SAND2010-2007C

Coherence of Donor Electron Spins in Isotopically Enriched Silicon

Wayne Witzel, Rick Muller, Malcolm Carroll, Andrea Morello, Lukasz Cywinski, Sankar Das Sarma

APS March Meeting
Portland, Oregon

What limits electron spin coherence in Silicon?

In particular, from spin noise:

Nuclear Spins	Electron Spins
^{29}Si, SiGe, other impurities.	P-donors, surface defects.
Hyperfine as well as dipolar interactions.	Only dipolar interactions.
Relatively weak dipolar interactions between nuclei.	Interactions all of comparable strength.
About 5% in natural Si, 50ppm has been achieved.	Coherence meas.: $10^{14}/cm^3$ Techn. limits: $10^{12}/cm^3$-$10^{12}/cm^3$
Thermal polarization not feasible (sub-mK).	Thermal polarization is feasible (sub-K).

Experiments show T_2=600 ms. What limits this?

Donors: $1.2\times10^{14}/cm^3$, ^{29}Si: ~50 ppm

QuickTime™ and a
decompressor
are needed to see this picture.

A. M. Tyryshkin et al, Silicon Qubit Workshop, August 2009, Berkeley, CA, USA

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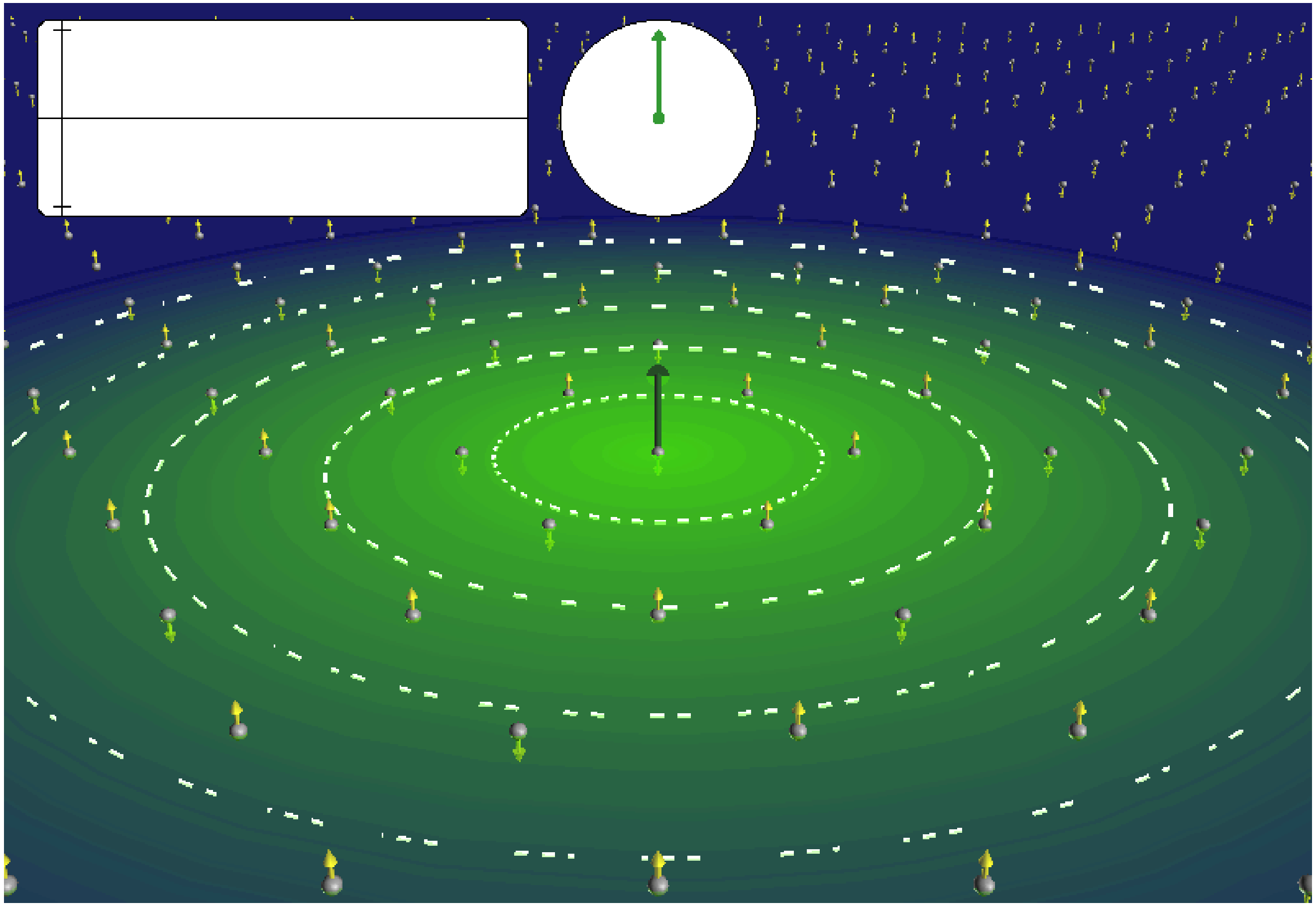
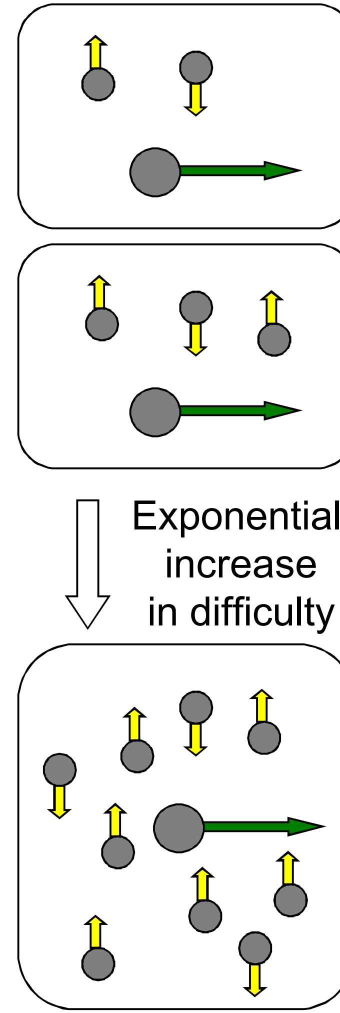
Central Spin Decoherence Problem





Spin Echo: decompressor
are needed to see this picture.

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

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Cluster Expansions Provide a Solution

Cluster Expansion Method[1]

No fitting Parameters!

Experiment:

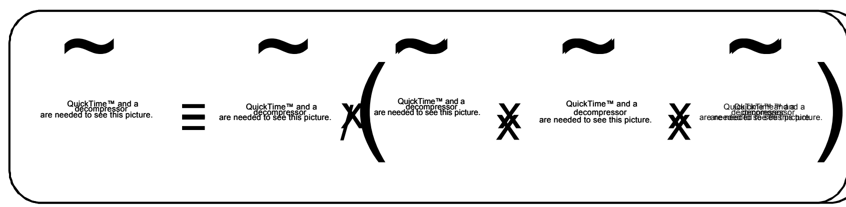
A.M. Tyryshkin, J.J.L. Morton, S.C. Benjamin, A. Ardavan, G.A.D. Briggs, J.W. Ager, S.A. Lyon, J. Phys.: Condens. Matter **18**, S783 (2006).

Cluster correlation expansion[2]:

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

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

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

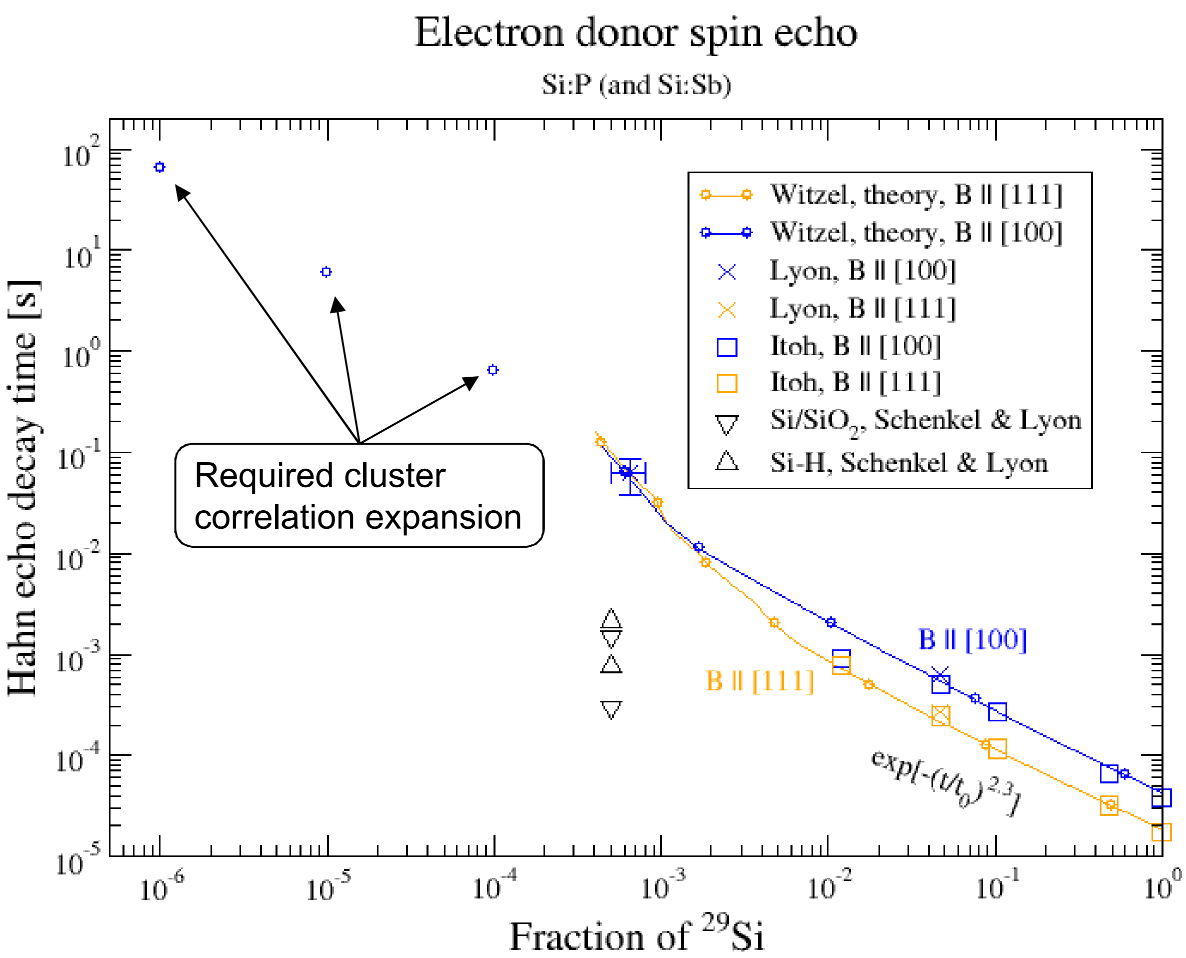


$$L_{\mathrm{CCE}}^{(k)} = \prod_{\|\mathcal{S}\| \leq k} \tilde{L}_{\mathcal{S}}.$$

[1] W. M. Witzel, Rogerio de Sousa, S. Das Sarma, Phys. Rev. B **72**, 161306(R) (2005); W. M. Witzel, S. Das Sarma, Phys. Rev. B **74**, 035322 (2006).

[2] Wen Yang, Ren-bao Liu, Phys. Rev. B **78**, 085315 (2008).

Dephasing due to ^{29}Si, T_2



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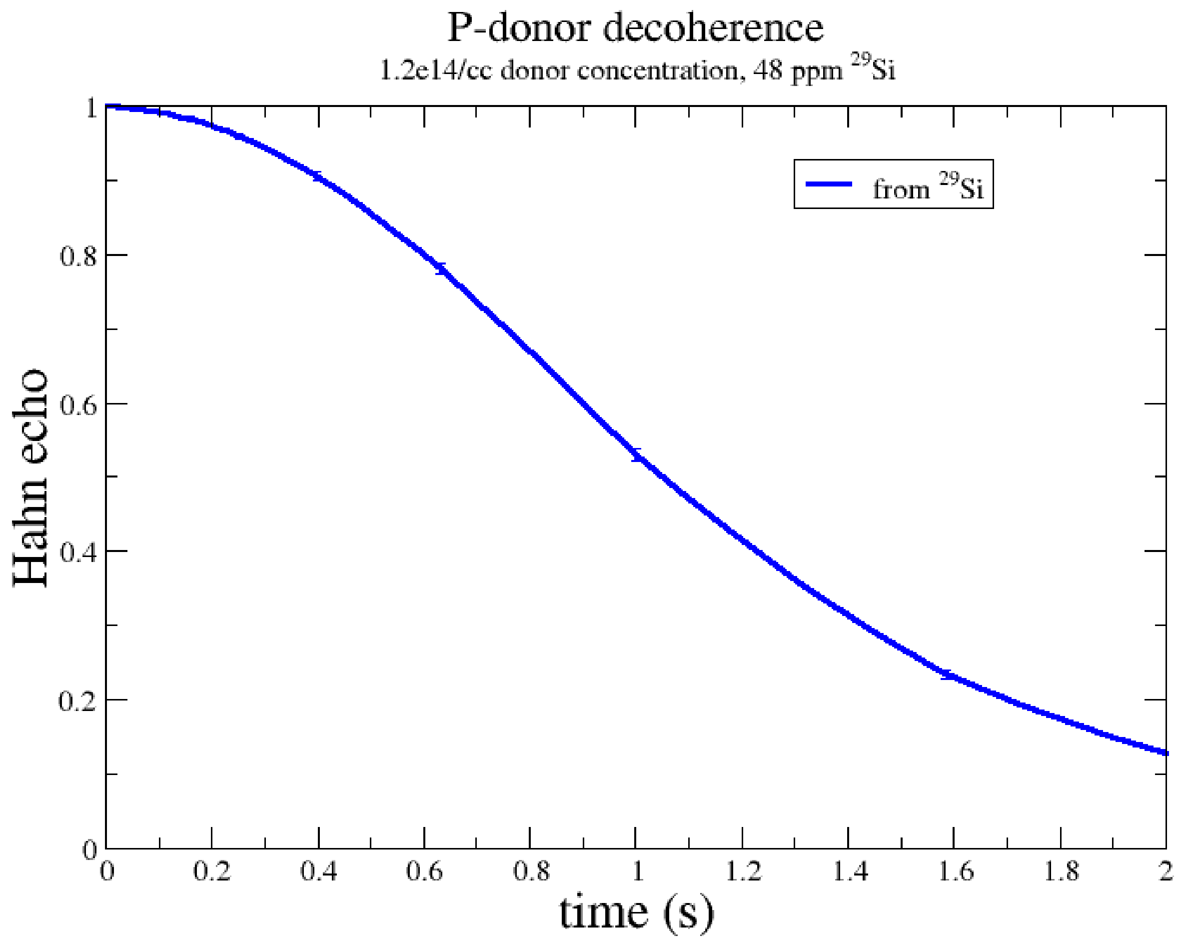
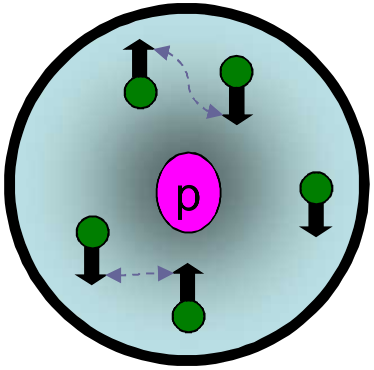
Theory: ^{29}Si spin noise





Sparse Electron Spin Systems Present New Challenges

Internal spin averaging:

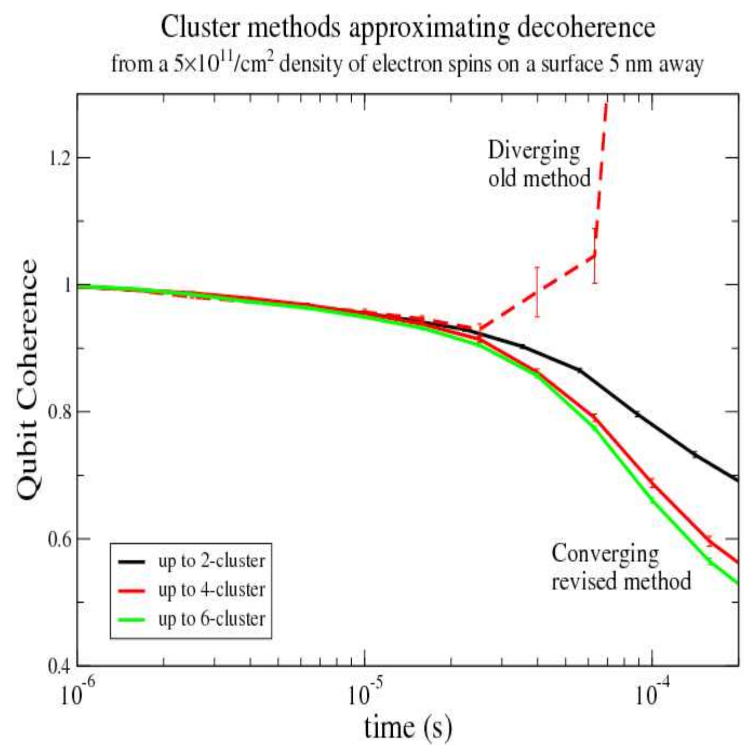
Set of spin configurations

Spin configuration

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

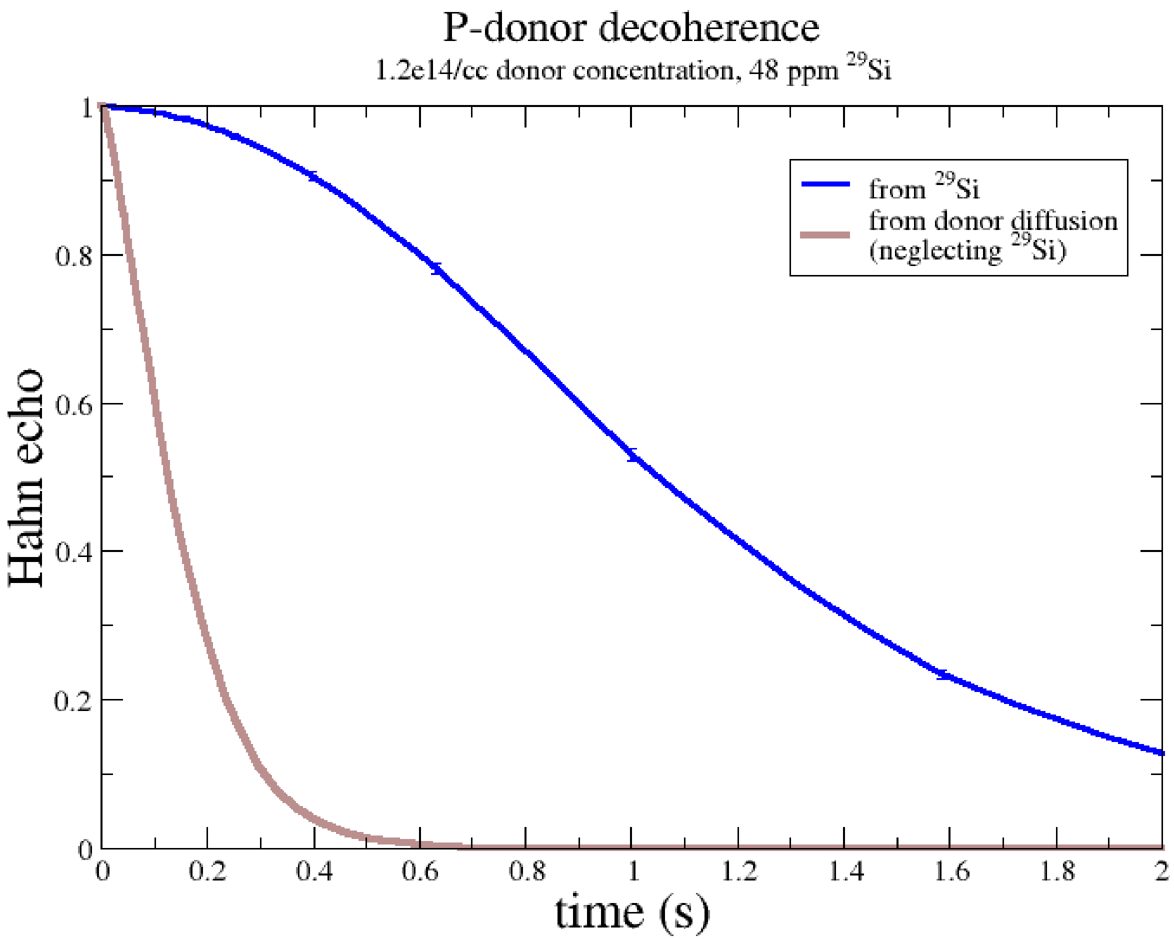
$$L^{(k)} = \left\langle \prod_{||\mathcal{S}||\le k} \tilde{L}_{\mathcal{S}}^{\mathcal{T}(J,\mathcal{S},k)} \right\rangle_J$$

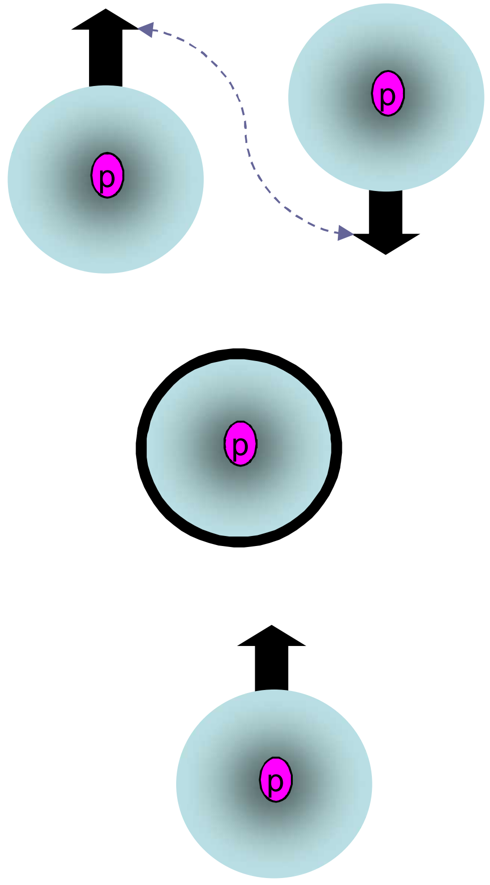
QuickTime™ and a
decompressor
are needed to see this picture.



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

Theory: donor diffusion noise (neglecting ^{29}Si)





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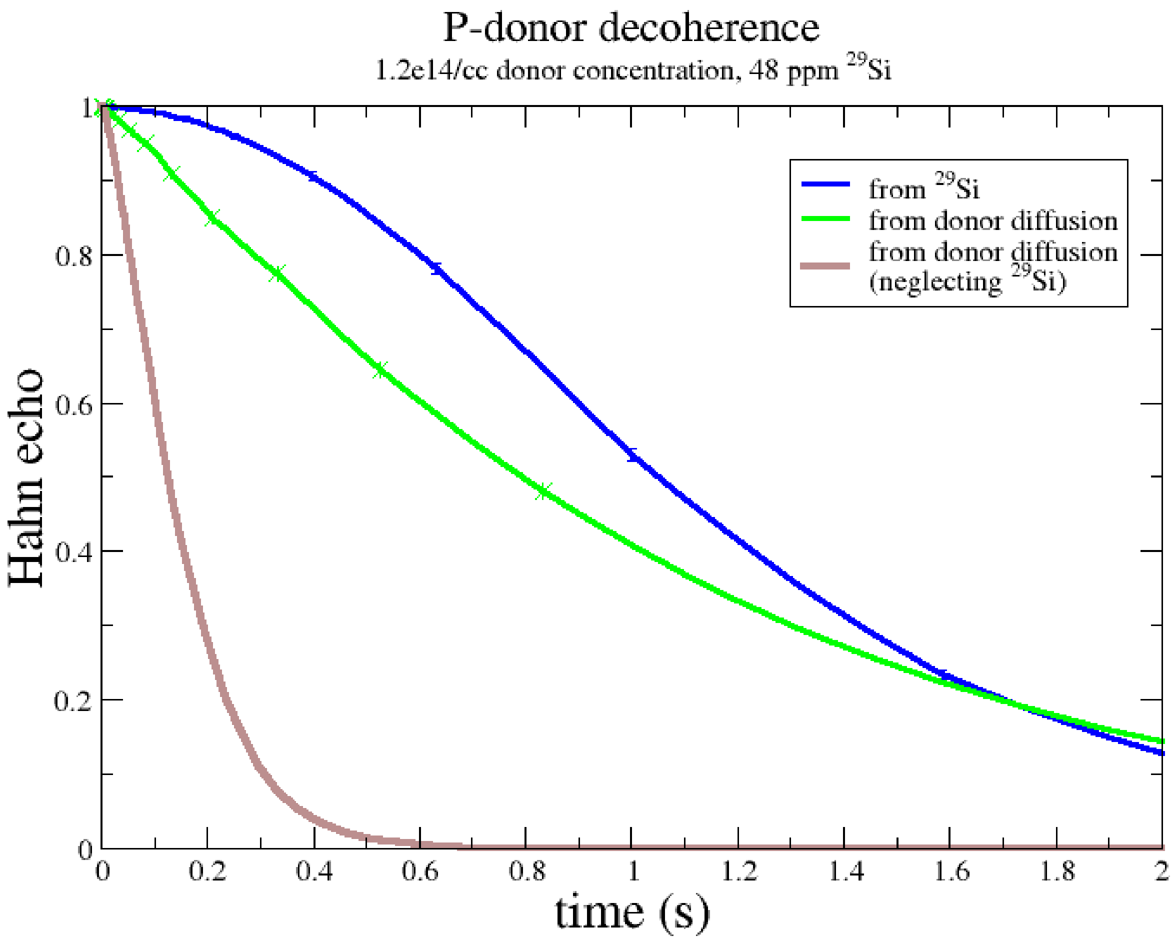
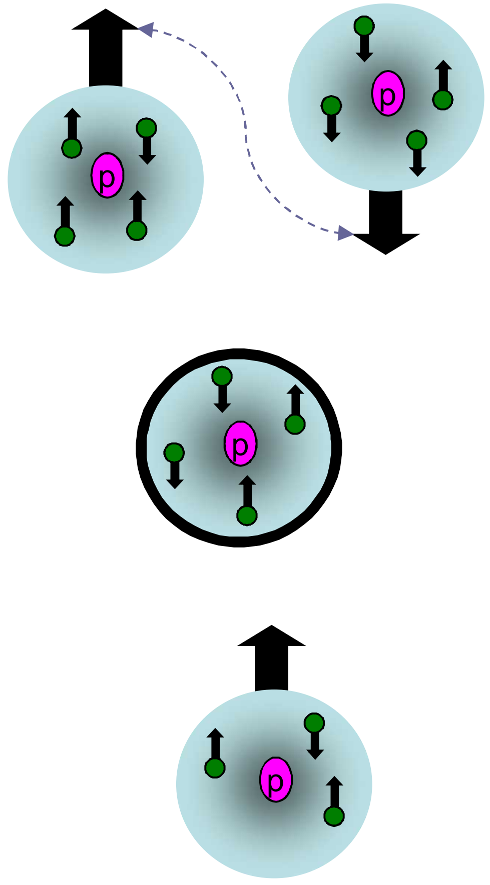
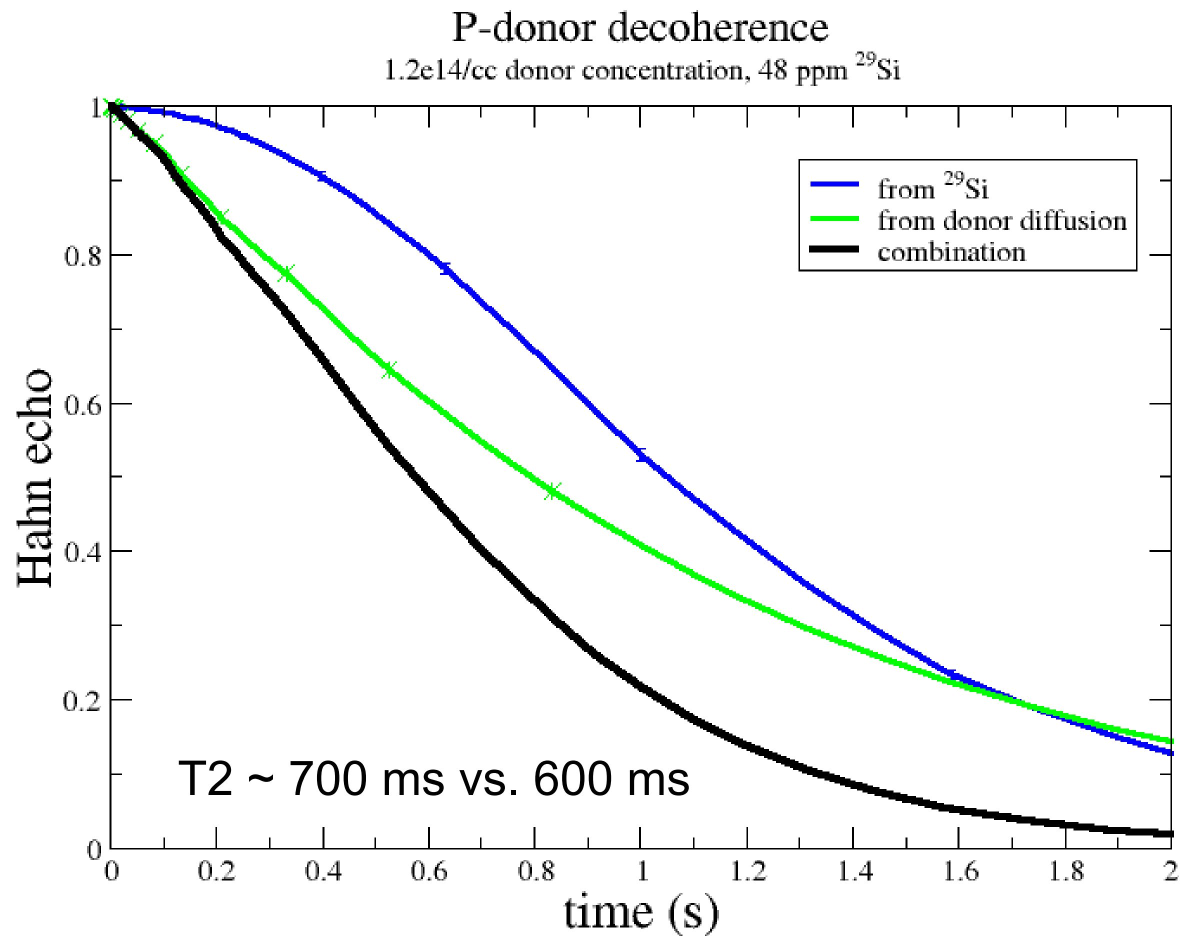
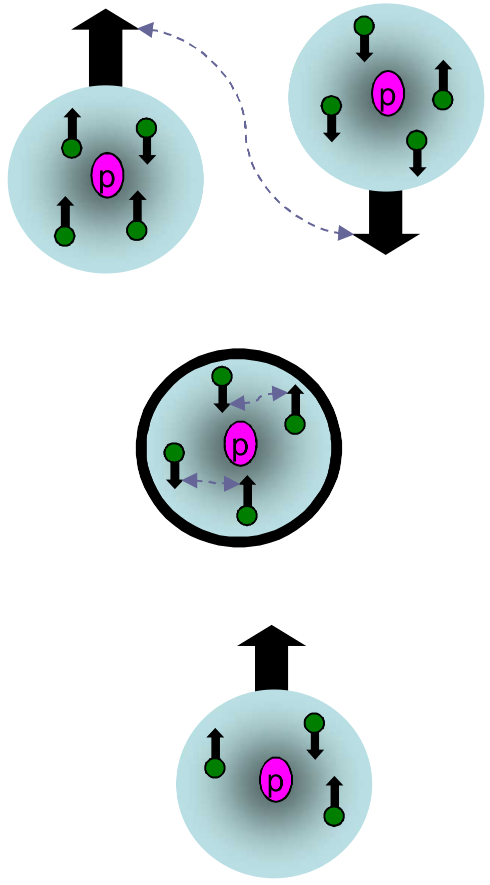
Theory: donor diffusion noise (with ^{29}Si)



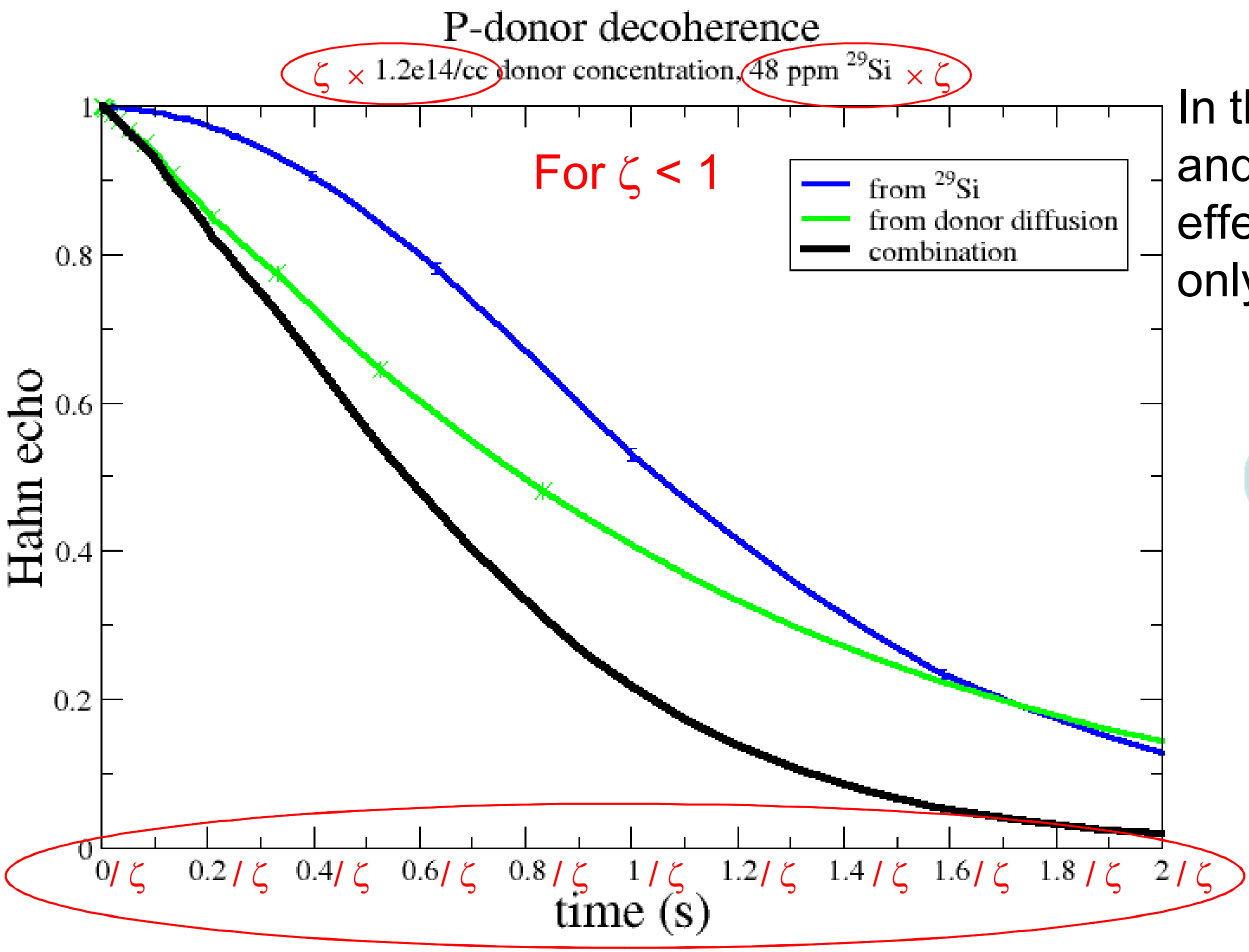


Theory: donor diffusion noise and ^{29}Si noise



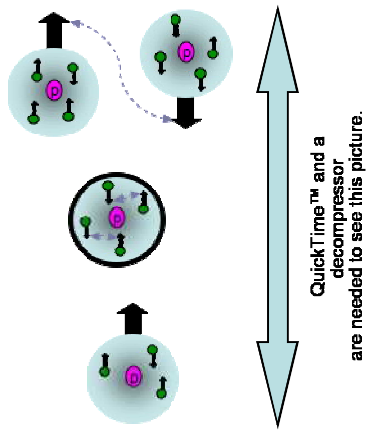


Benefit of theory: changing concentration



In this regime of low ^{29}Si and high B-field, the effective Hamiltonian has only dipolar interactions.

QuickTime™ and a decompressor are needed to see this picture.



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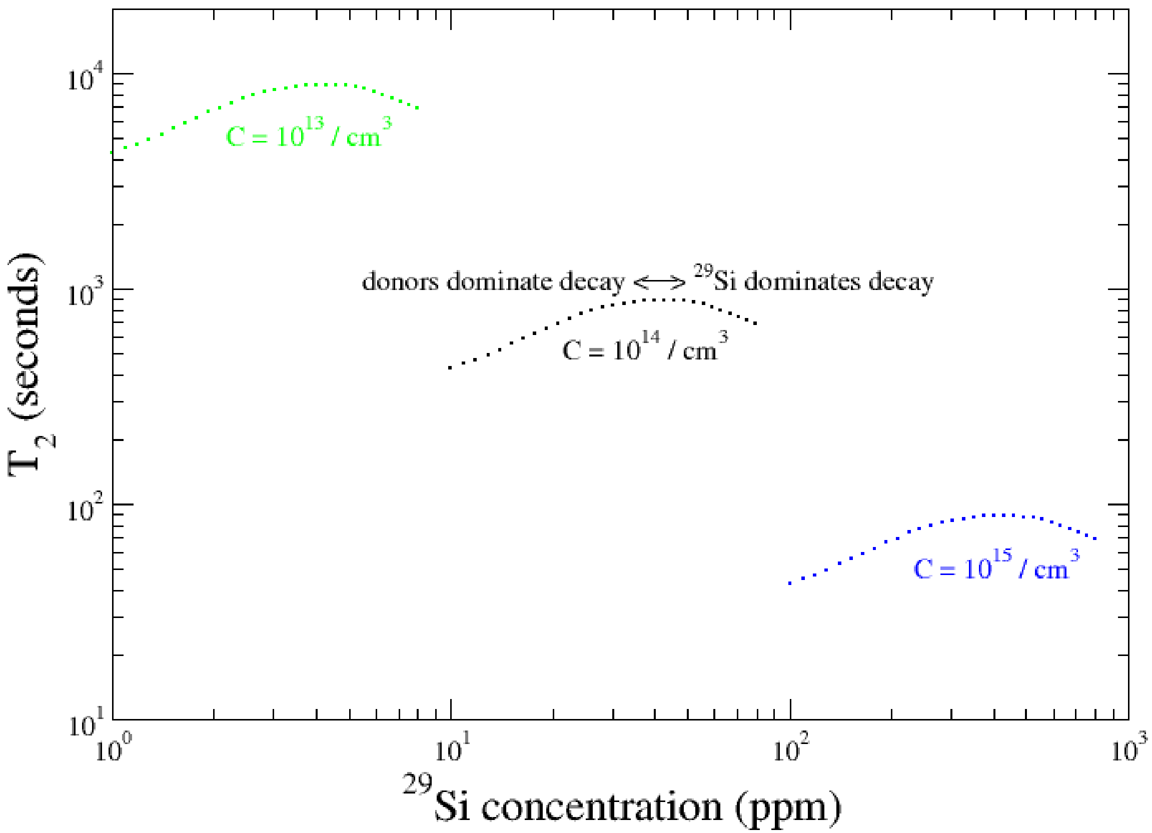
Benefit of theory: changing concentration

T_2 can actually improve with increasing ^{29}Si!



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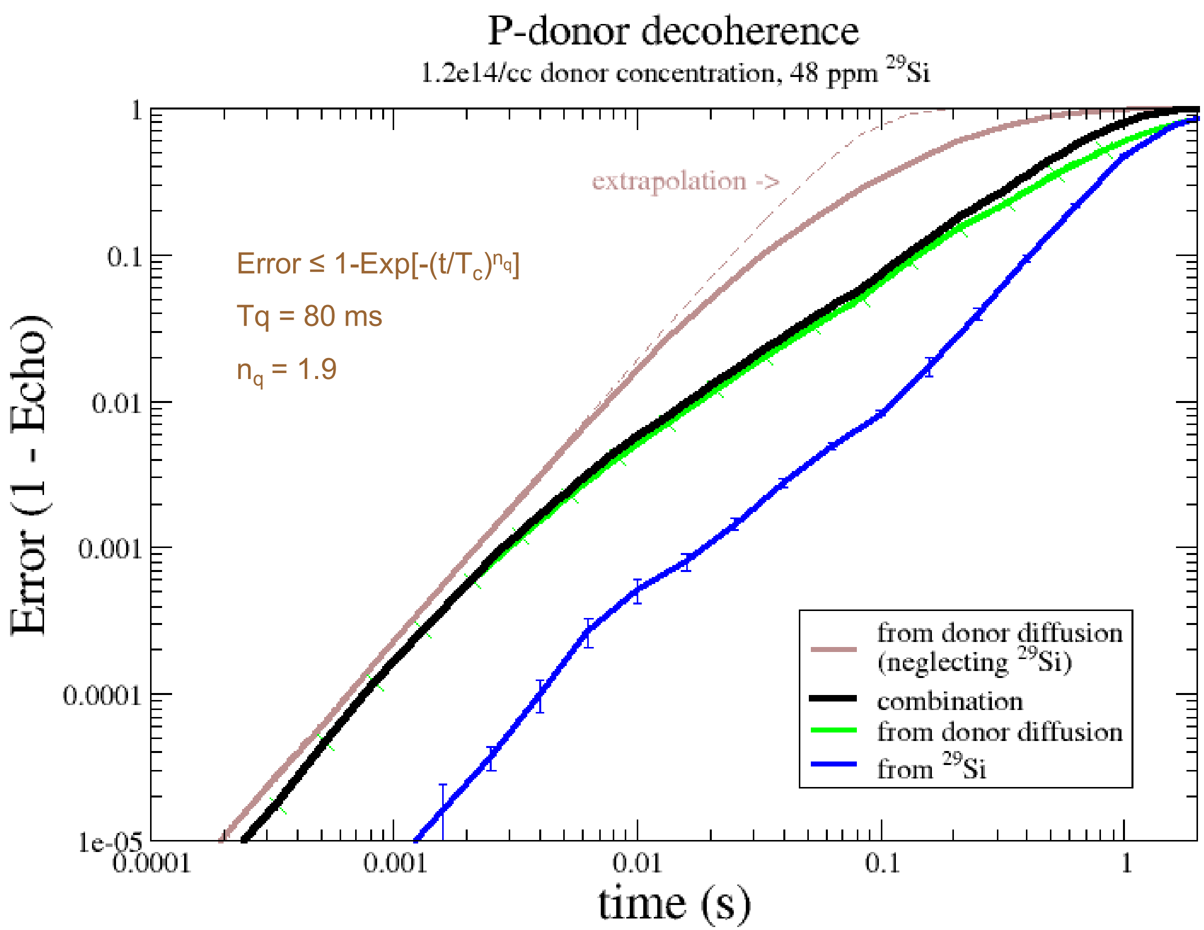
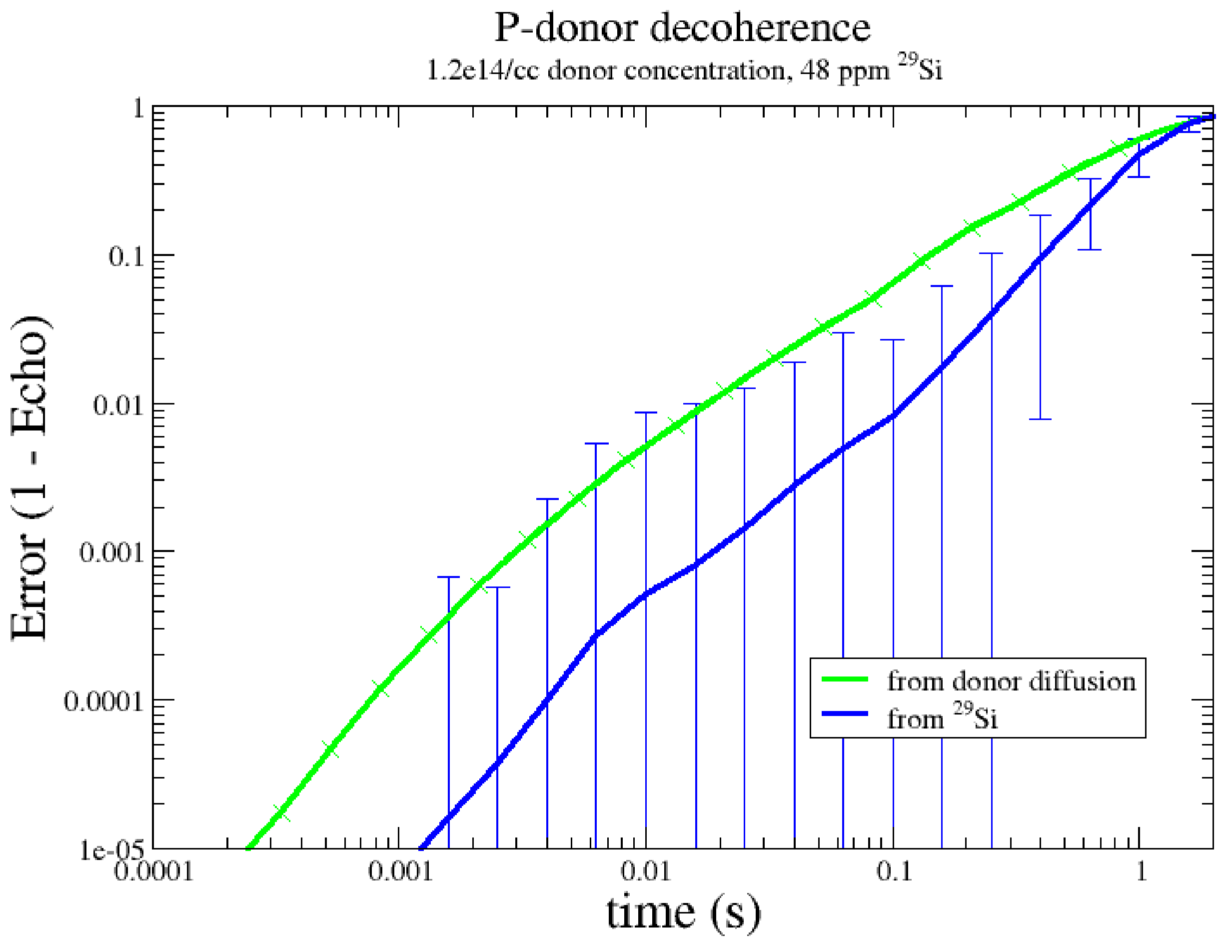
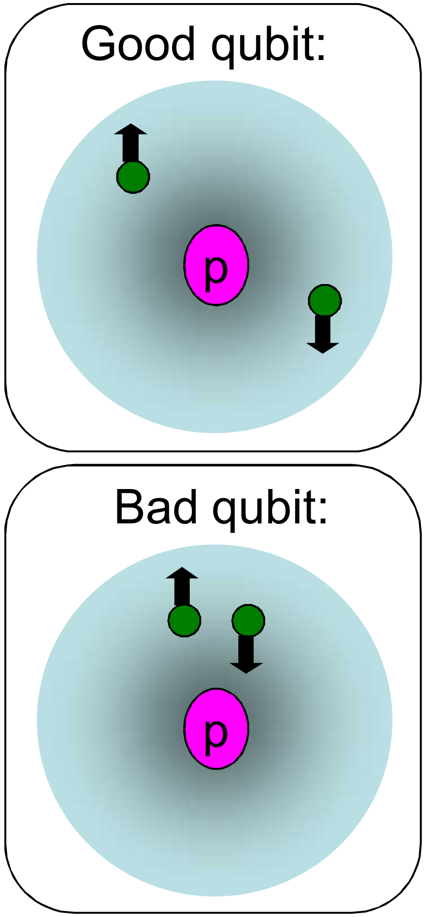
Benefit of theory: low error behavior



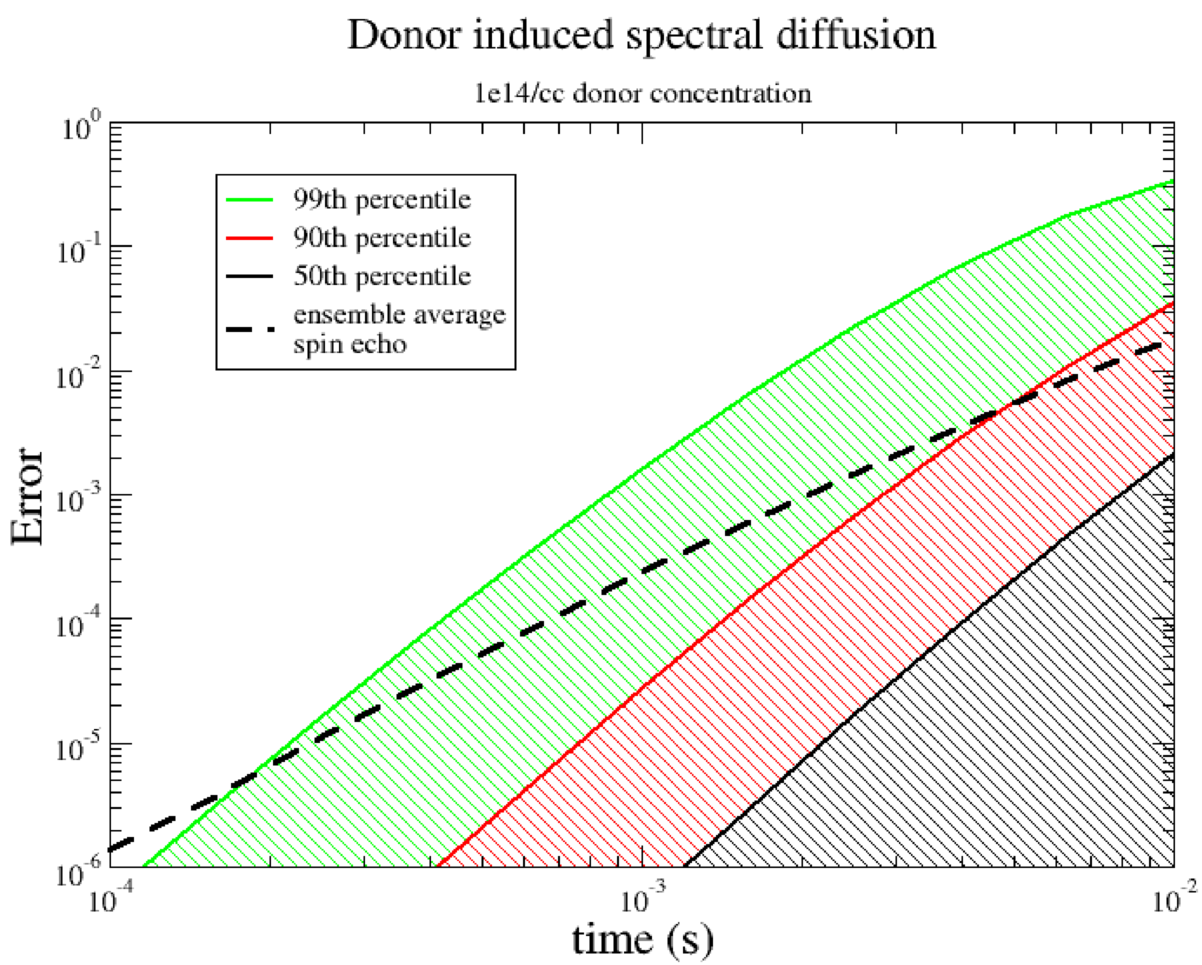
For Q. C., it's better to characterize the low error behavior. For this, we introduce T_q and n_q. An example is given in the "donor diffusion without ^{29}Si" case.

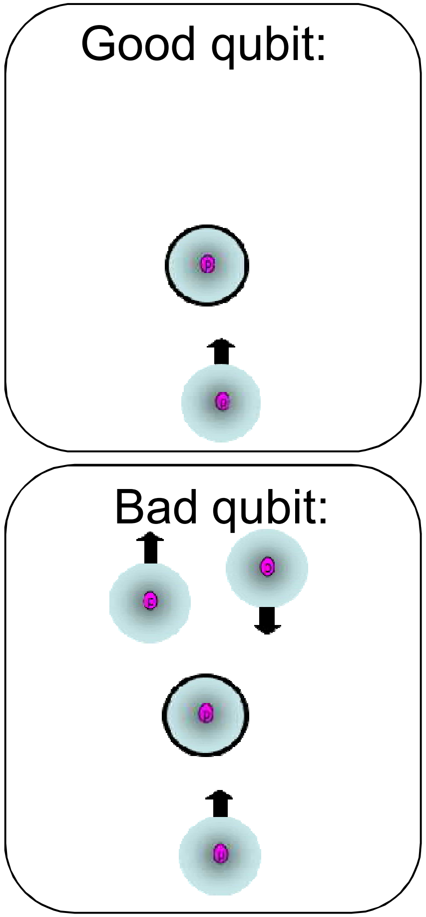
Benefit of theory: sample-to-sample variation (^{29}Si decay)



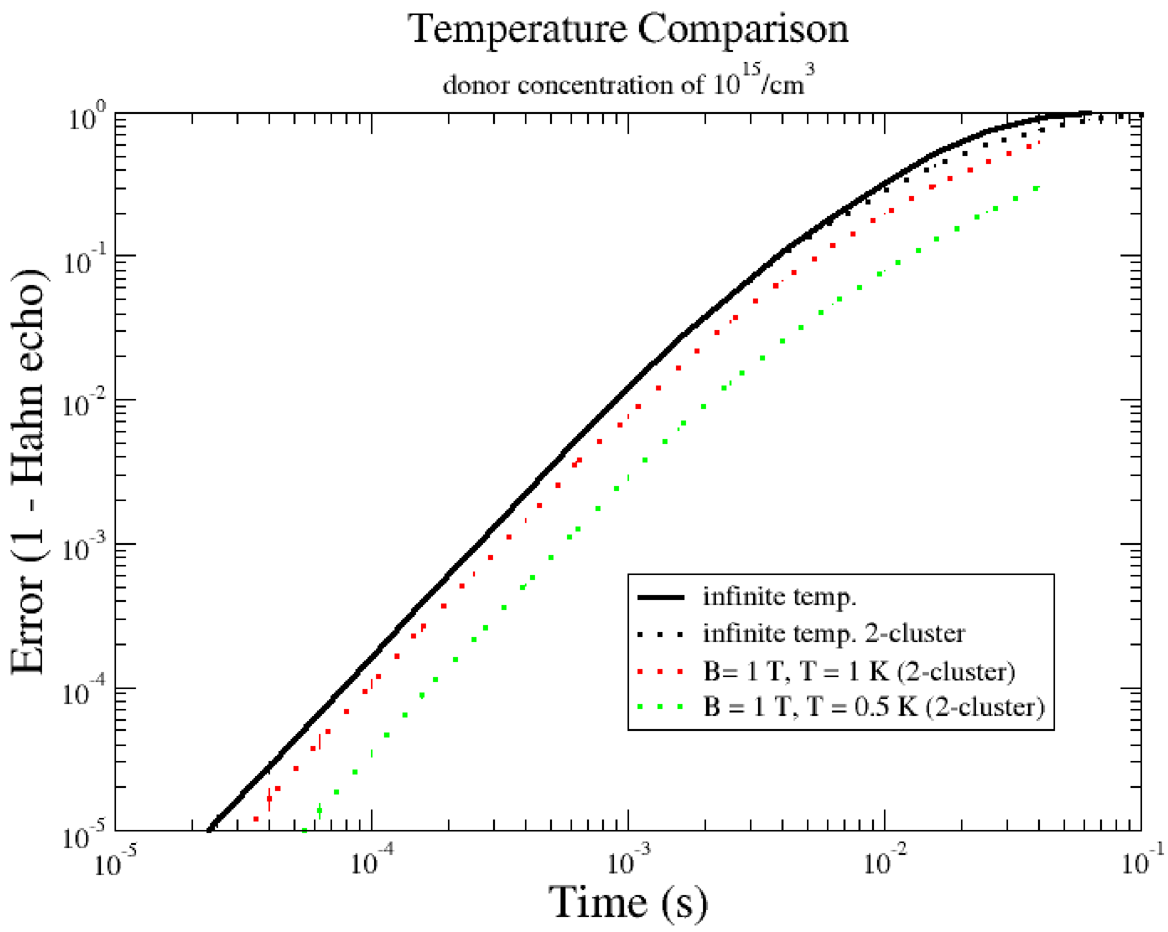


Benefit of theory: sample-to-sample variation (donor decay)



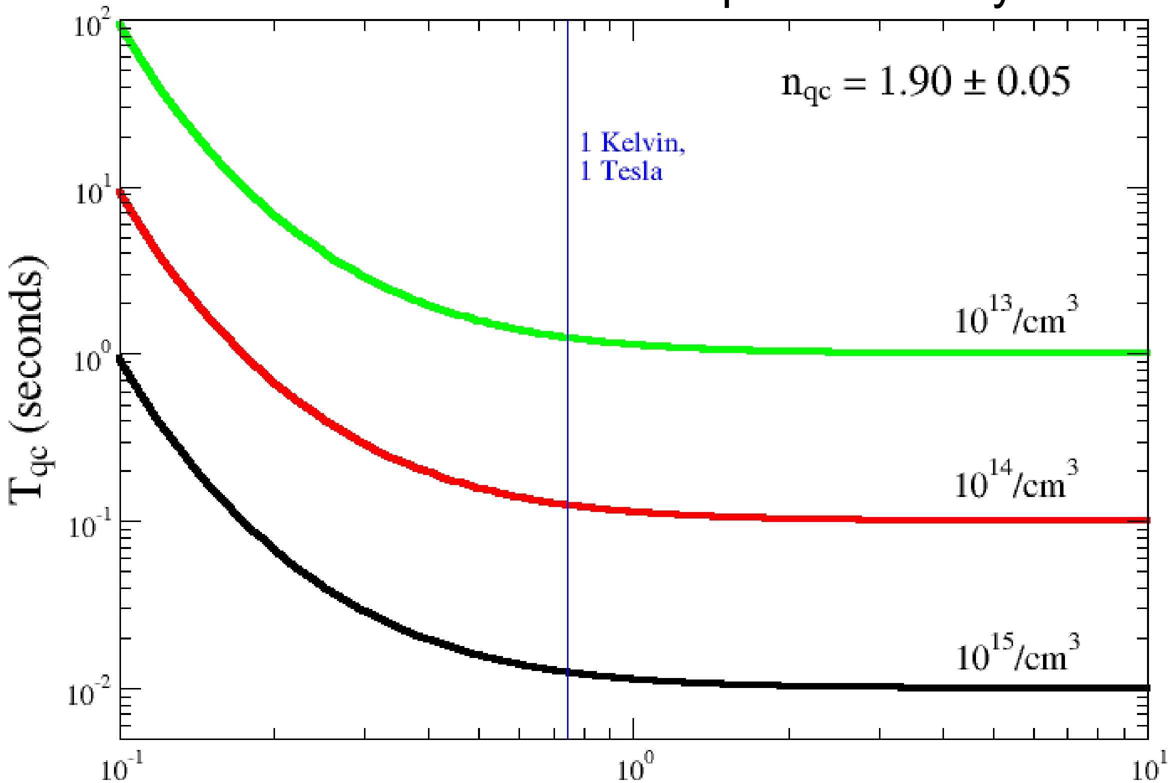


Benefit of theory: low temperature



Benefit of theory: low temperature

From considerations of spin noise only



2-cluster approx.:
$\log(\text{Echo}) \propto p_\uparrow p_\downarrow$

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.
- Coherence may be limited by ^{29}Si *or* background donors.
- Having some ^{29}Si improves T_2 at low donor concentrations.
- But T_2 isn't the right figure of merit! We present T_{qc}, n_{qc} as an alternative to capture low error behavior.
- For low errors, both ^{29}Si and dopants should be reduced.
- There is a large sample-to-sample variation in baths of sparse spins; yield is more informative then average decoherence.