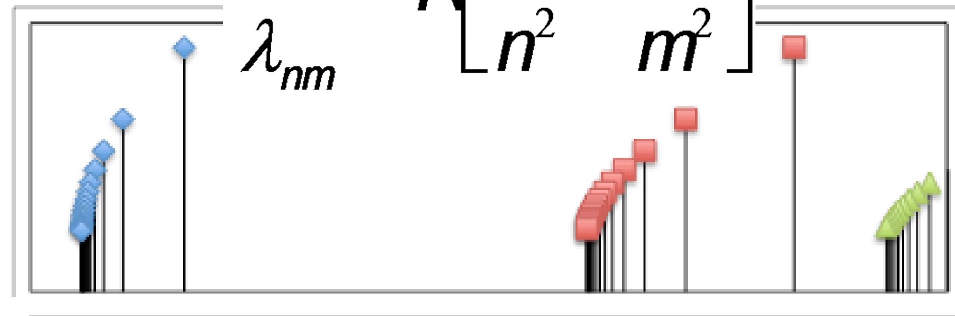
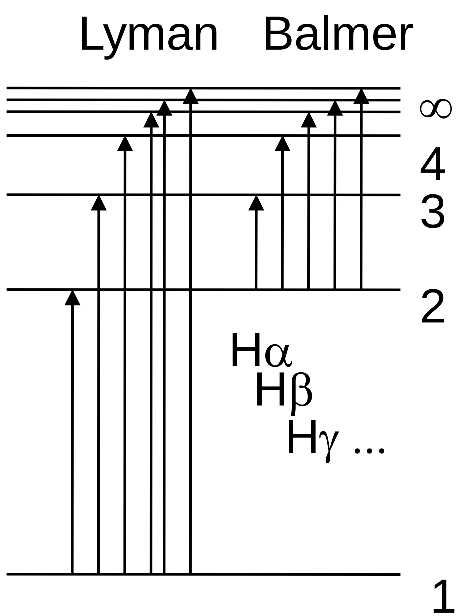
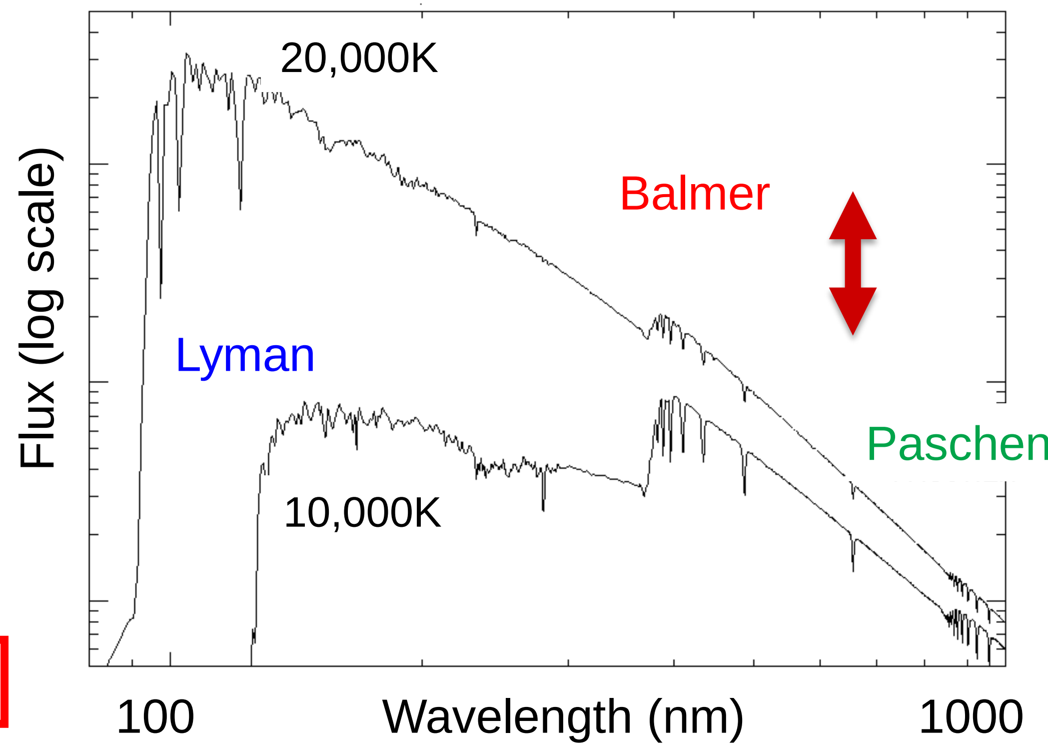
Rydberg spectrum of hydrogen

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

$$\frac{1}{\lambda_{nm}} = R\left[\frac{1}{n^2} - \frac{1}{m^2}\right]$$

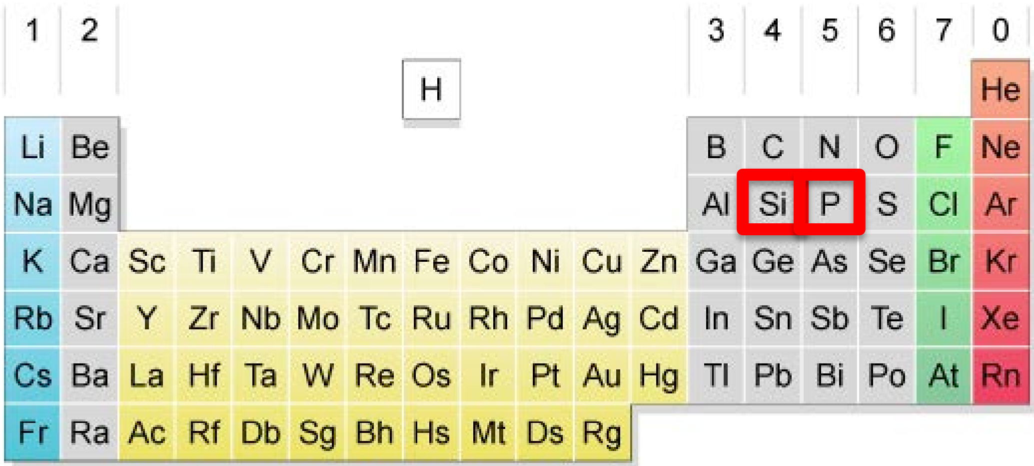


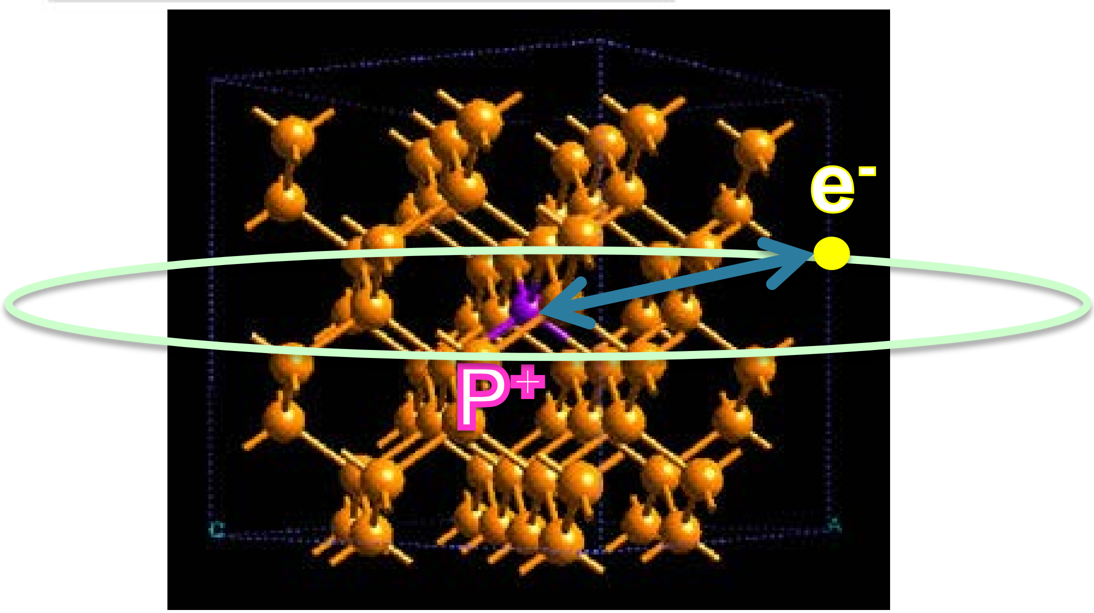




Hα line: E_3-E_2=$^5/_{36}$13.6eV≡ 656nm

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





- P looks like silicon 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

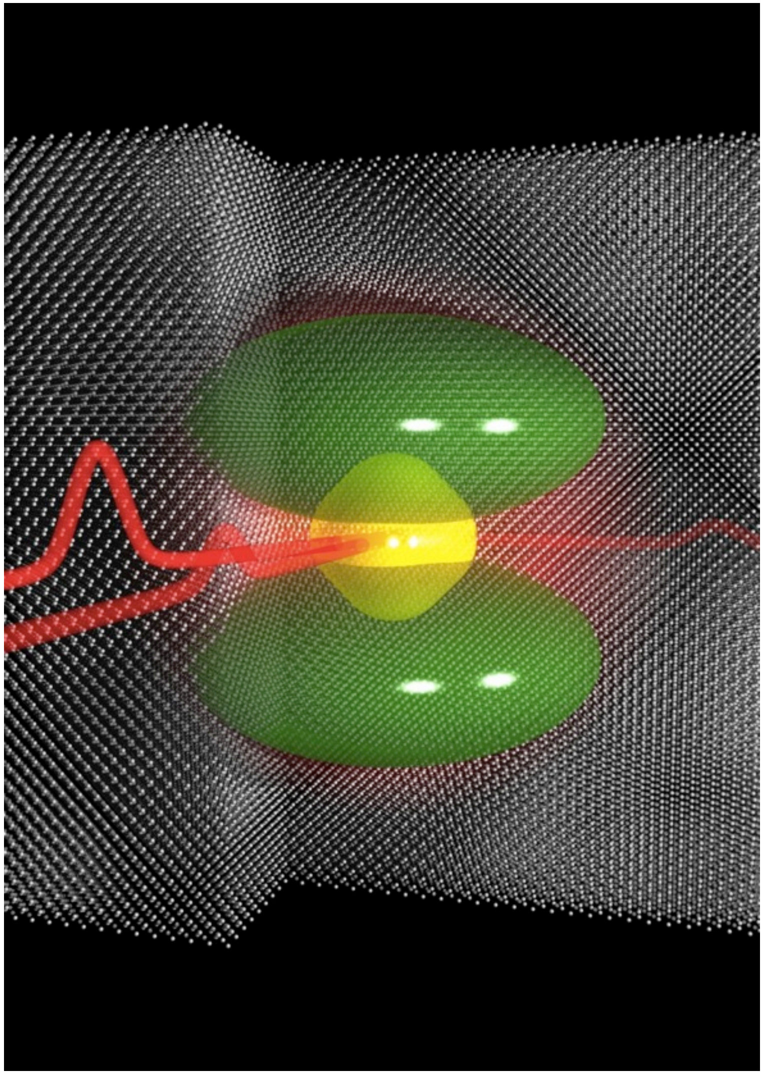
- Binding energy:

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

- Bohr radius

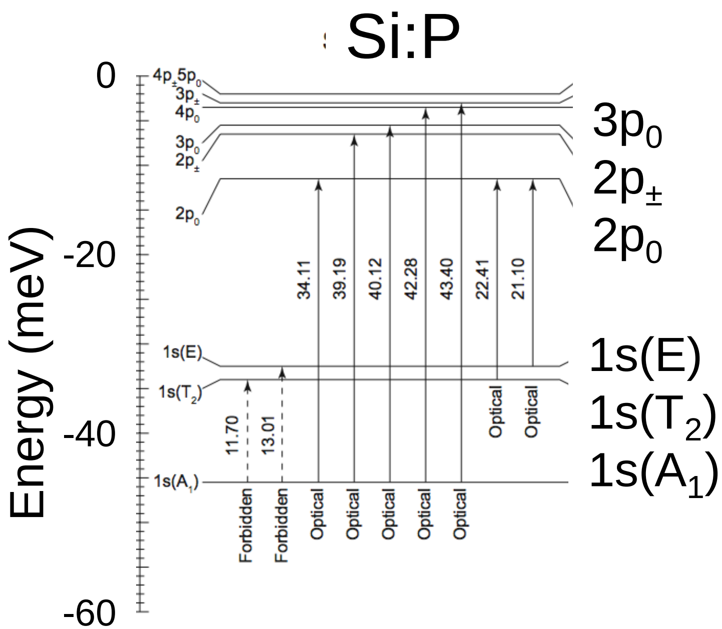
$$a_0 = \frac{4\pi\hbar^2}{e^2}\frac{\varepsilon}{m_e}$$

	H	Si:P
ε_r	1	11.4
m_e	1	0.19
E_R	13.6 eV	0.020 eV
a_0	0.056 nm	3.2 nm



Hydrogen like spectrum in Si:P

SA Lynch et al, Phys. Rev. B (2010)

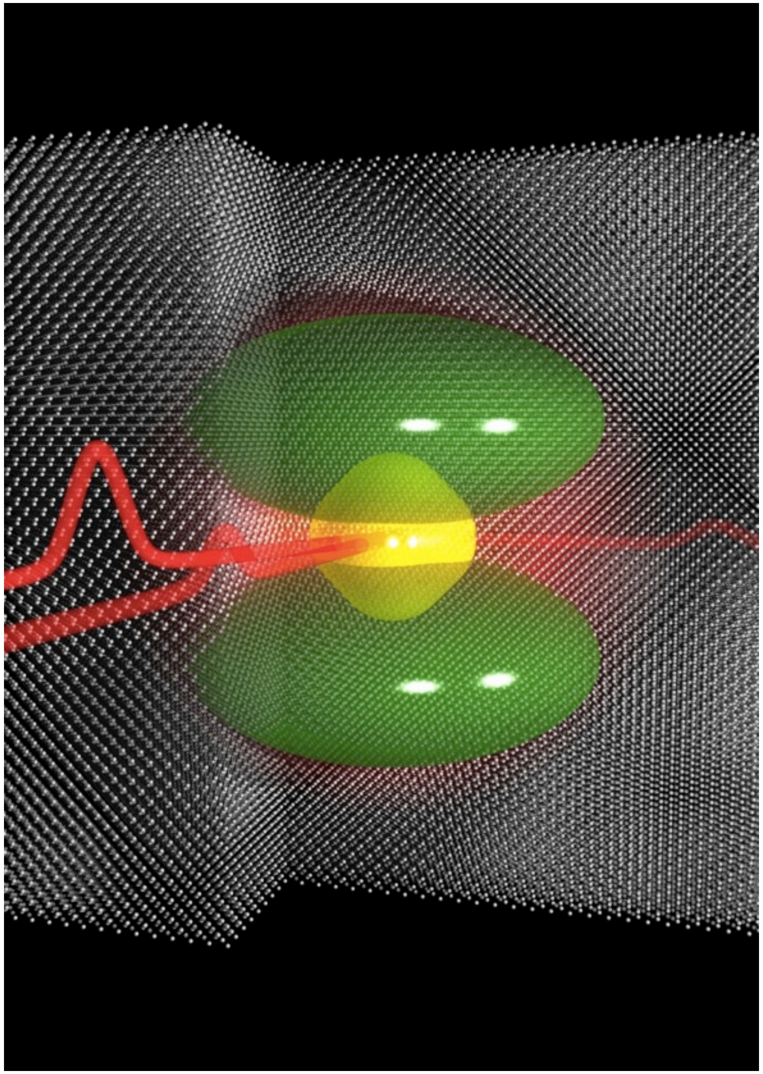


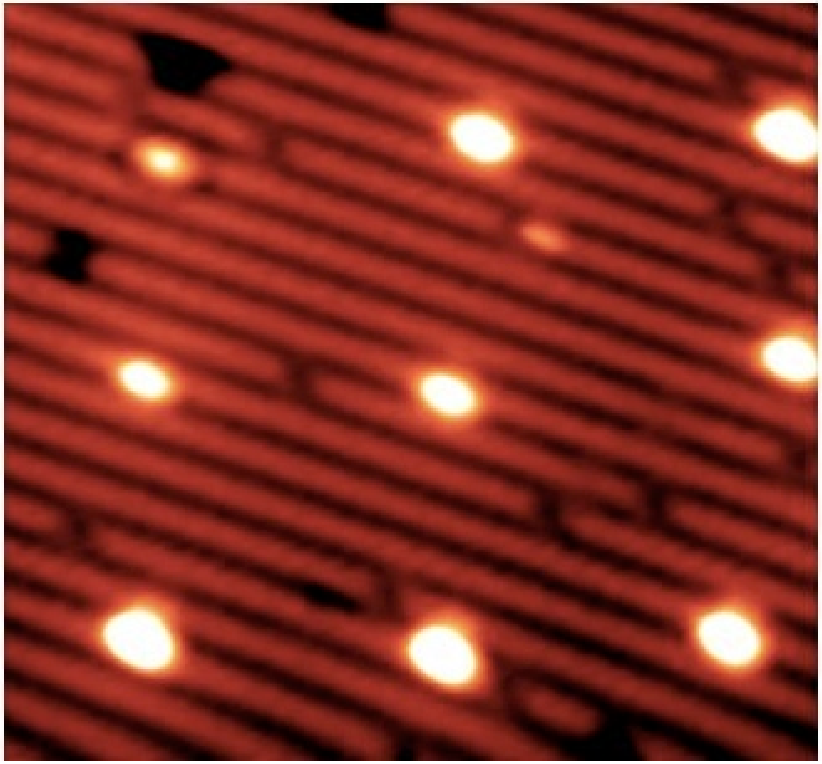
T (K)

Photon energy (meV)

- Some qualitative differences between hydrogen and donor
  - States split by cubic crystal symmetry (e.g. $2p_0$ and $2p_\pm$)
  - s-states shifted down in energy by “quantum defect” (a.k.a. “chemical shift” or “central cell correction”) due to the P^+ ion not being point-like

Control of donors in time & space

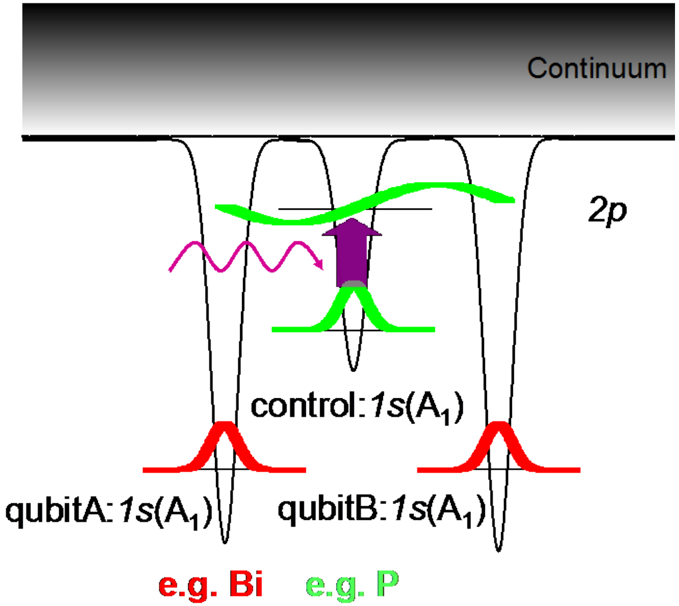




Silicon atomic scale electronics

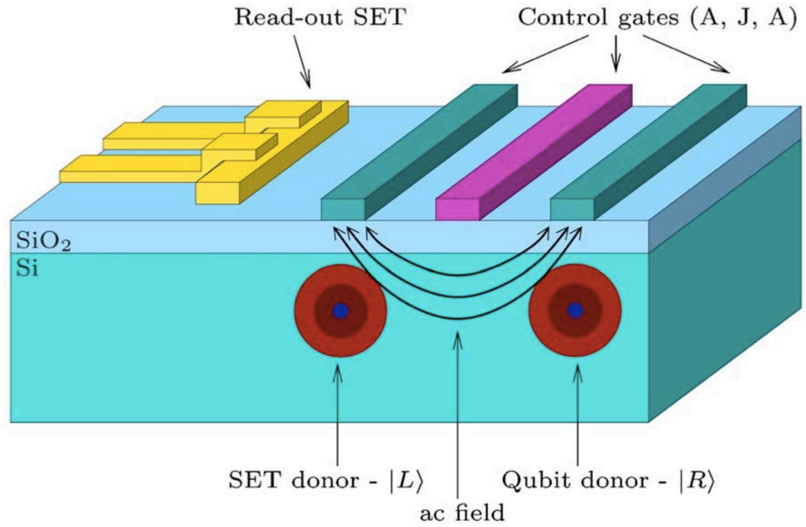
a) Silicon is easy to process into sophisticated electronic devices ⇒ good connection to impurity
b) Impurities are exactly reproducible ⇒ scalable
c) Silicon donors can be positioned with single atom precision ⇒ large registers
d) Si:P electron spin T_2 up to millisec and nuclear spin T_2 is 3 hours! ⇒ good quantum memory
e) Si:P orbitronics (our work): Rydberg excitations with wavefunction radius up to 100nm (!!!) are lifetime broadened with T_2 up to 0.1ns ⇒ good electric dipolar quantum control

Importance of THz in Si QIP



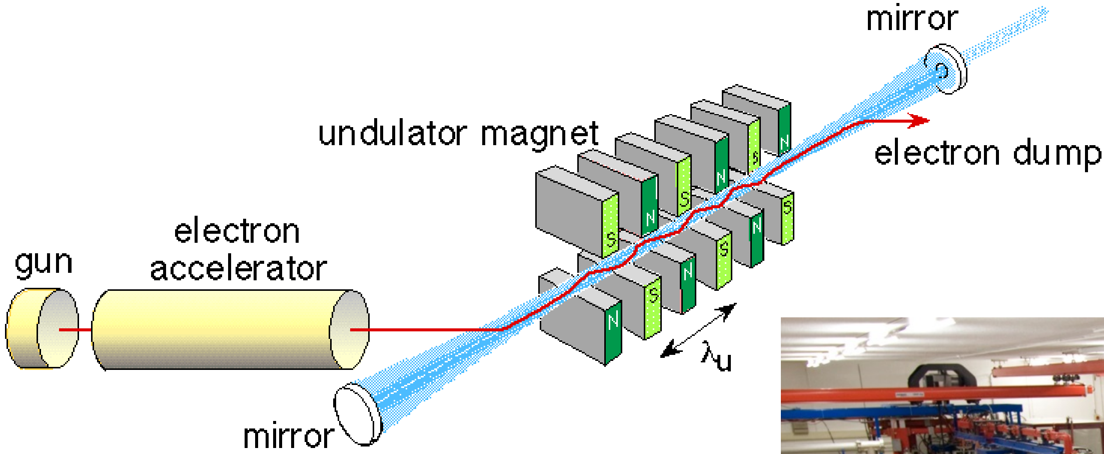
- Stoneham-Fisher-Greenland scheme: THz gated entanglement/ control/gating between qubits

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



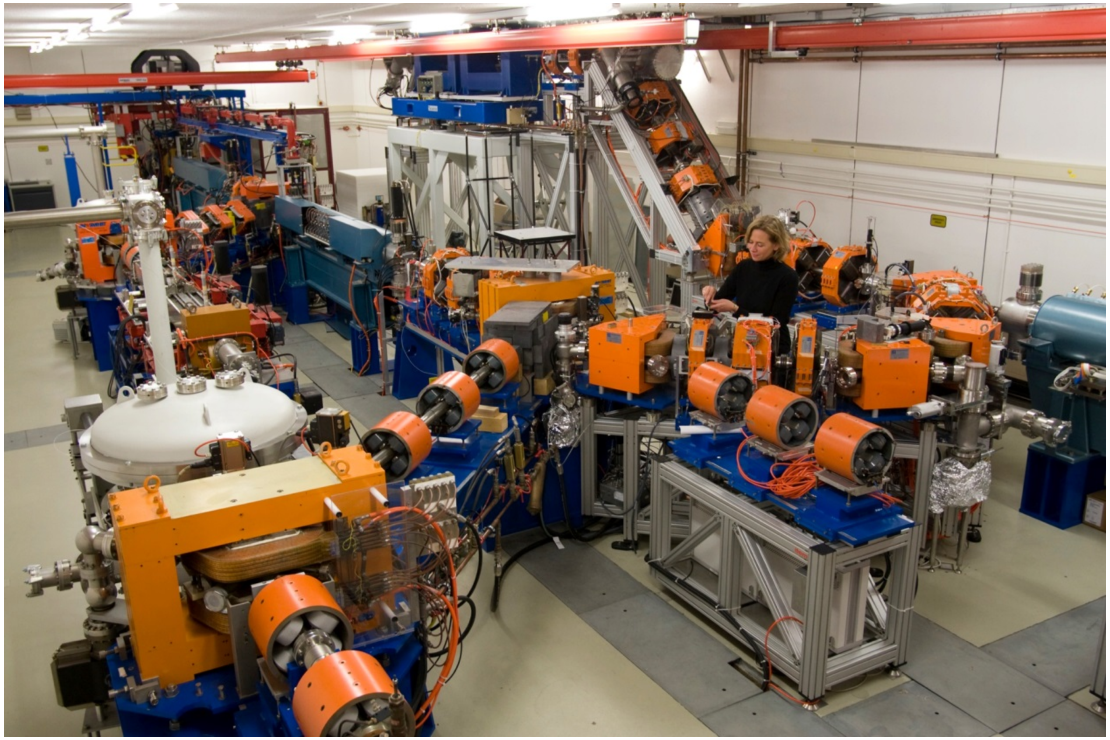
- Kane/Hollenberg scheme: THz induced spin-to-charge conversion between qubit and SET donors

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



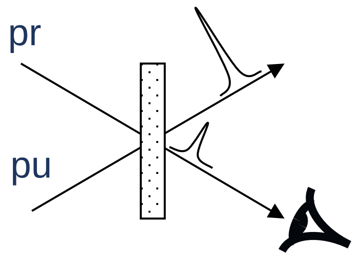
$$n\,\lambda_s = \frac{\lambda_u\,(1 + K^2)}{2\,\gamma^2}$$

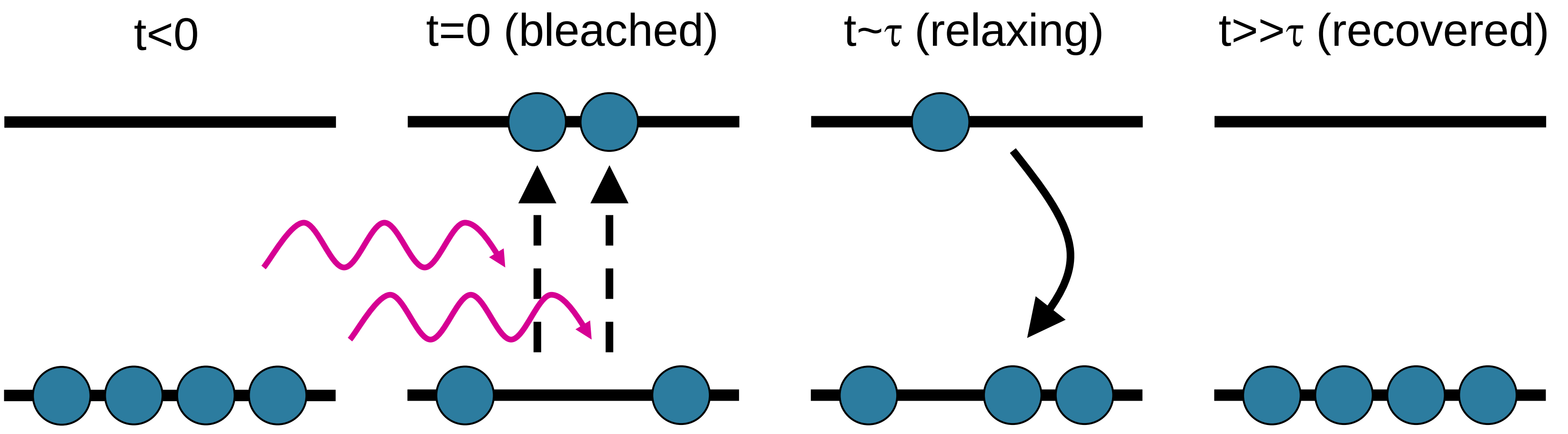
- wavelength
  - 4-250μm
  - 1-100THz
- Pulse duration
  - 1-10 ps
- Pulse energy
  - ~10μJ



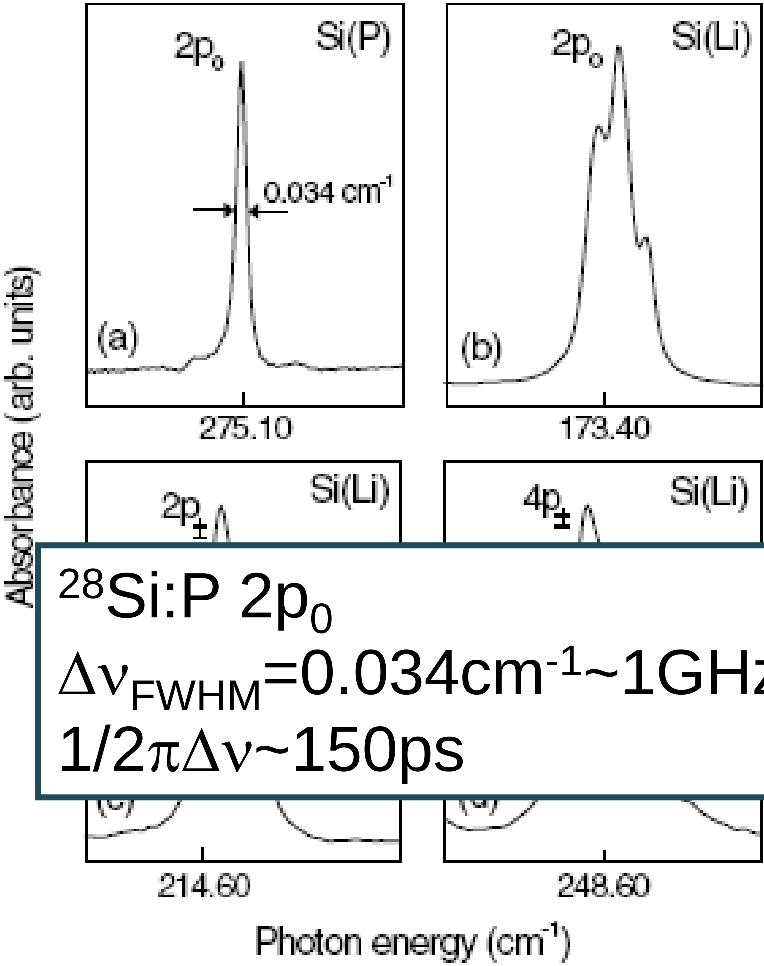
FELIX, the Free-Electron Laser for Infrared eXperiments (Nijmegen)

- A strong pump pulse bleaches the transmission by exciting ~50% of the oscillators
- A weak probe measures the transmission recover as a function of time delay





Incoherent dynamics experiment: pump-probe

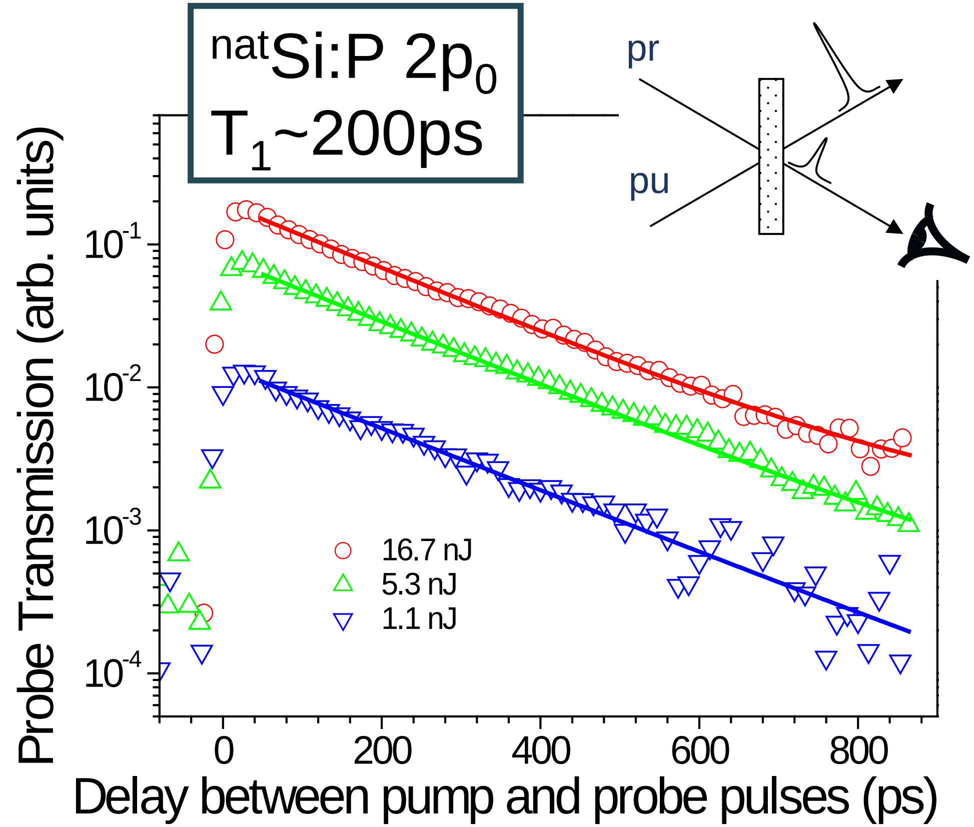


^{28}Si:P $2p_0$

$\Delta\nu_{FWHM}$=0.034cm^{-1}~1GHz

1/2$\pi\Delta\nu$~150ps

Thewalt *et al. PRL* **90** (2003)



^{nat}Si:P $2p_0$

T_1~200ps

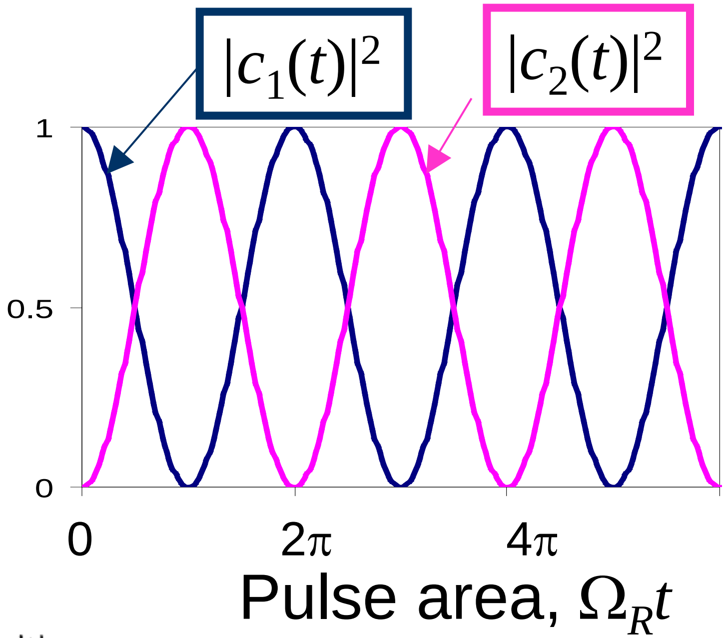
NQ Vinh *et al, PNAS* **105,** 10649 (2008)

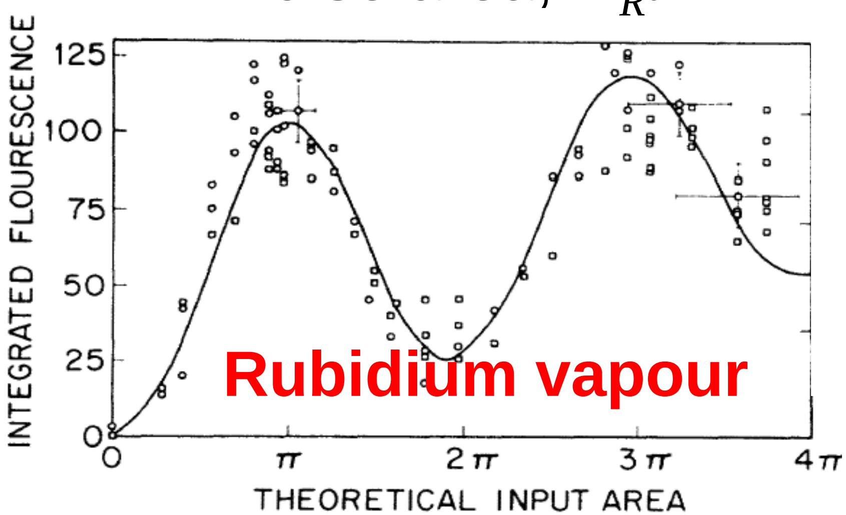
NQ Vinh *et al, PRX* **3,** 3, 011019 (2013)

HW Hubers *et al PRB* **88**, 035201 (2013)

Spectral and time domain spectroscopy of orbital excitations

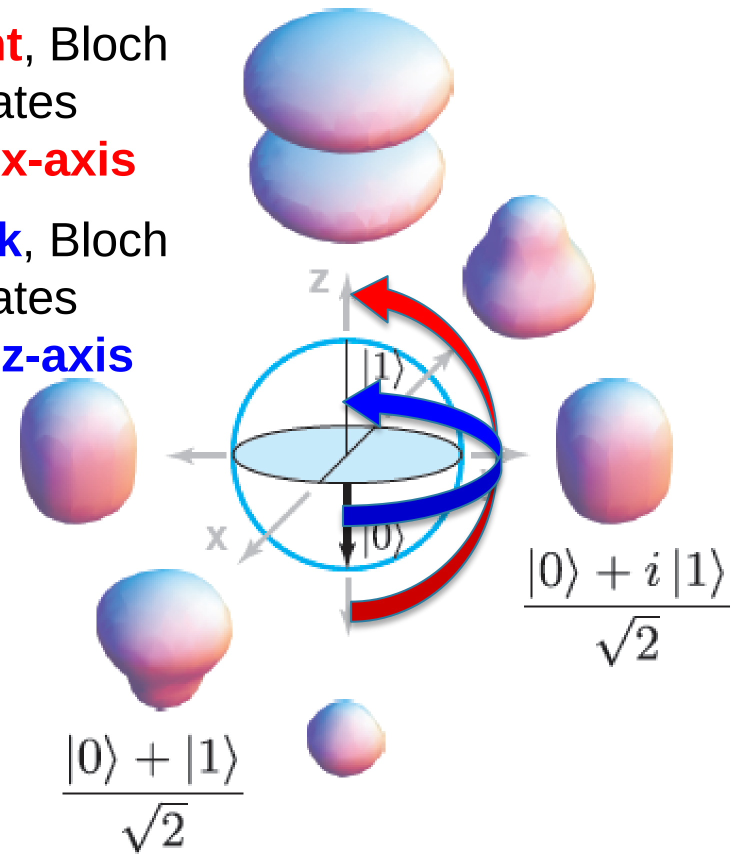
Dynamics during light pulse: Rabi flopping





In the **light**, Bloch vector rotates about the **x-axis**

In the **dark**, Bloch vector rotates about the **z-axis**

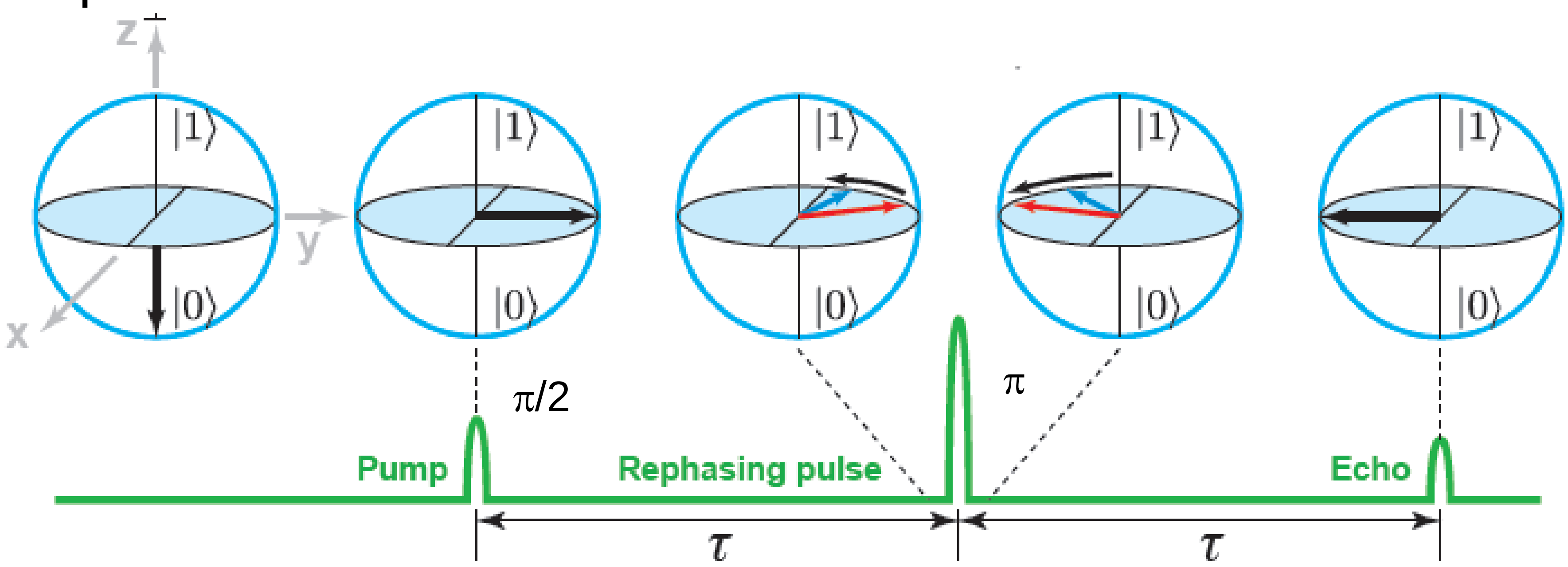


The Bloch Sphere

H.M. Gibbs,
Phys. Rev. Lett. 29, 495 (1972),
Phys. Rev. A8, 446 (1973)

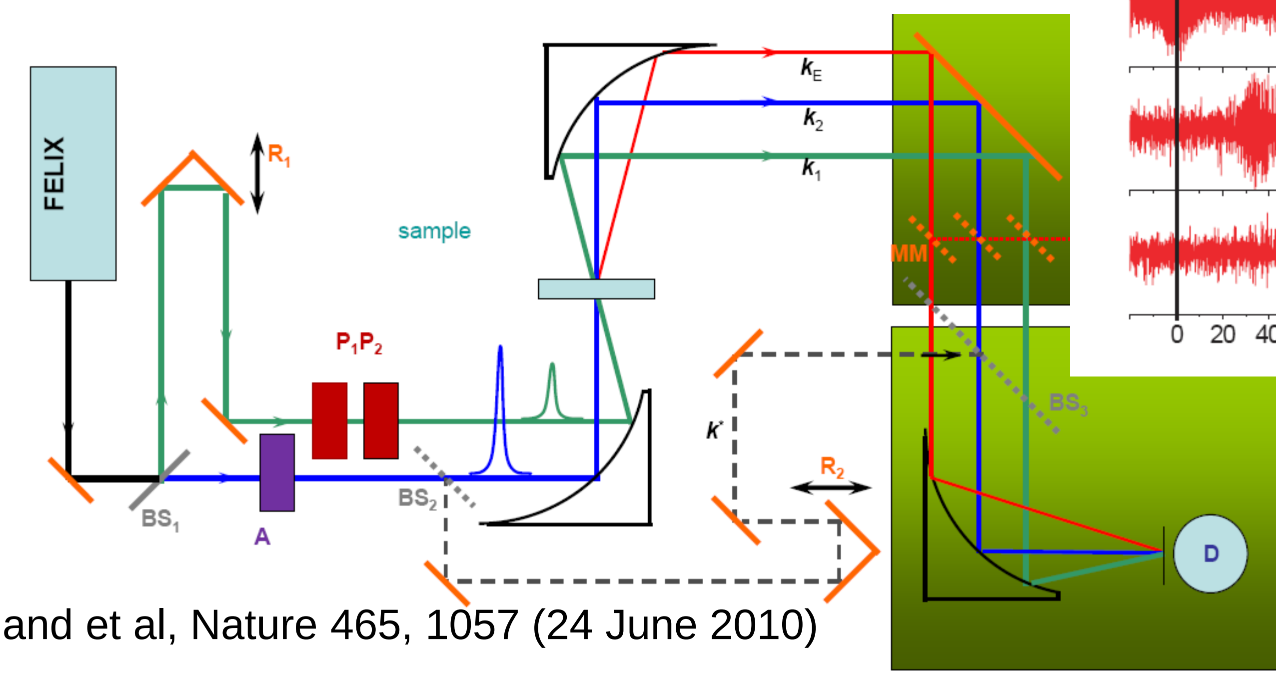
The Hahn Echo

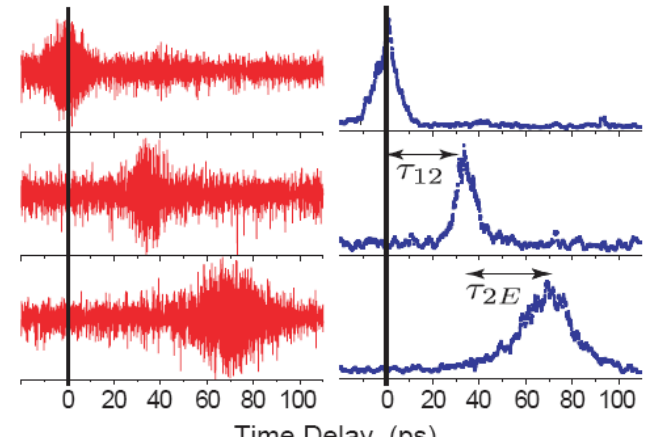
- The photon echo is analogous to the spin echo of ESR/NMR
- For an ensemble of oscillators with inhomogeneity in the natural frequency, a π-pulse can reverse the loss of phase

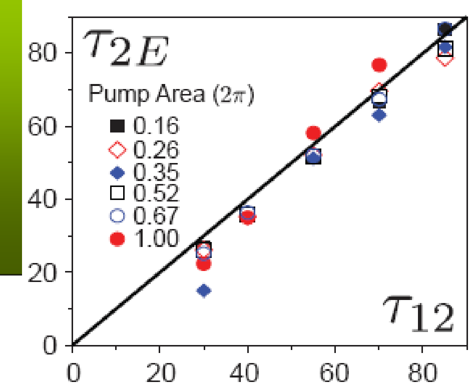


Hahn echo in Si:P

- The arrival time of the echo is controlled by the delay between the pump and rephasing pulses
- Echo duration set by inverse inhomogeneous linewidth



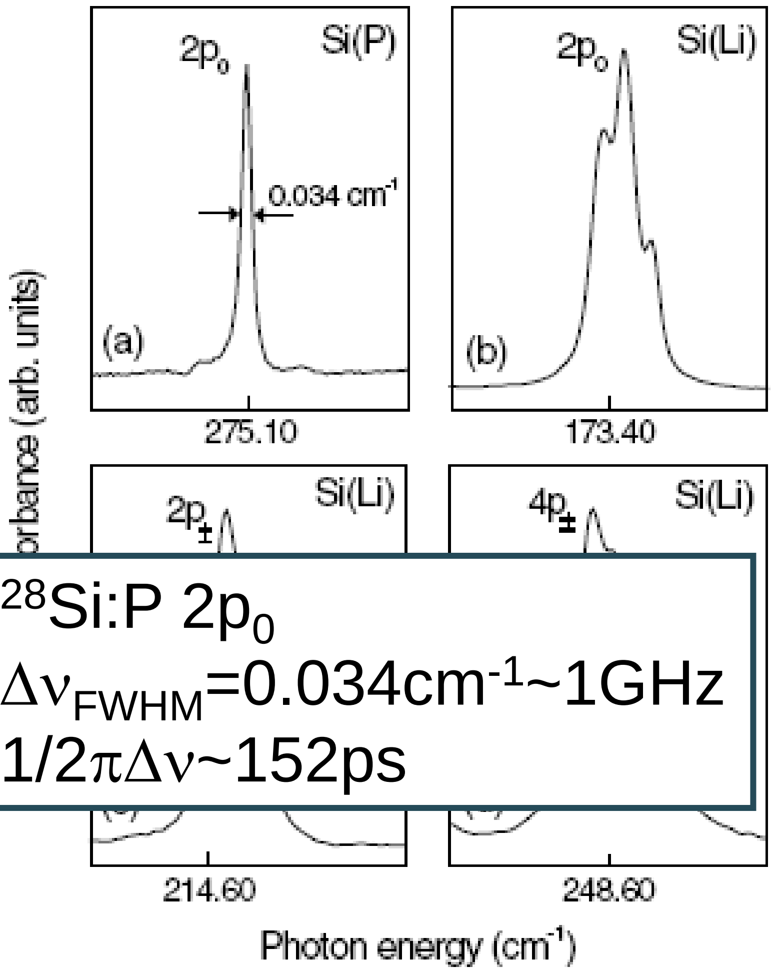




Greenland et al, Nature 465, 1057 (24 June 2010)

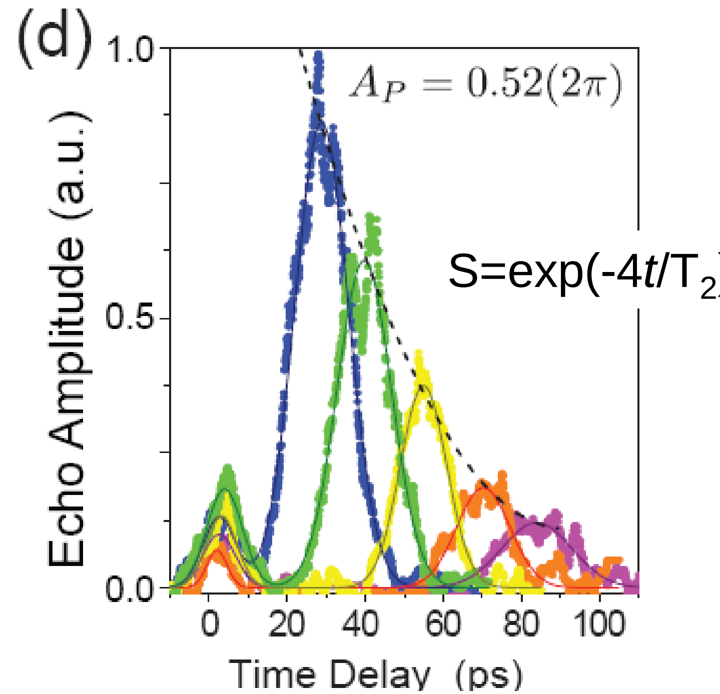
nature International weekly journal of science

Photon echoes for excited state T_2



^{28}Si:P $2p_0$
$\Delta\nu_{FWHM}$=0.034cm^{-1}~1GHz
$1/2\pi\Delta\nu$~152ps

Thewalt *et al. PRL* **90** (2003)



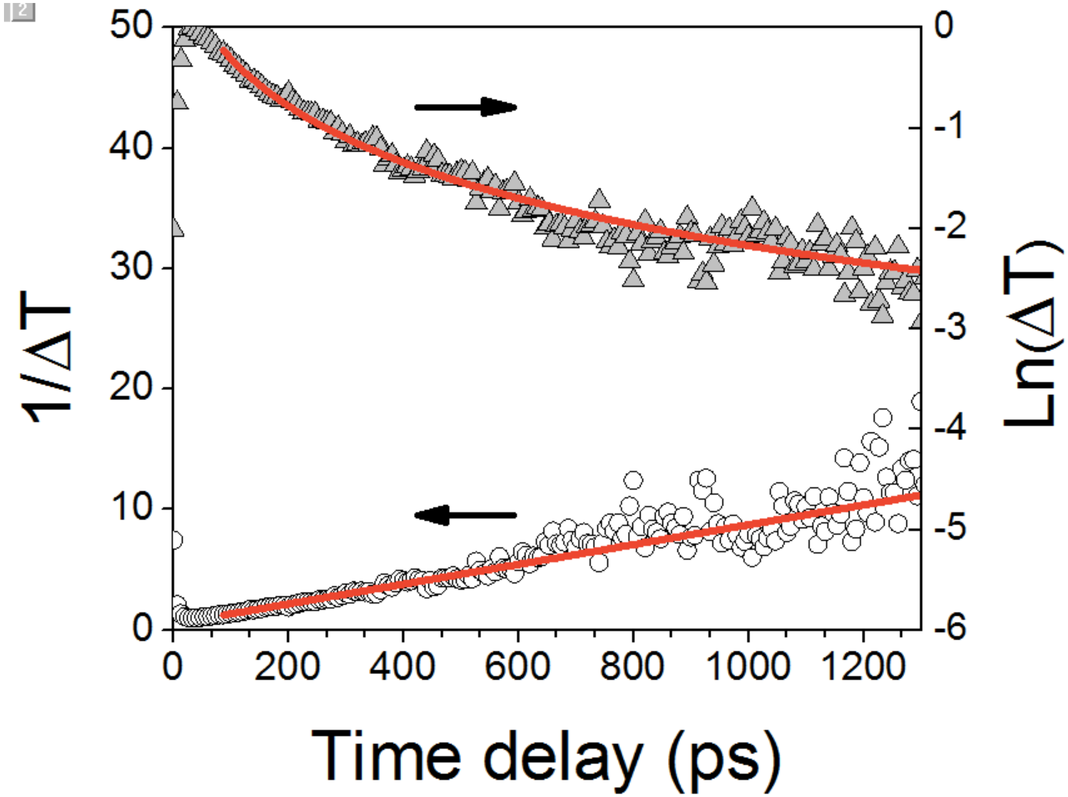
Greenland et al,
Nature 465, 1057 (24 June 2010)

THz induced resonant charge transfer between donors

- Recombination from the continuum results in a reciprocal decay

$$\frac{dN_e}{dt} = -RN_eN_{D+} = -RN_e^2$$

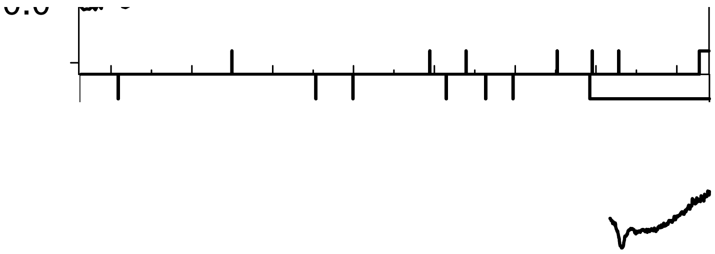
$$\frac{1}{N_e} - \frac{1}{N_e(0)} = Rt$$



- Whereas relaxation is exponential

$$\frac{dN_{2p}}{dt} = -\frac{1}{T_1}N_{2p} \qquad \ln(N_{2p}) = -\frac{t}{T_1}$$

Pumping to the continuum



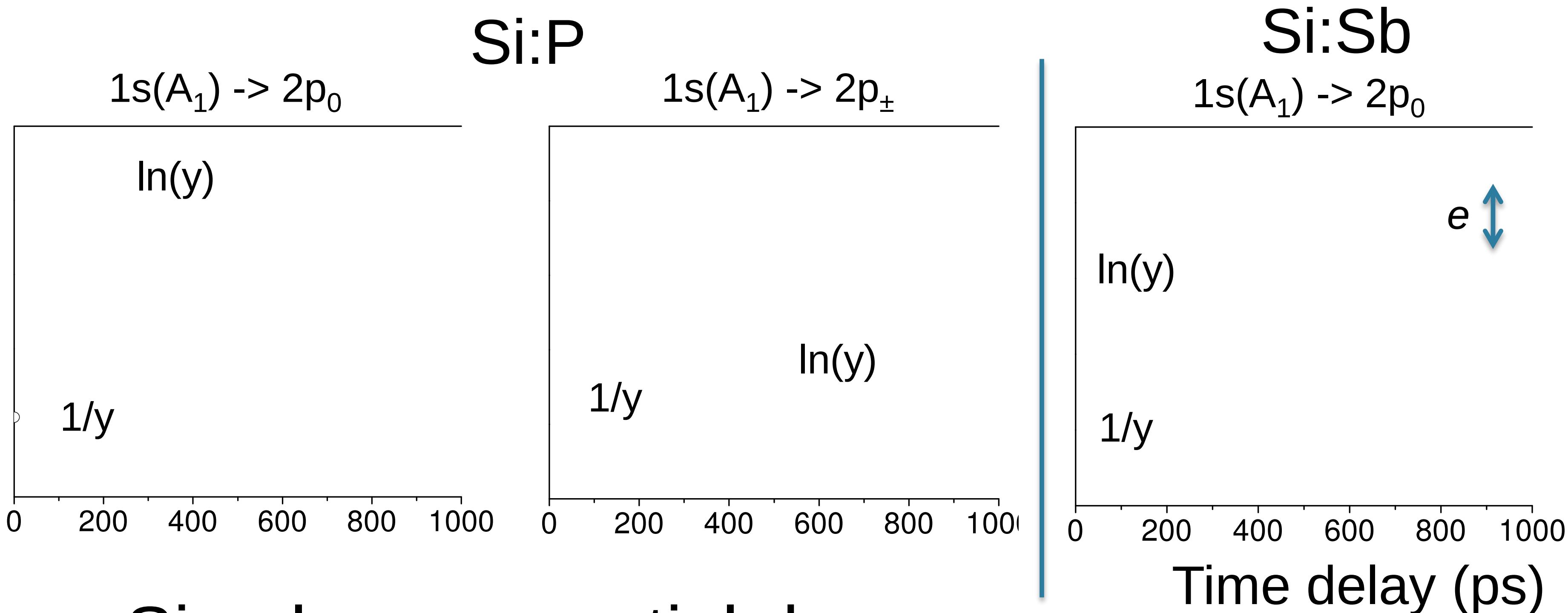
P
Sb

1 – 2p$_0$,
2 – 2p$_\pm$,
3 – 3p$_0$,
4 – 3p$_\pm$,
5 – 4p$_\pm$,
6 – 5p$_\pm$,
7 – cb

- Co-doped sample
  - P, 1.8E15 cm^{-3} + Sb, 1.2E15 cm^{-3}
- Control samples, (monodoped)
  - P, 4.0E15 cm^{-3}
  - Sb, 3.8E15 cm^{-3}

- Samples all mounted at the same time on cold finger of LHe cryostat at base temperature, for pump-probe experiments

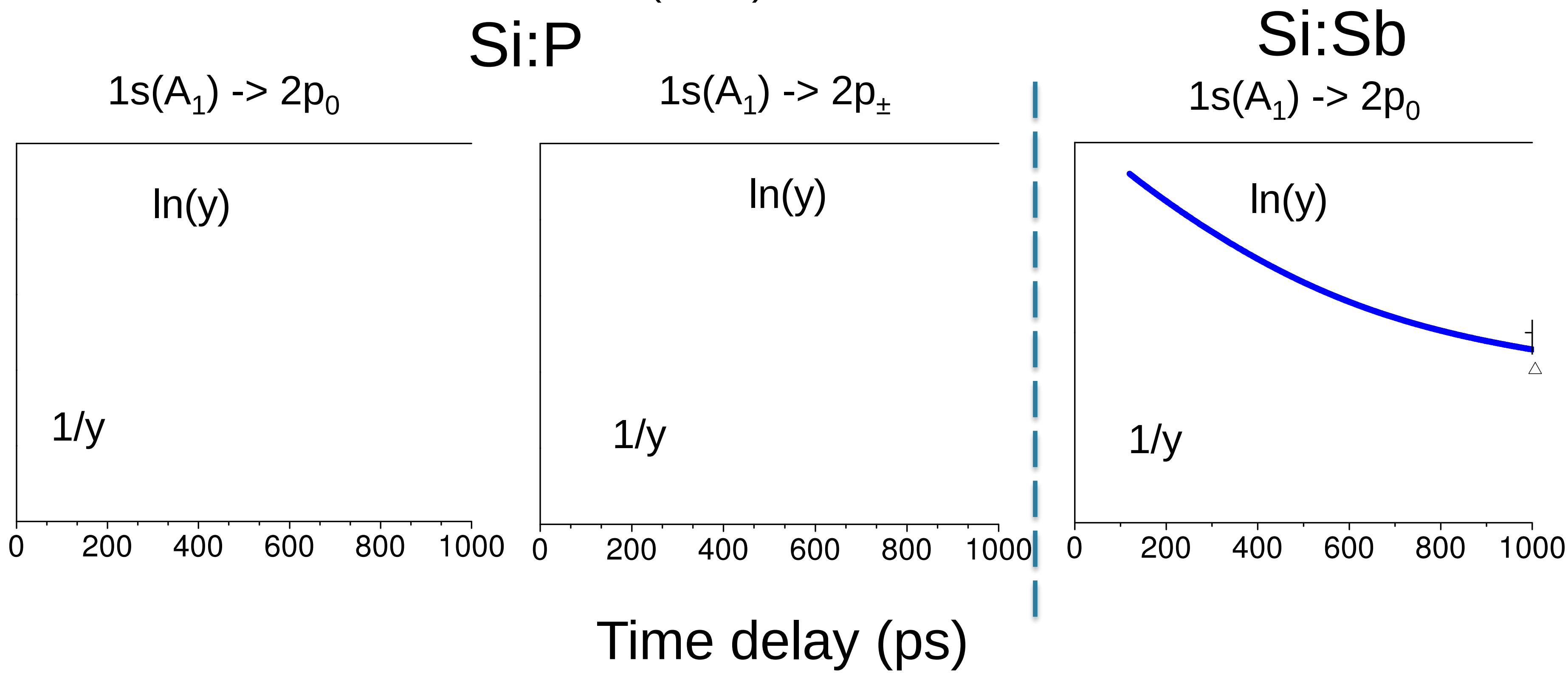
Co-doped sample



- Simple exponential decays
- The codoped sample was mounted at the same time and translated into the beam…

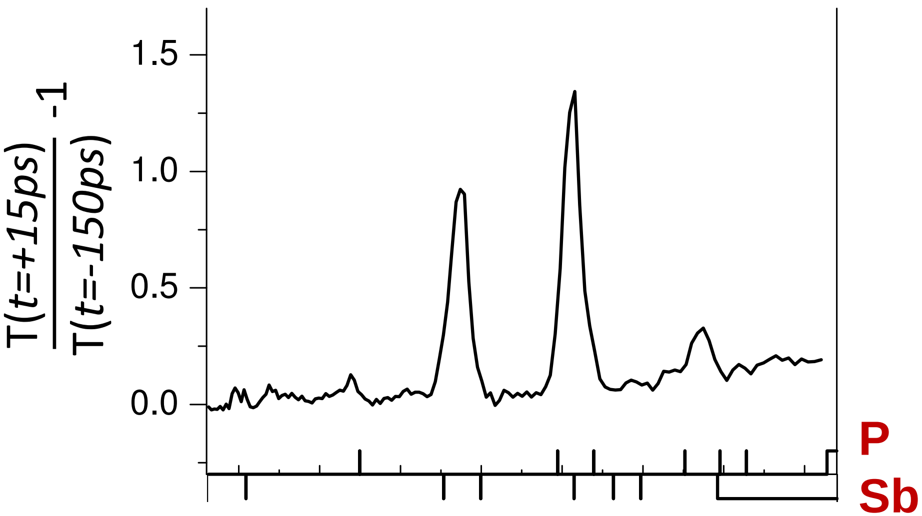
Resonant pumping in monodoped control samples

K Litvinenko et al, *PRB* **89**, 235204 (2014)

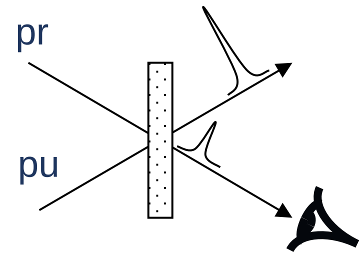


- Always get some combination of reciprocal and exponential
- Reciprocal contribution is ~10%

Resonant pumping in codoped samples



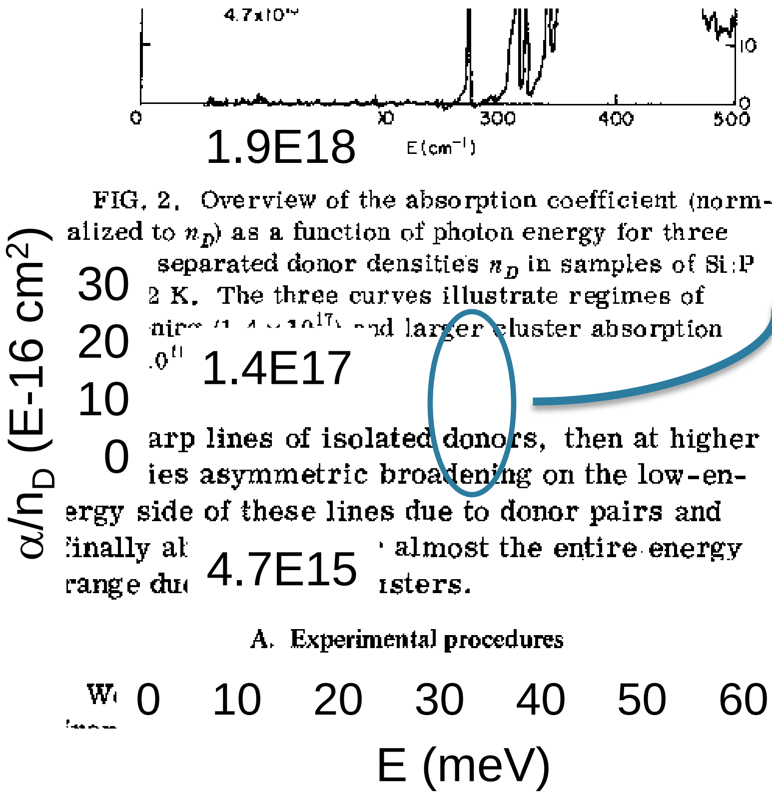
1 – $2p_0$,
2 – $2p_\pm$,
3 – $3p_0$,
4 – $3p_\pm$,
5 – $4p_\pm$,
6 – $5p_\pm$,
7 – cb

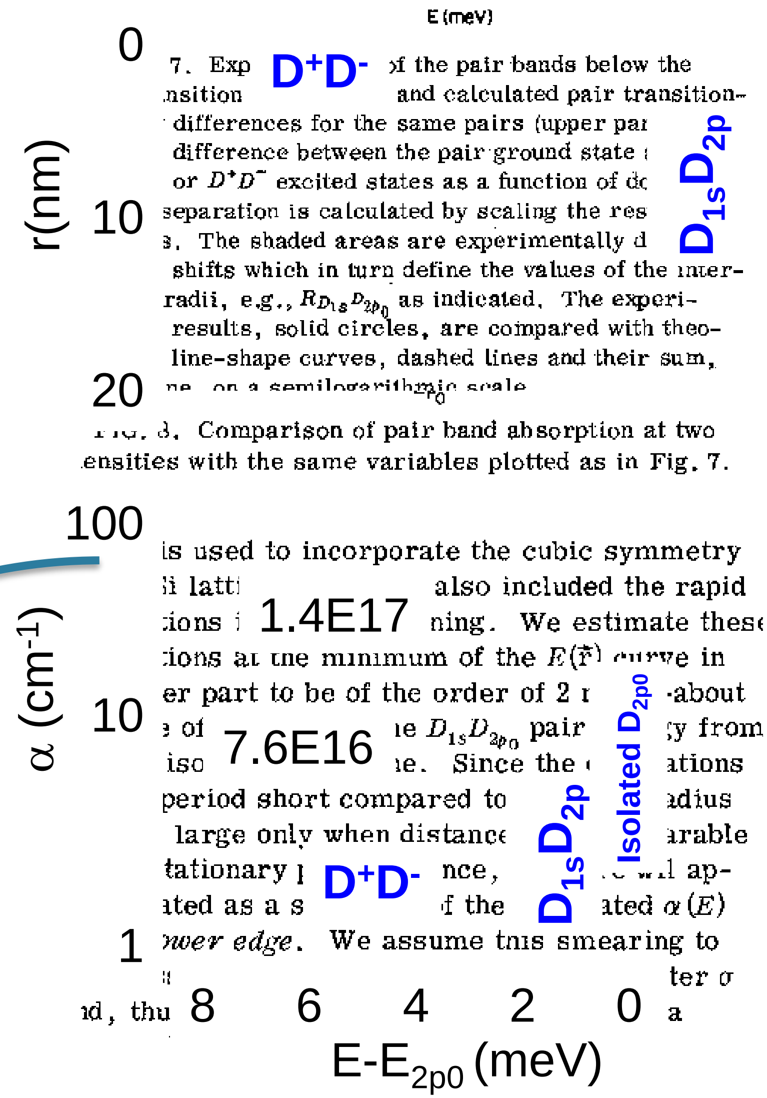


- Co-doped sample
  - P, 1.8×10^{15} cm^{-3} + Sb, 1.2×10^{15} cm^{-3}

Pump-probe signal is resonant

- Thomas et al PRB 23 5472 (1981)
- Concentration broadening
  - $D_{1s}D_{2p}$ -> $D_{1s}D_{2p}$ transtions
- Appearance of “charge transfer states”
  - $D_{1s}D_{1s}$ -> D^+D^- transtions

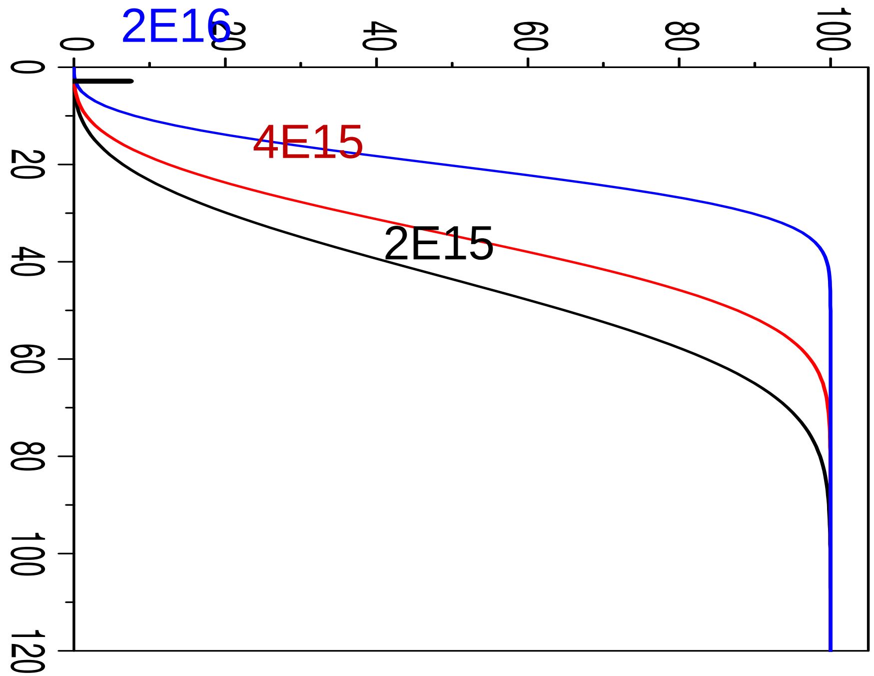




Pair energetics

- P(no donors in vol *V*) $= e^{-nV}$
- cumulative probability

$$P(r) = 1 - \exp\left(\frac{-4\pi n r^3}{3}\right)$$

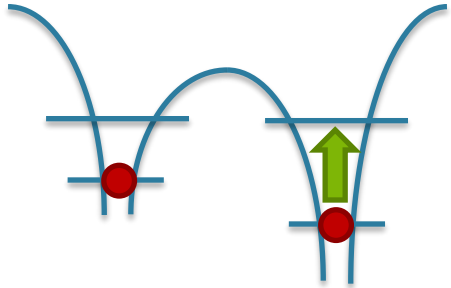


$$p(r)dr = 4\pi n r^2 \exp\left(\frac{-4\pi n r^3}{3}\right)dr$$

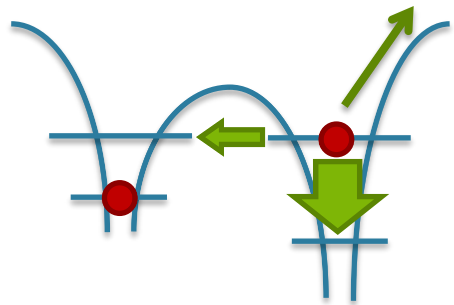
$$\langle r \rangle = 0.554 n^{-1/3}$$

Poisson statistics of randomly doped samples

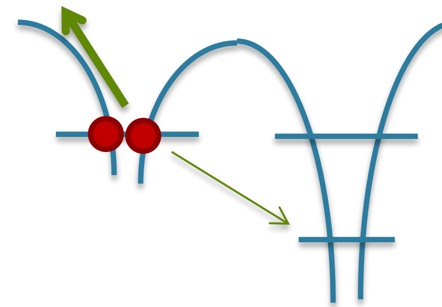
K Litvinenko et al, *PRB* **89**, 235204 (2014)



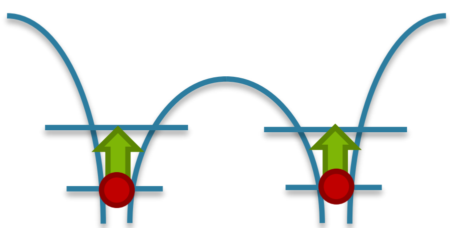
Resonant 1s-2p pumping



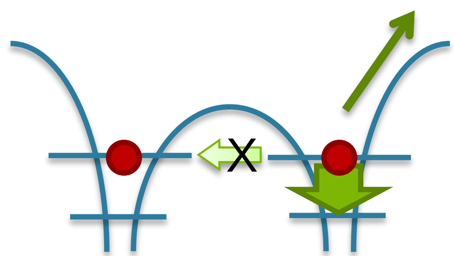
Resonant D+D- tunnelling, branching ratio 1:10



Relaxation is slower than thermal ionisation



Resonant 1s-2p pumping

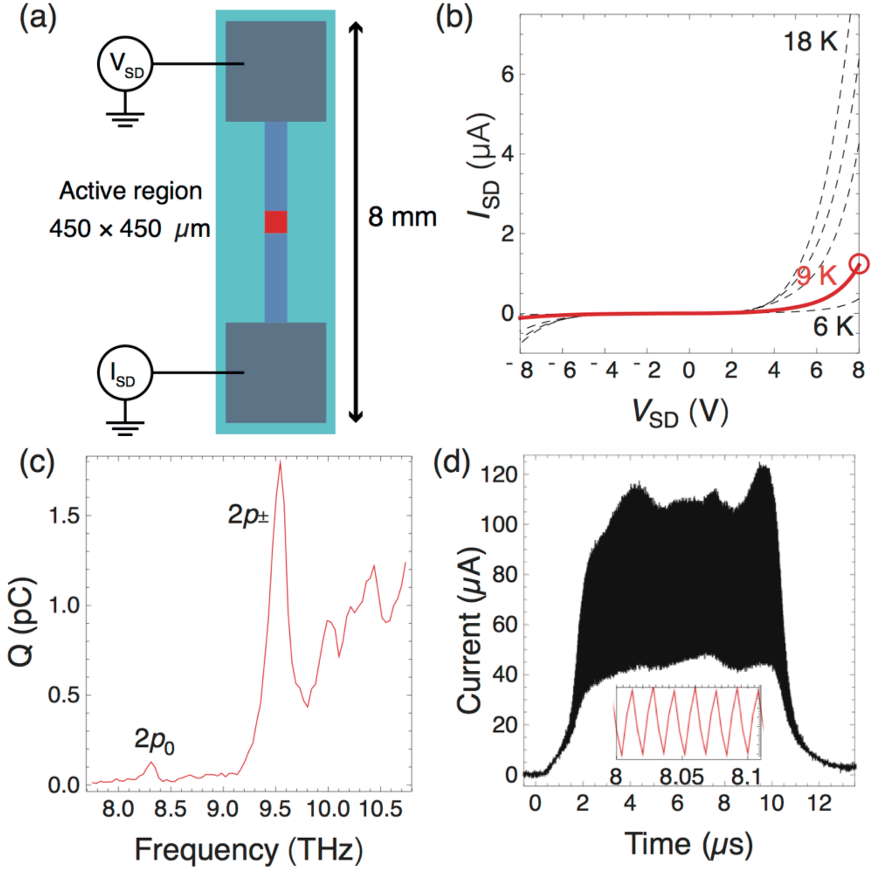


Resonant D+D- tunnelling is blocked if neighbour is excited

conclusions

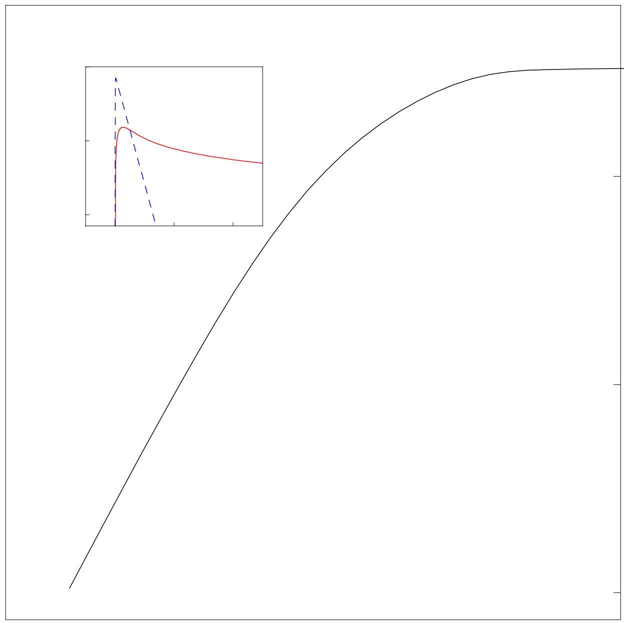
Electrical readout

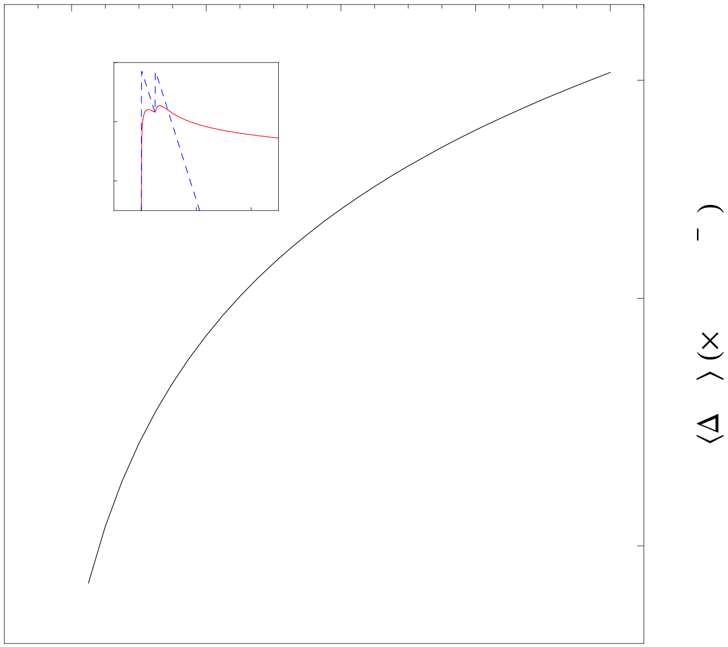
- Thermally excited electrons can be useful for readout



Excitation dynamics

- Results can tell us the recombination rate coefficient R=1.3±0.3)x10^{-11} m^{-3}s^{-1}
- Now current can be used to calibrate the excitation





COMPASS

Si:P as a quantum information scheme

The Economist