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Coherence of Donor Electron Spins in Isotopically Enriched Silicon

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There Are Always Noisy Spins Around

- Nuclear spins (e.g., ^{29}Si, but many others)
  - Hyperfine as well as dipolar interactions.
  - Relatively weak dipolar interactions between nuclei.
  - About 5% in natural Si, 50ppm has been achieved.
  - Thermal polarization not feasible.
- Electron spins (e.g., P-donors, but also surface)
  - Only dipolar interactions (assuming sparse enough to neglect exchange).
  - Coherence experiments: $10^{14}/cm^3$
  - Current technological limit: $10^{13}/cm^3$
  - Thermal polarization is feasible.

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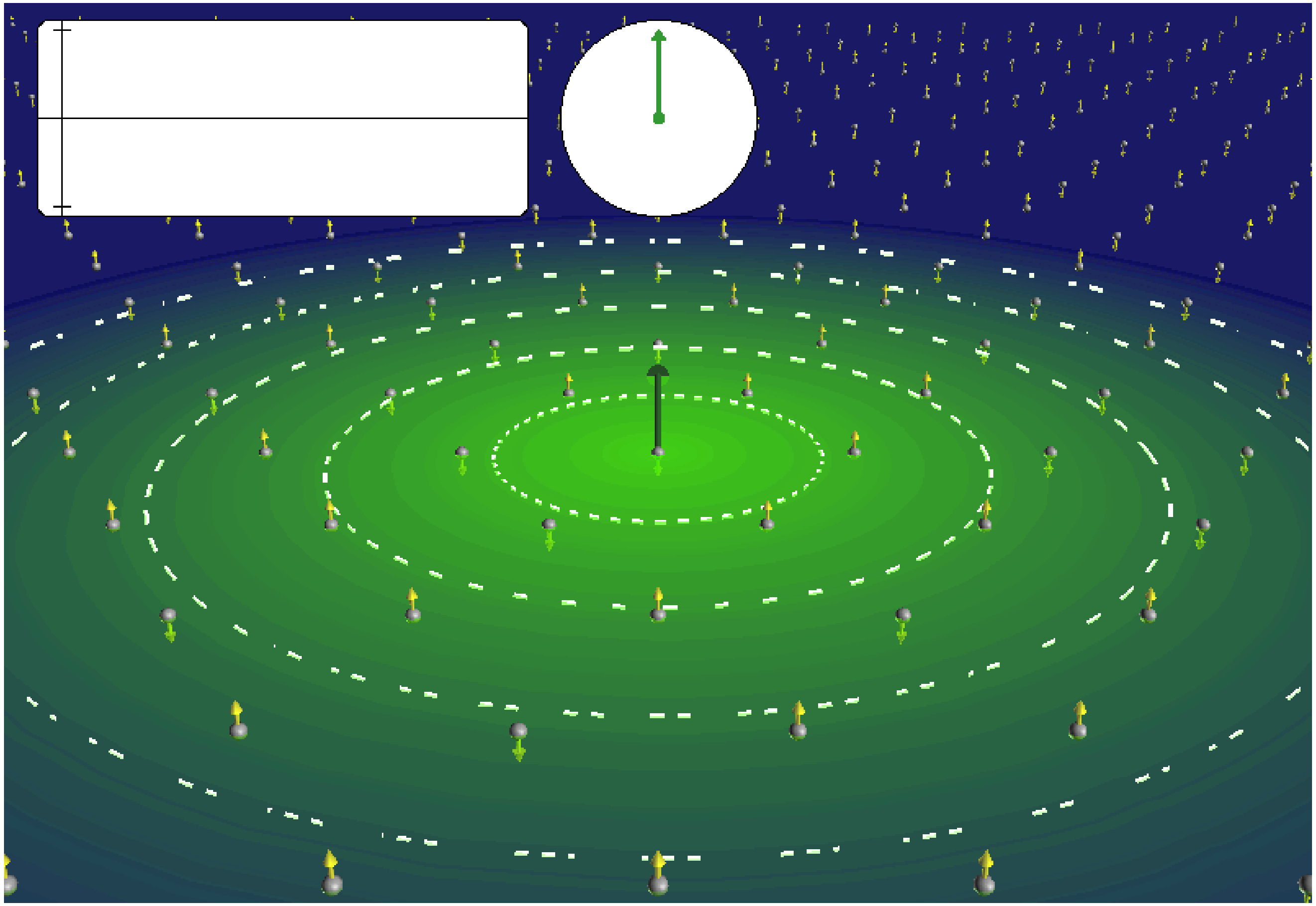
Central Spin Decoherence Problem



Spin Echo:

decompressor
are needed to see this picture.

$$\rho(t) = \hat{U}\rho(0)\hat{U}^{\dagger}, \quad \rho_q(t) = \mathrm{Tr}_B\,\rho(t)$$

Cluster Expansions Provide a Solution

Cluster correlation expansion[1] (based upon earlier[2] cluster expansion methods for the central spin decoherence problem):

$$L = \rho_q^{+-}(t)/\rho_q^{+-}(0)$$

$$L_{\mathcal{S}} = L$$ with the exclusion of spins outside of set $\mathcal{S}$

$$L = \prod_{\mathcal{S}} \tilde{L}_{\mathcal{S}}, \quad L_{\mathcal{S}} = \prod_{\mathcal{C} \subseteq \mathcal{S}} \tilde{L}_{\mathcal{C}},$$

$$\tilde{L}_{\mathcal{S}} = L_{\mathcal{S}} / \prod_{\mathcal{C} \subset \mathcal{S}} \tilde{L}_{\mathcal{C}}$$

$$L_{\mathrm{CCE}}^{(k)} = \prod_{\|\mathcal{S}\| \leq k} \tilde{L}_{\mathcal{S}}.$$

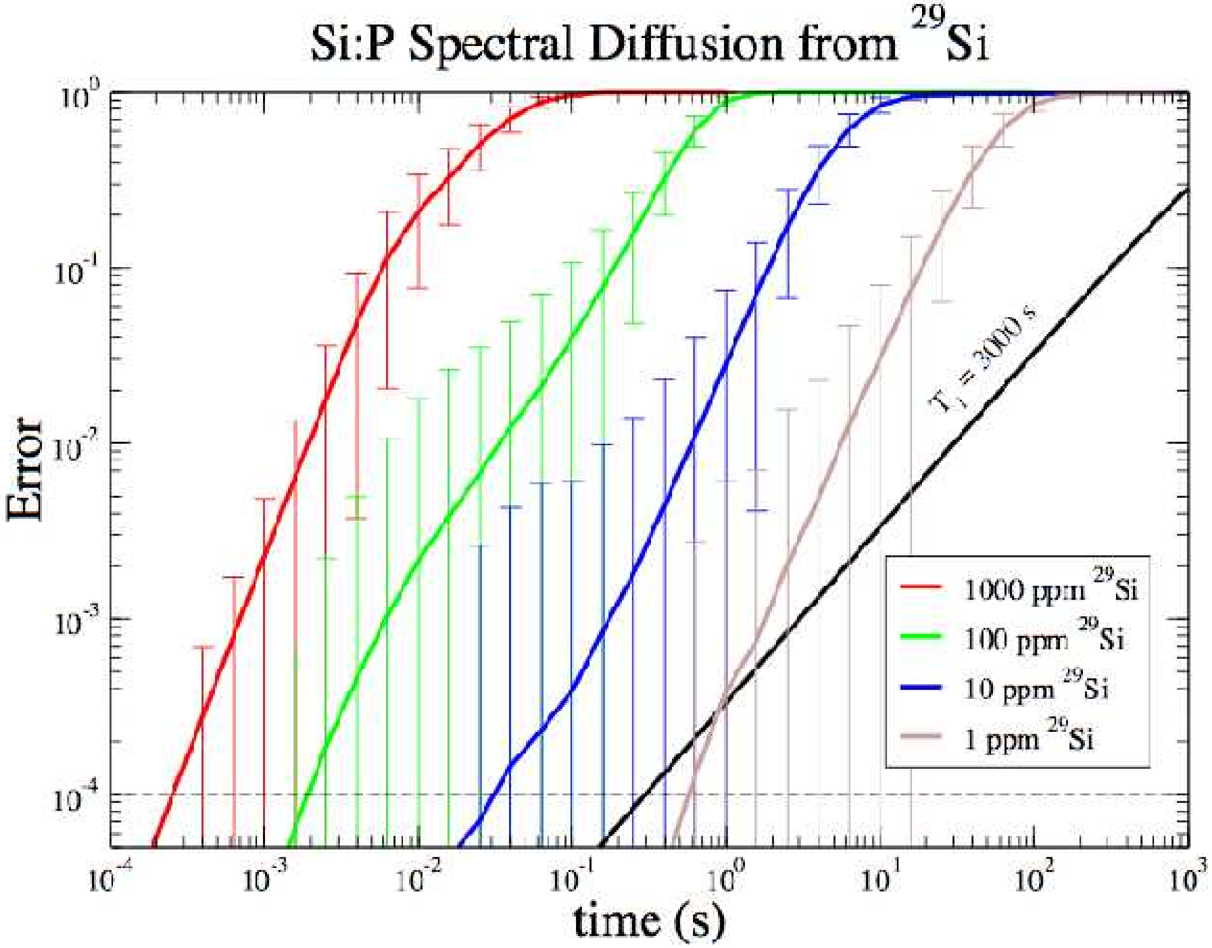
No fitting Parameters!

Experiment:

A.M. Tyryshkin, J.J.L. Morton, S.C. Benjamin, A. Ardavan, G.A.D. Briggs, J.W. Ager, S.A. Lyon, J. Phys.: Condens. Matter **18**, S783 (2006).

[1] Wen Yang, Ren-bao Liu, Phys. Rev. B **78**, 085315 (2008).
[2] W. M. Witzel, Rogerio de Sousa, S. Das Sarma, Phys. Rev. B **72**, 161306(R) (2005); W. M. Witzel, Rogerio de Sousa, S. Das Sarma, Phys. Rev. B **74**, 035322 (2006).

Dephasing due to ^{29}Si



Sparse Electron Spin Systems Present New Challenges

Internal spin averaging:

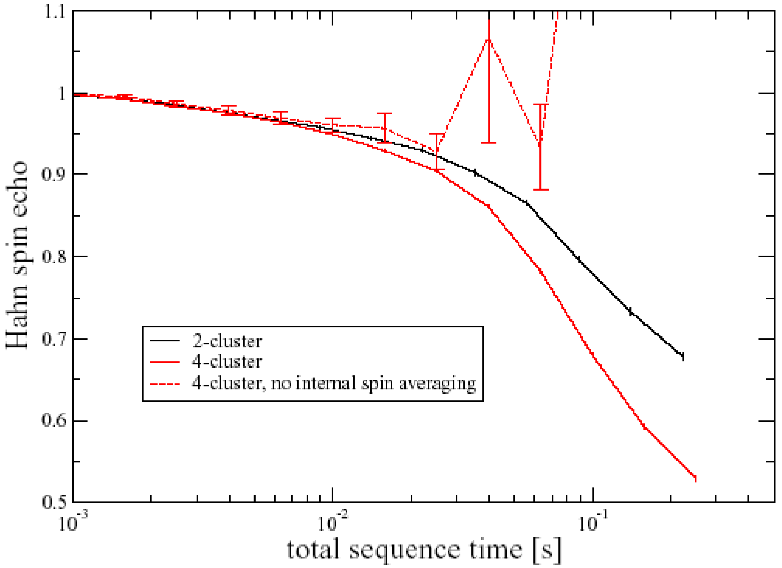
$$\tilde{L}_{\mathcal{S}}^{\mathcal{J}} = \frac{\langle L_{\mathcal{S}}^{J} \rangle_{J \in \mathcal{J}}}{\prod_{\mathcal{C} \subset \mathcal{S}} \tilde{L}_{\mathcal{C}}^{\mathcal{J}}},$$

Spin configuration

Set of spin configurations

$$L^{(k)} = \left\langle \prod_{\|\mathcal{S}\| \leq k} \tilde{L}_{\mathcal{S}}^{\mathcal{T}(J,\mathcal{S},k)} \right\rangle_{J}$$

$$\mathcal{T}(J,\mathcal{S},k) = \{J' \mid \|\mathcal{D}(|J\rangle, |J'\rangle) \cup \mathcal{S}\| \leq k\}$$



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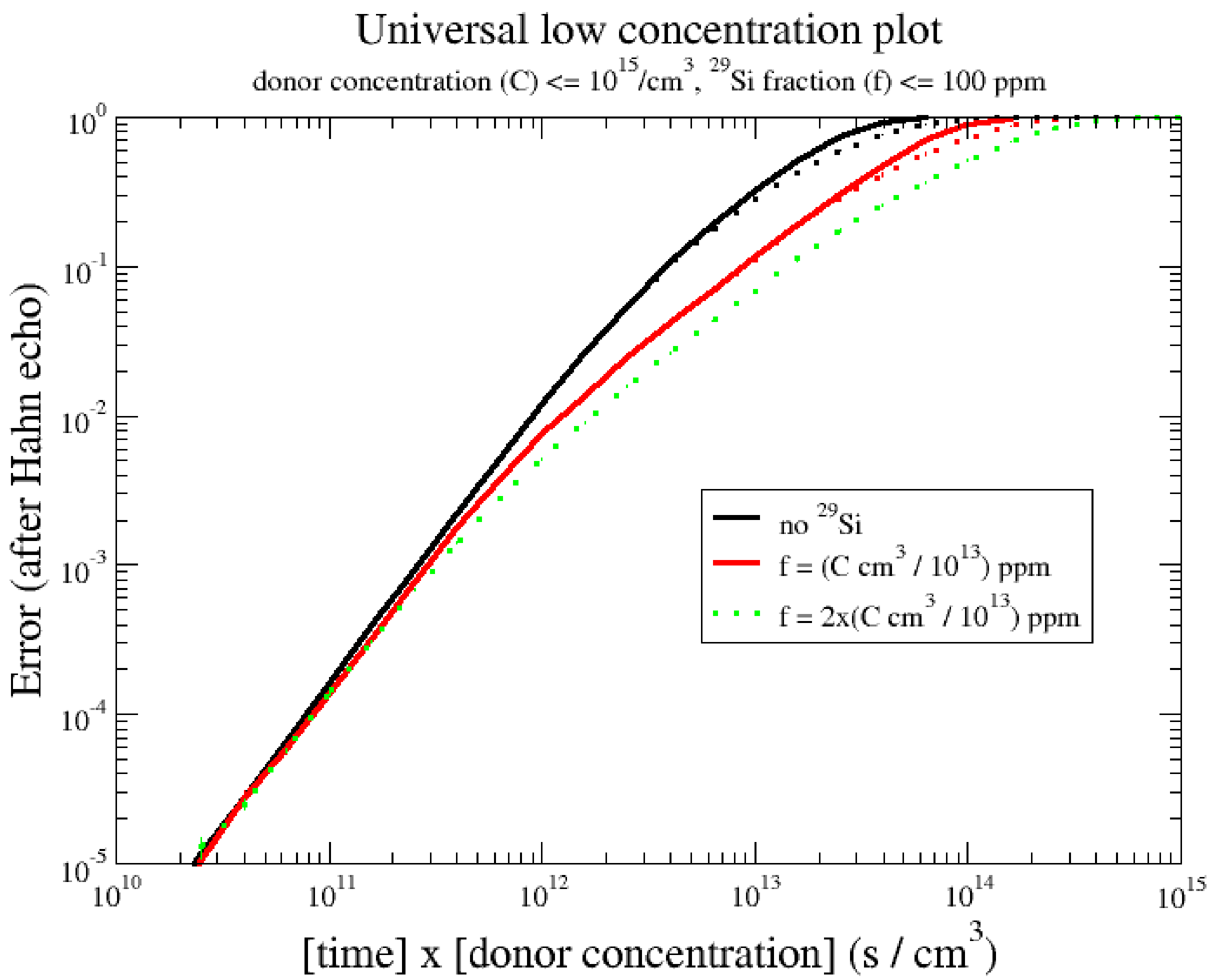
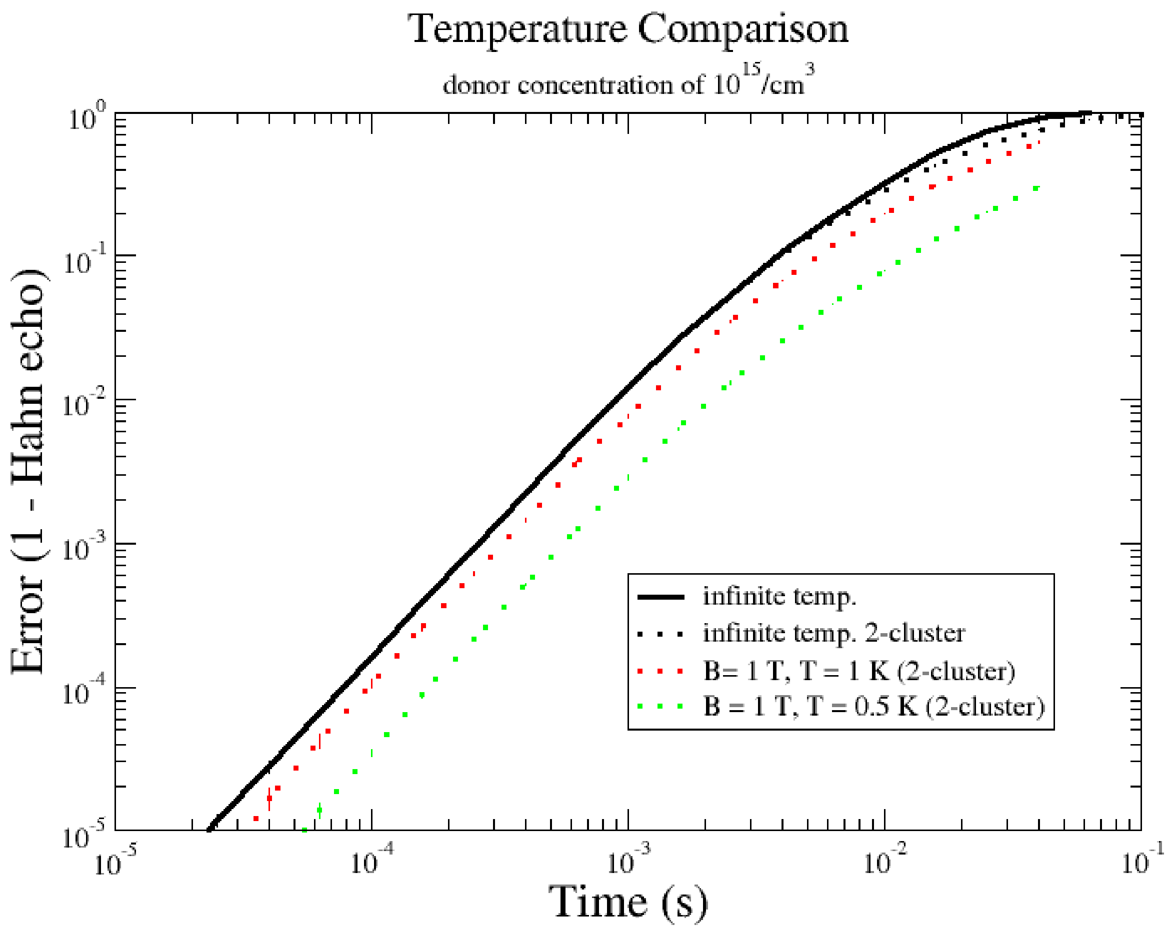
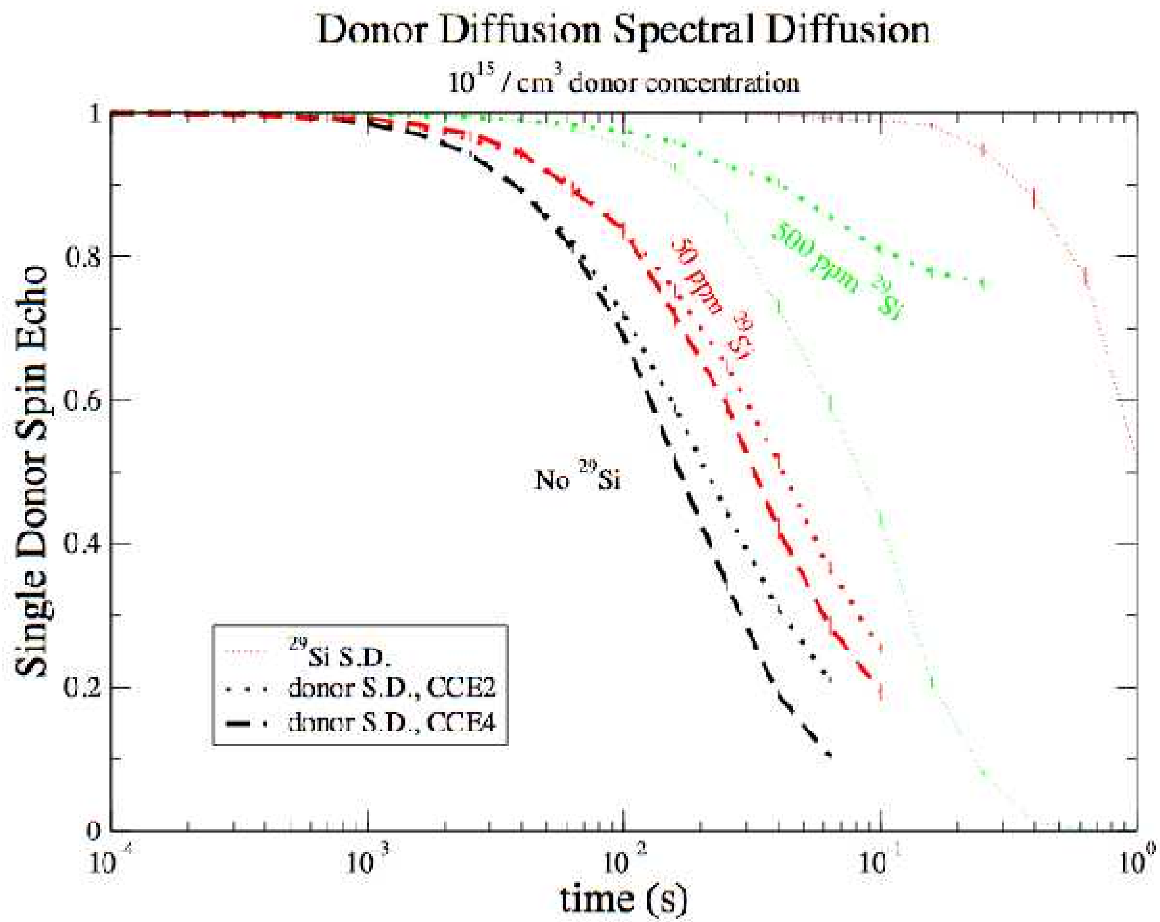
Dephasing due to P-donors



Temperature Dependence (polarizing the P-donors)



Some ^{29}Si Actually Improves T_2! (But Not in the Low Error Regime)



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Qubit Yield for Good Coherence

Figure, not yet ready, showing percent of qubit samples (with differing spatially random baths) that maintains coherence by some set amount for some set amount of time for both P-donor and ^{29}Si baths.

Conclusions

- Cluster expansions successfully solve the central spin decoherence problem.
- We have adapted the Cluster Correlation Expansion technique to have the versatility to solve problems of sparse electron spin baths.
- We've calculated decoherence for low donor concentrations and low ^{29}Si concentrations.
- Having some ^{29}Si improves T_2 at low donor concentrations.
- But T_2 isn't the right figure of merit! In the low error regime for QC, ^{29}Si is not good to have around.
- There is a large sample-to-sample variation in baths of sparse spins; yield is more important then average decoherence.