Spin Coherence of Isolated and Exchange-Coupled Donors in Silicon

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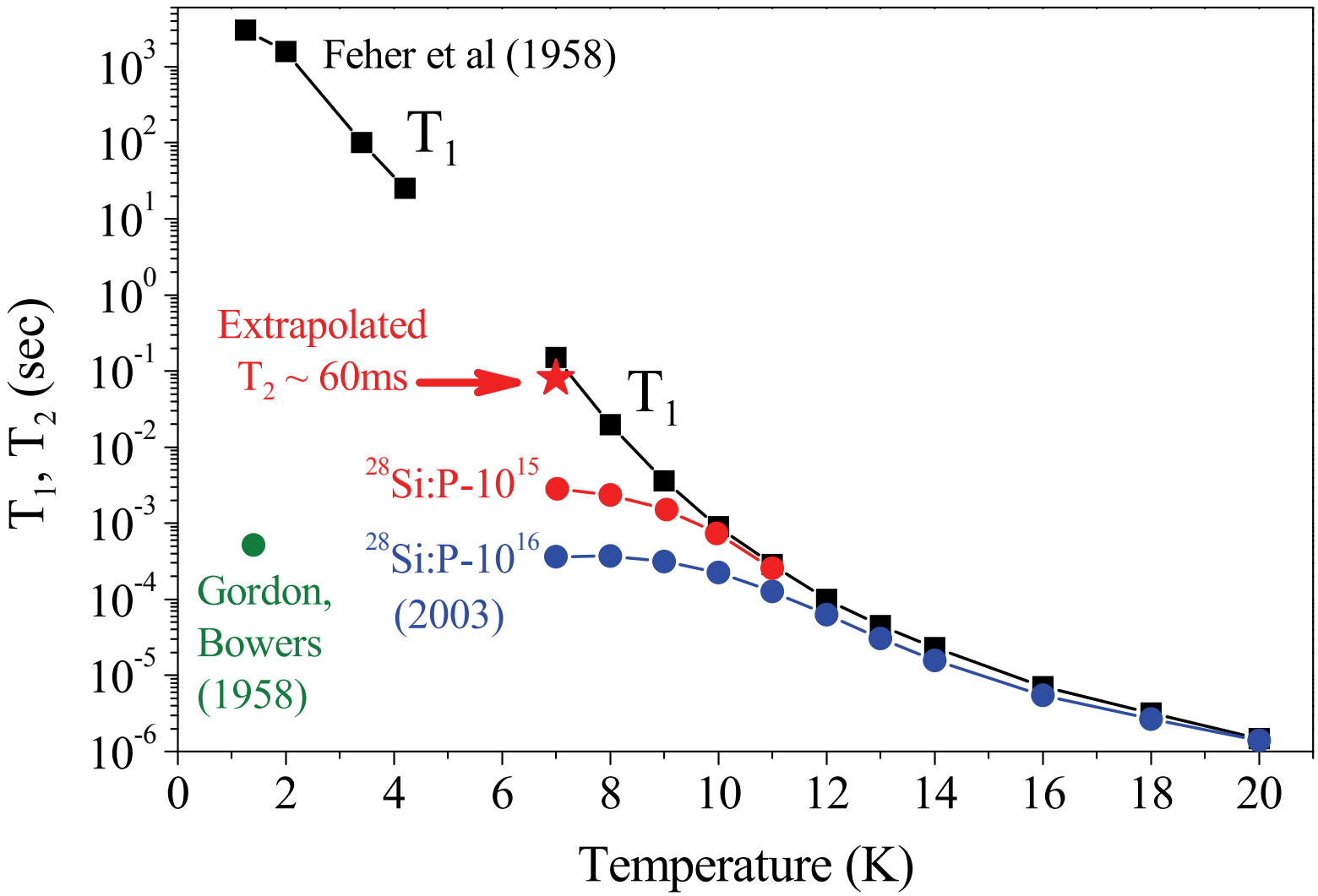
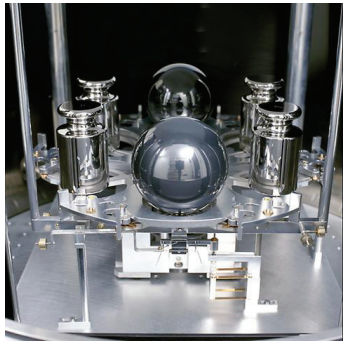
Outline:

- Isolated donors (very pure ^{28}Si)
  - **T_2 = 0.6 seconds at 1.8K**
- Exchange-coupled donors
  - **T_2 = 1 microseconds at 5K**
- Summary

Donor T_2 in ^{28}Si: History



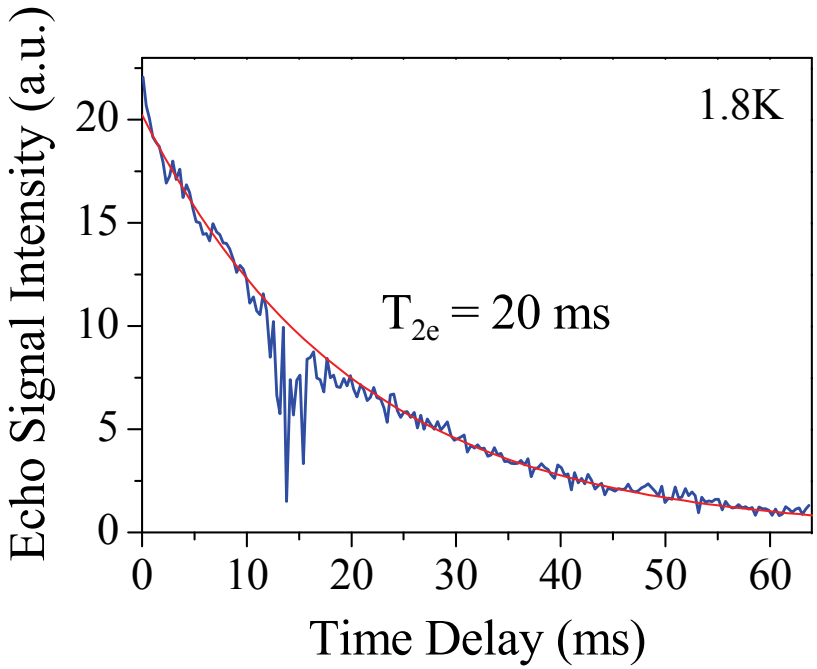
Several Improvements

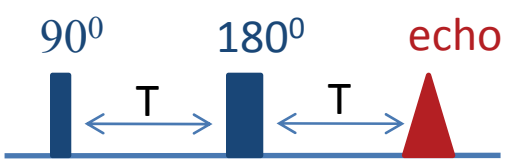


- **Sample:**
  - Very pure ^{28}Si (~50ppm ^{29}Si, Avogadro project)
  - Low donor densities (1e14 P/cm^3) in a large crystal
  - Slow cooling to LHe temperatures $\Rightarrow$ Less strain
  - Surface passivated with HF
- **Instrumental:**
  - **Magnetic field noise:**
    - Magnitude detection
    - Hall probe wires enclosed in iron tubes
  - **Microphonics noise:**
    - Sand bags to isolate from mechanical noise of the pump
    - BeCu springs for extra support of the resonator
- **LED (1050nm) flash to quickly recover to thermal equilibrium:**
  - Faster measurements at lower temperature

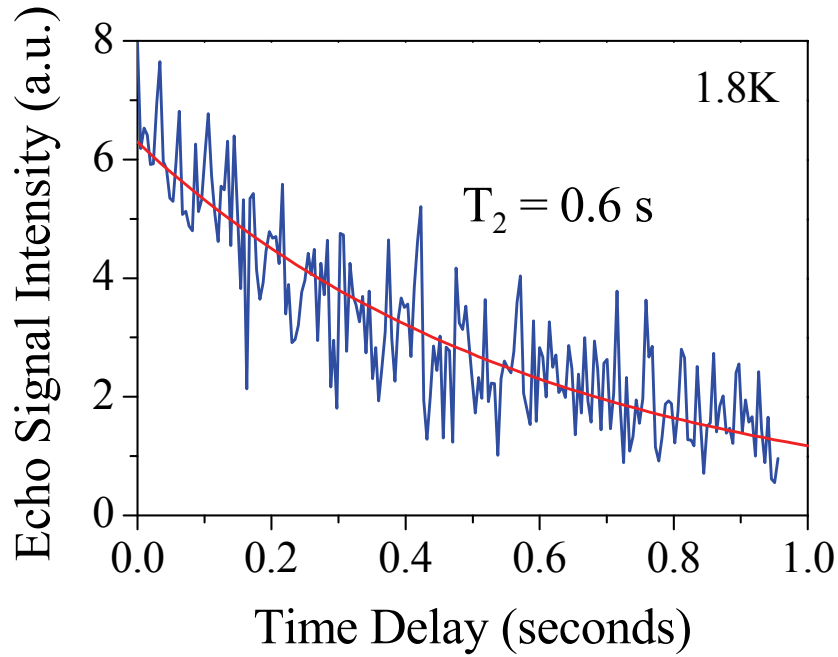
Donor T_2 = 0.6 sec at 1.8K

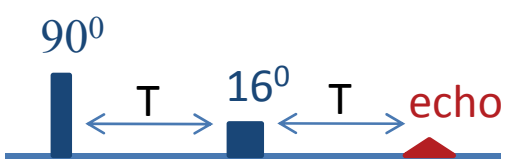
(^{28}Si:P, ~50ppm ^{29}Si, 1.2e14 P/cm^3)





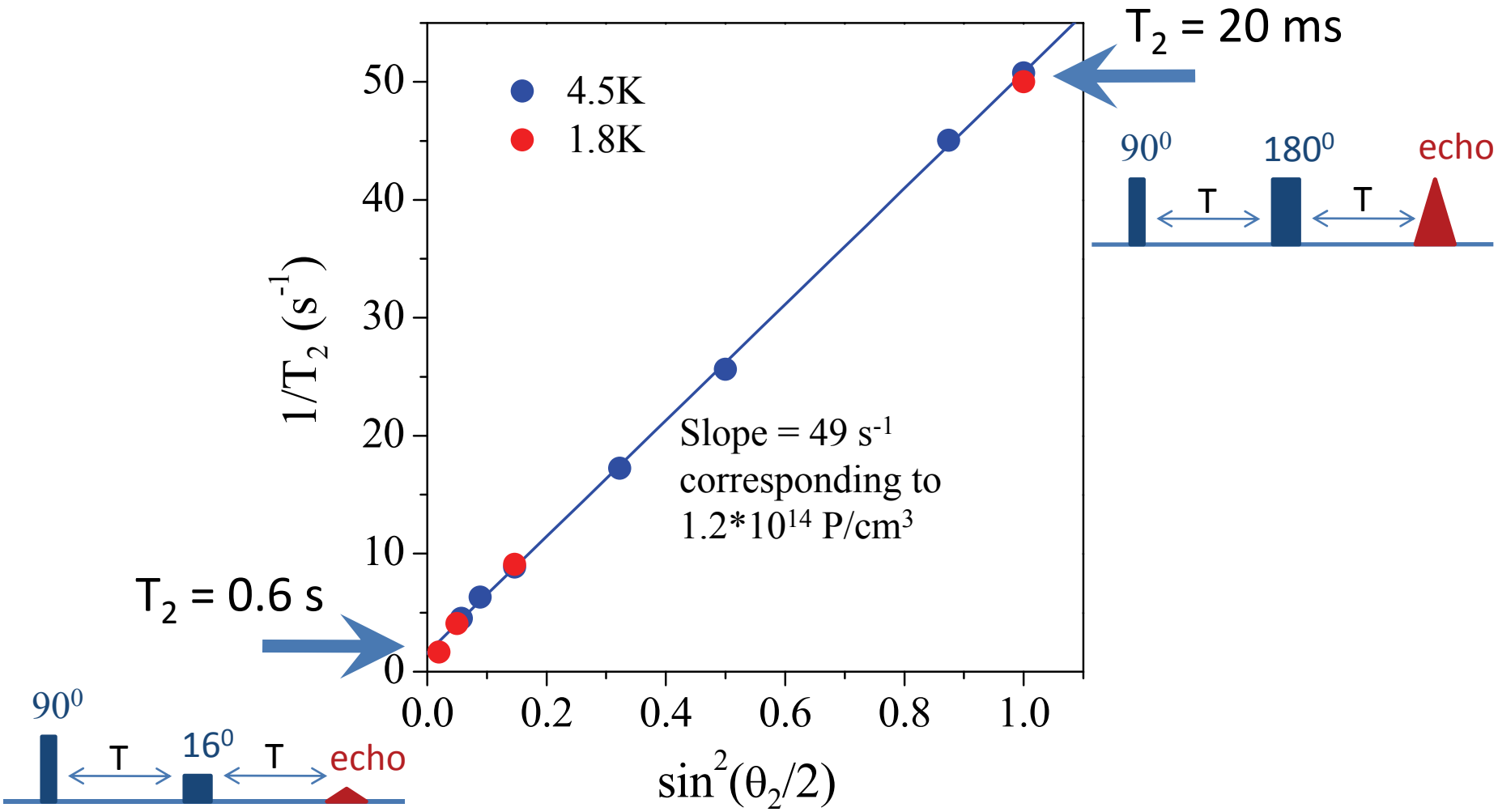
Instantaneous diffusion causes fast T_2



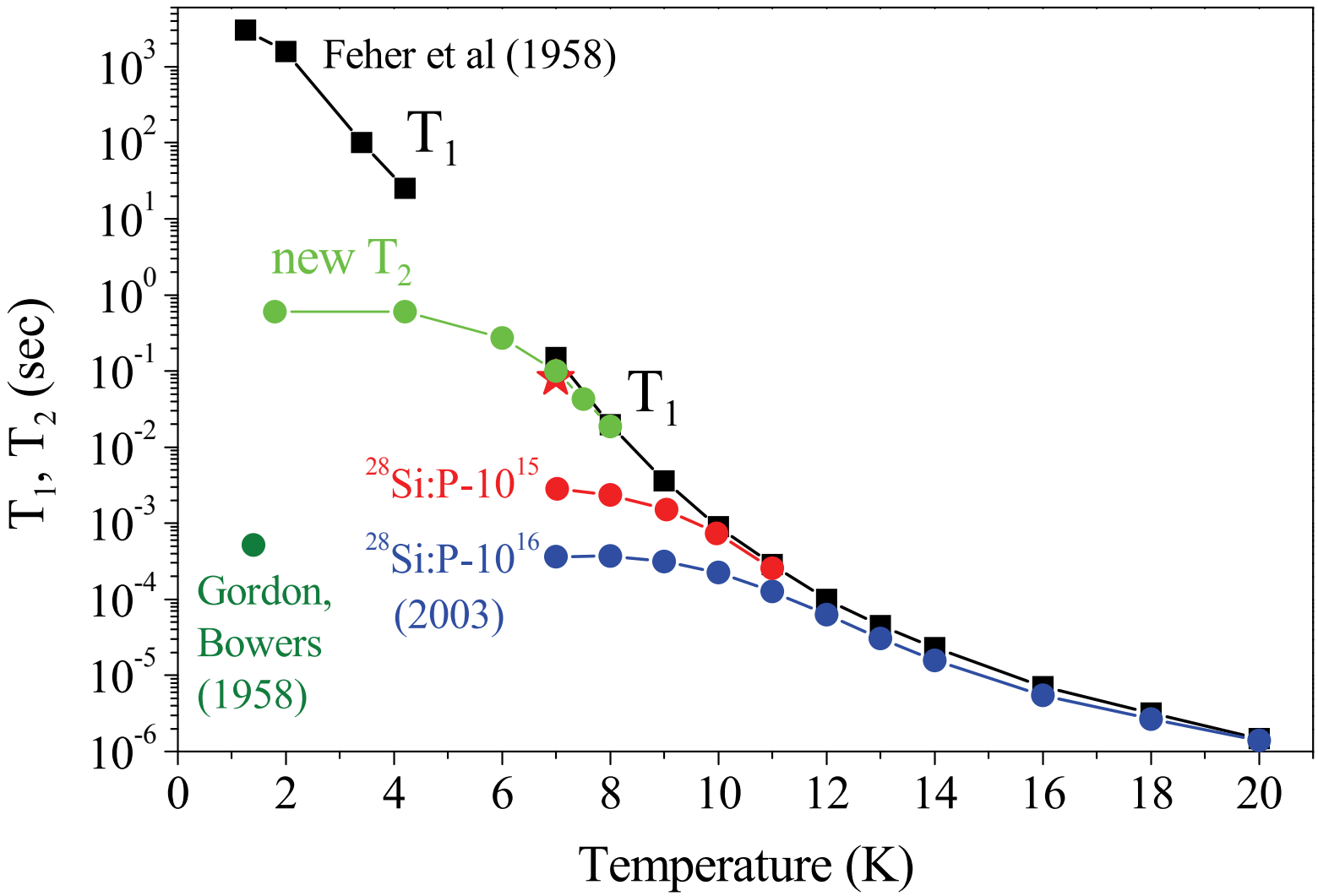


Instantaneous diffusion suppressed!

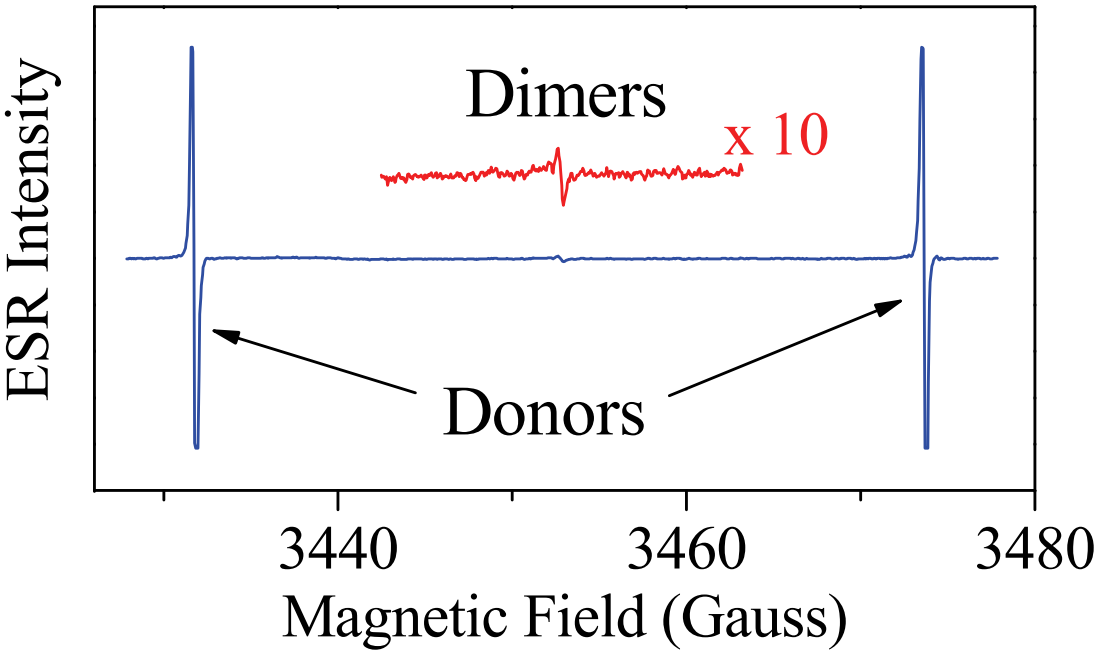
Instantaneous Diffusion is a Dominant T_2 Mechanism (^{28}Si:P, ~50ppm ^{29}Si, 1.2e14 P/cm^3)

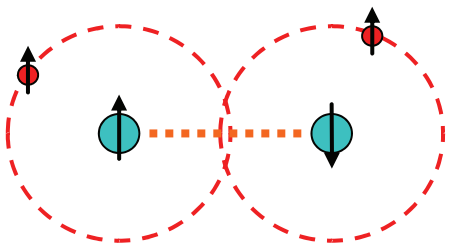


Donor T_2 in ^{28}Si



Exchange-Coupled Donors (Dimers)

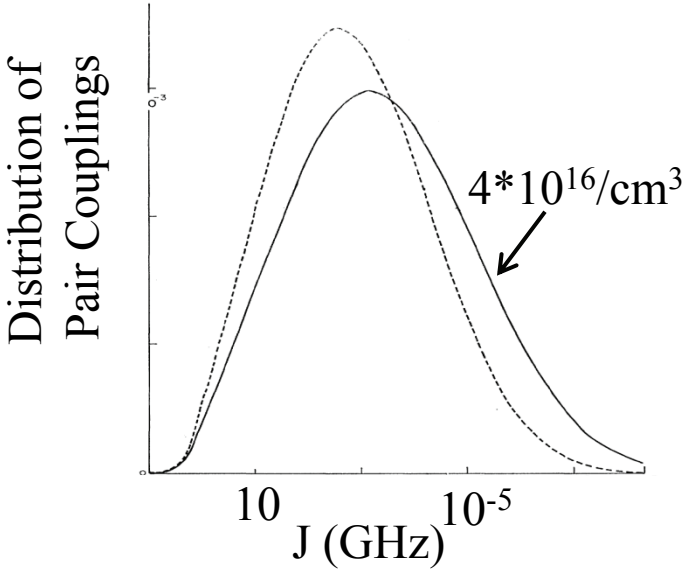




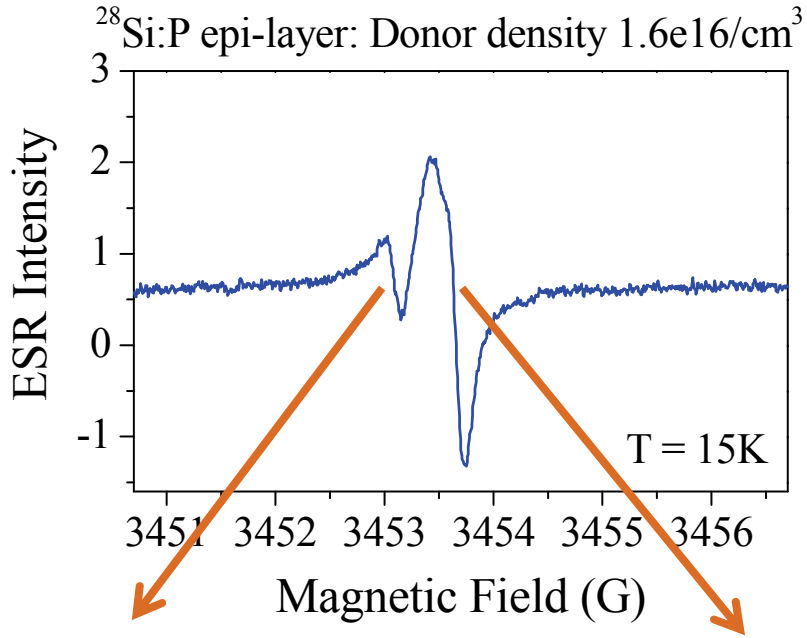
Feher, Fletcher, Gere, PR 100, 1784 (1955)
Cullis, Marko, PRB 1, 632 (1970)
New, Castner, PRB 29, 2077 (1984)

Sample: ^{28}Si:P, with $1.6*10^{16}$ P/cm^3

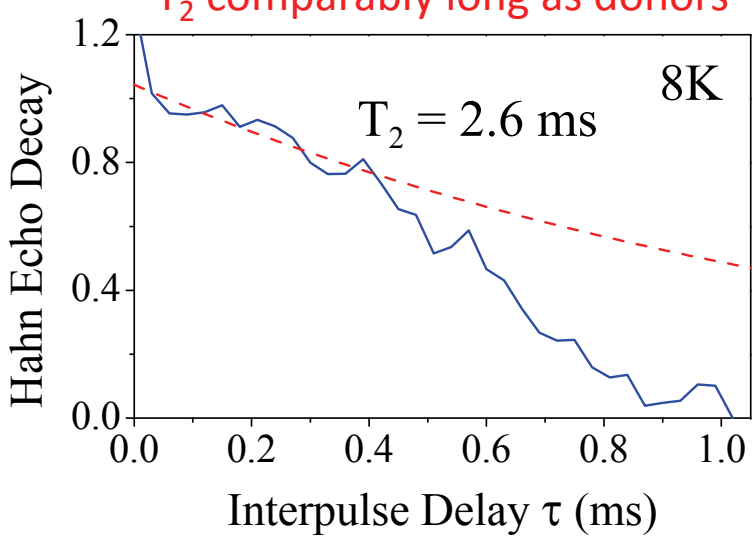
- Random dimers
- Broad distribution of J couplings



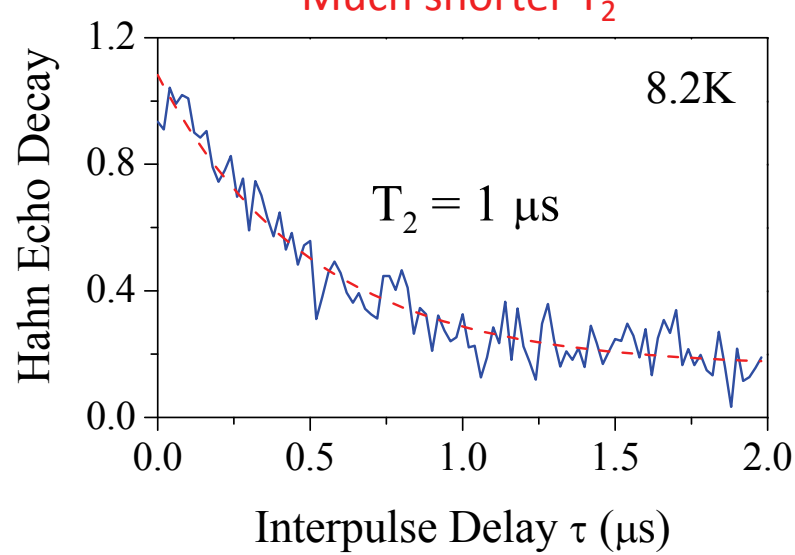
Two Central Lines ⇒ Two Distinct T_2



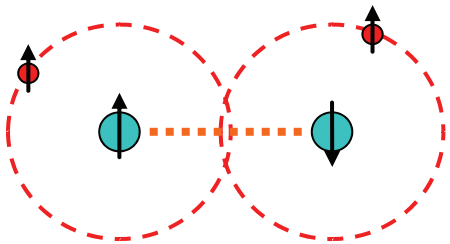
T_2 comparably long as donors



Much shorter T_2

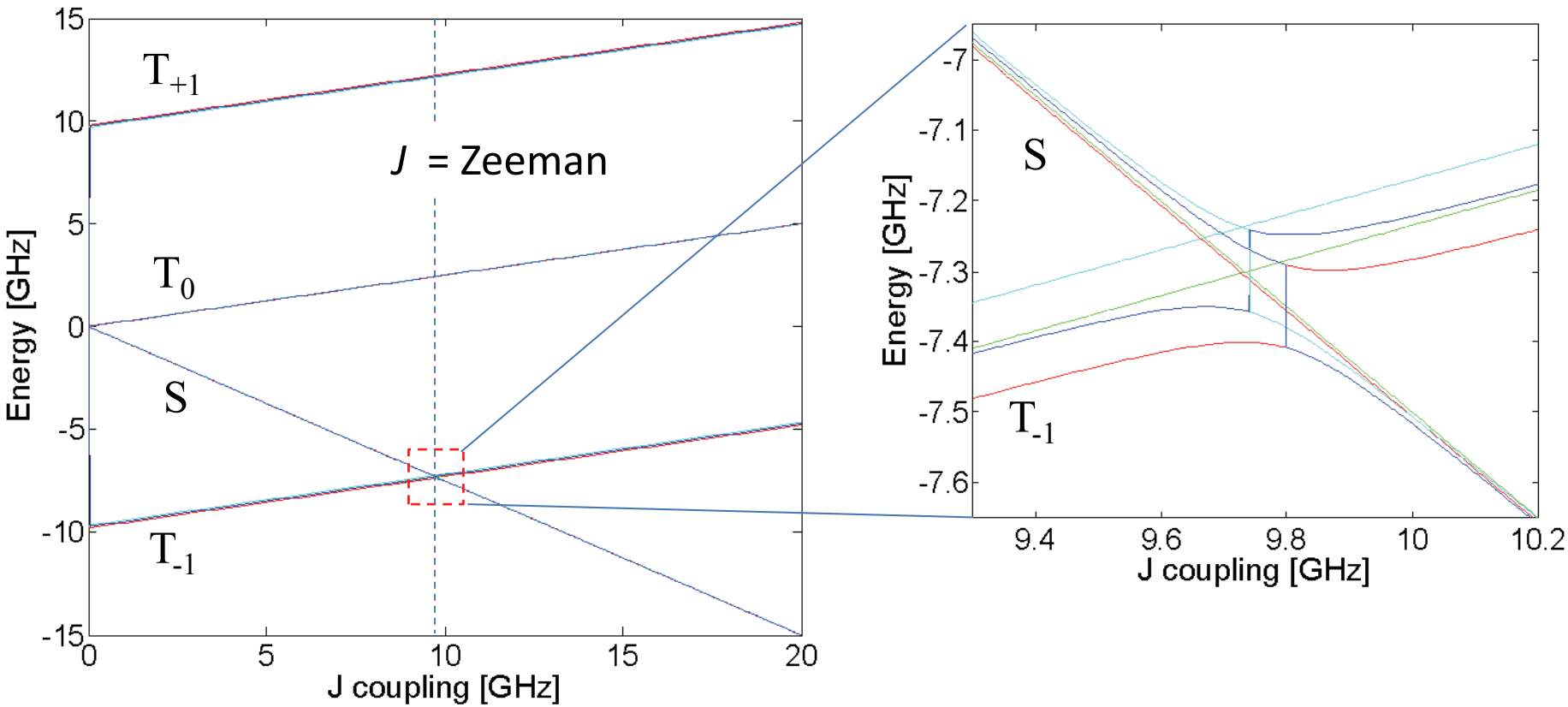


Four Spins ⇒ Sixteen States

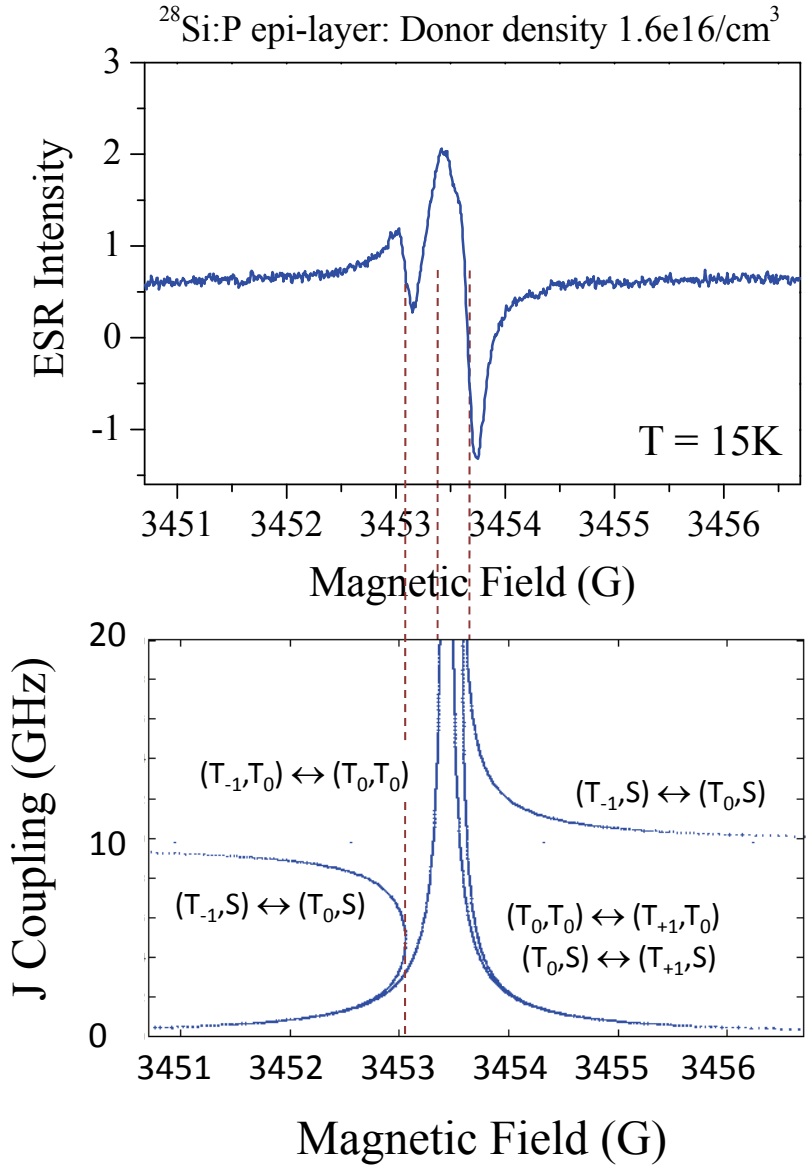


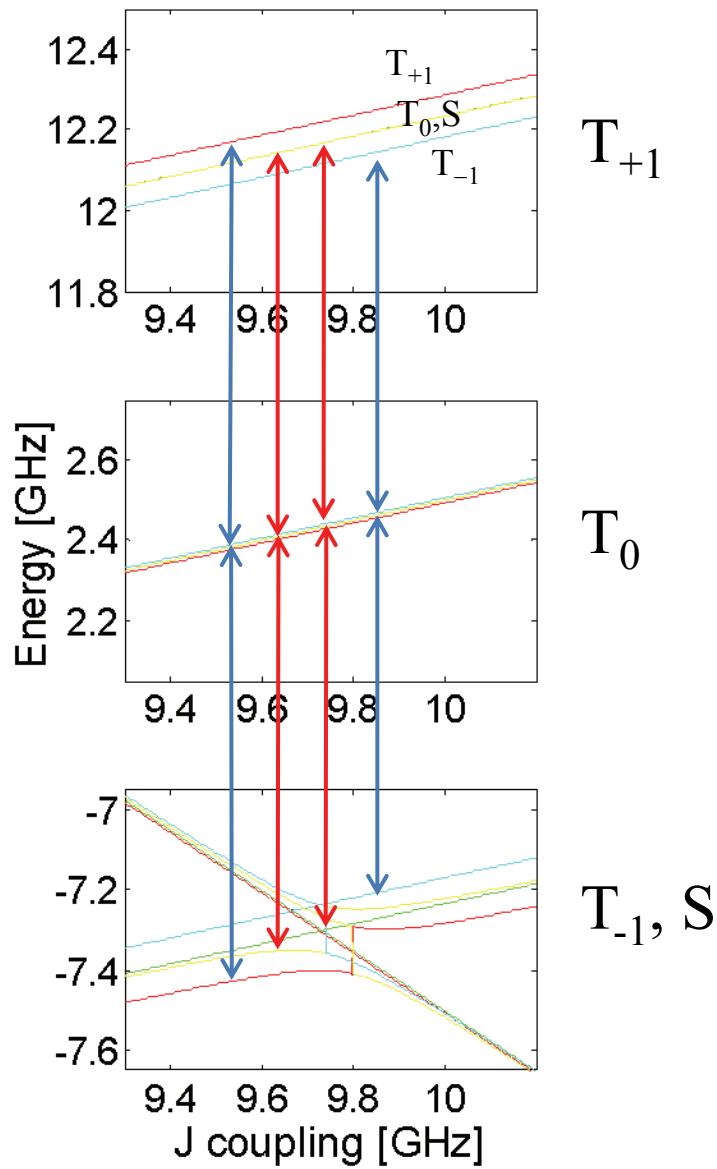
$$H = \omega_e \left(S_{Z1} + S_{Z2} \right) + J \cdot \overrightarrow{S_1}\overrightarrow{S_2} + a_P \overrightarrow{S_1}\overrightarrow{I_1} + a_P \overrightarrow{S_2}\overrightarrow{I_2}$$

- Zeeman frequency, ω_e = 9.7GHz
- Exchange coupling, J = 0 – 100GHz
- Hyperfine coupling, a_p = 117MHz

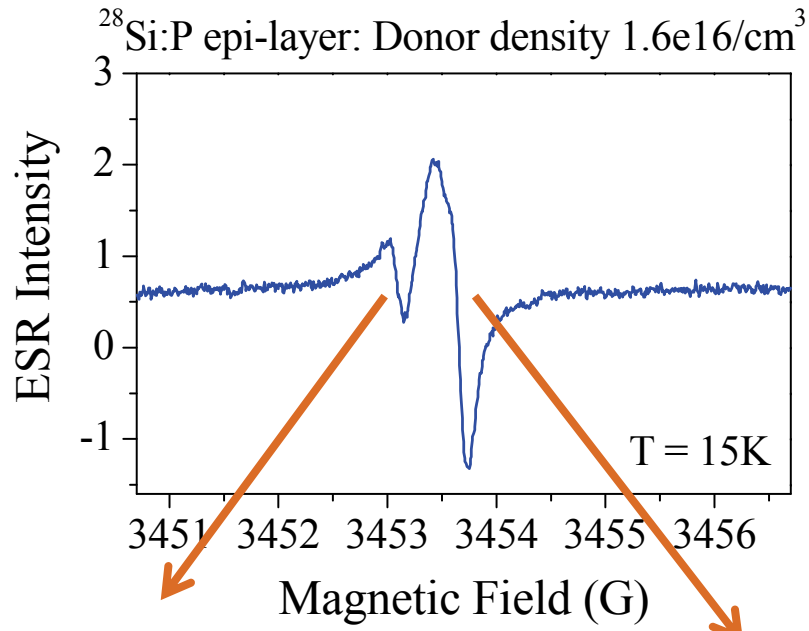


Central Dimer Line: Interpretation





Effect of J-Coupling on T_2



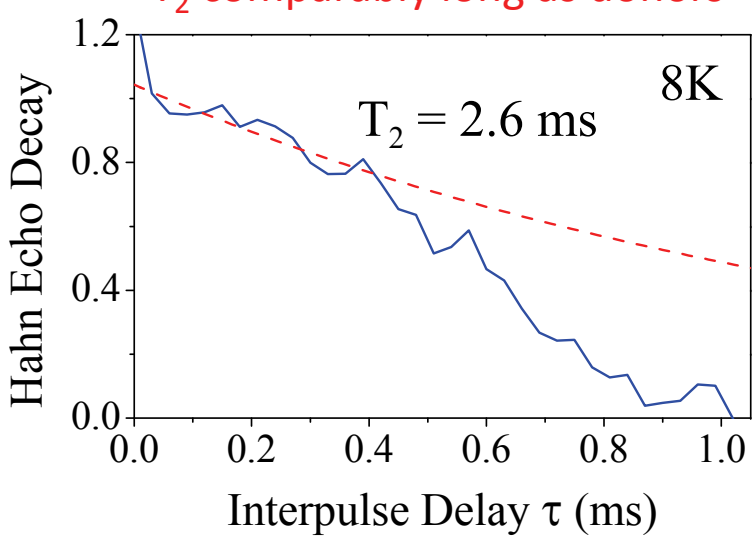
$(T_{-1},S) \leftrightarrow (T_0,S)$ for J = 3-7 GHz

$(T_0,S) \leftrightarrow (T_{+1},S)$ for J > 4 GHz

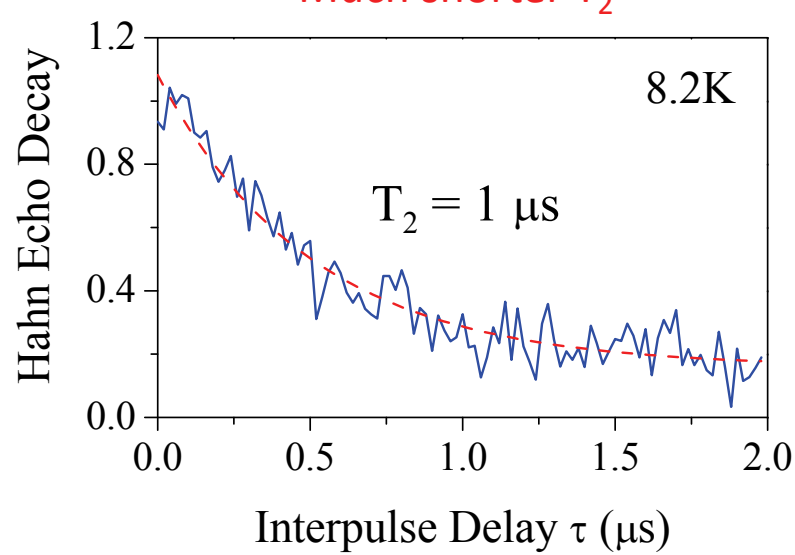
$(T_{-1},T_0) \leftrightarrow (T_0,T_0)$ for J > 12 GHz

$(T_0,T_0) \leftrightarrow (T_{+1},T_0)$ for J > 6 GHz

T_2 comparably long as donors



Much shorter T_2



Summary

- **Donor T_2 = 0.6 seconds in ^{28}Si at 1.8K:**
  - Almost same long as ^{31}P nuclear T_2 = 2 seconds!
  - Still much shorter than $T_1 \sim 1000$ seconds at 1.8K
  - There are evidences that T_2 can be further improved! $\Rightarrow$ However, at what cost?
    - Crystal quality
    - Surface passivation
- **Exchange-coupled donors (dimers):**
  - Some transitions, like $(T_0,T_0) \leftrightarrow (T_{+1},T_0)$, show short T_2 = 1 μs
  - Mechanism unknown:
    - Some part of it is a complex coherent evolution in 16x16 Hilbert space. Possibly refocusable?
    - Some part is a real relaxation. E.g. J-coupling fluctuation caused by electric charge noise
  - **Dimers are complicated!**