LETTERS
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A quantum-dot spin qubit with coherence limited by charge noise and fidelity higher than 99.9%

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07/07/2020 - Simon Geyer

(all figures are from this paper or ist supplementary unless indicated otherwise)

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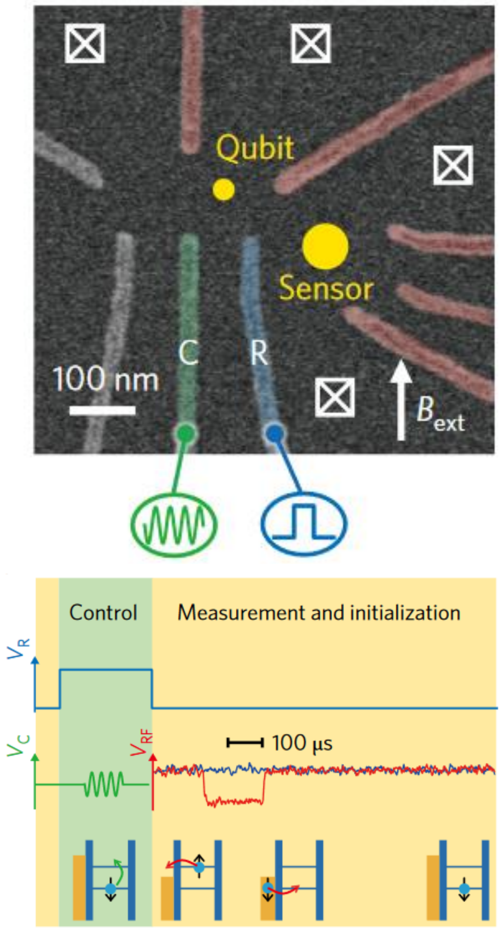
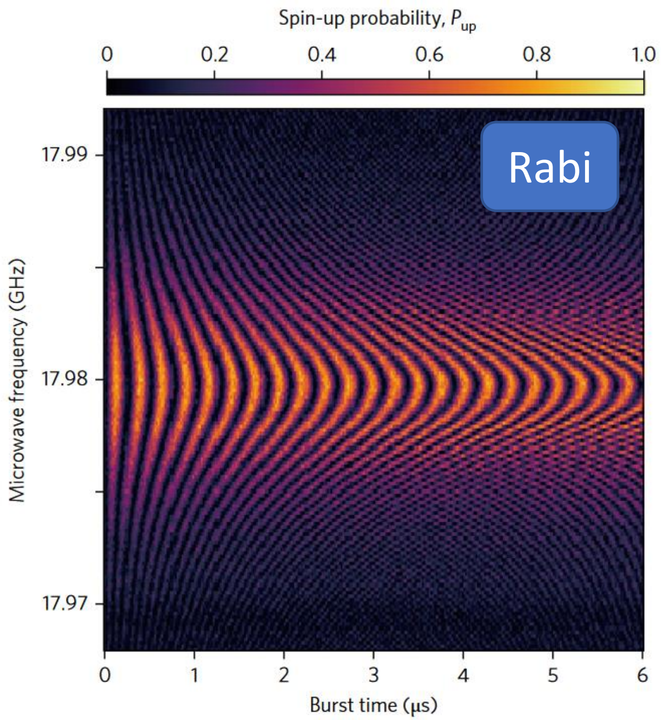
- Quantum dot device
- „Standard“ qubit experiments
- Electrical tuning of qubit frequency
- Analysing the noise spectral density
- Digression into dynamical decoupling sequences

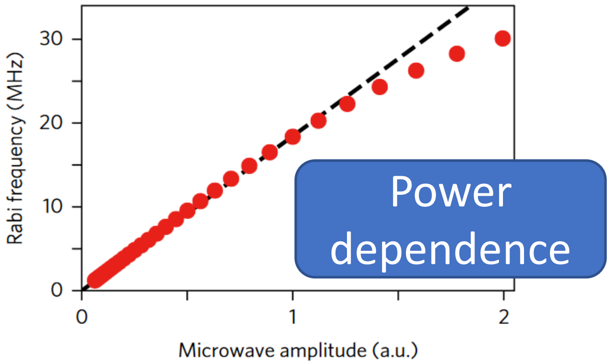
Device

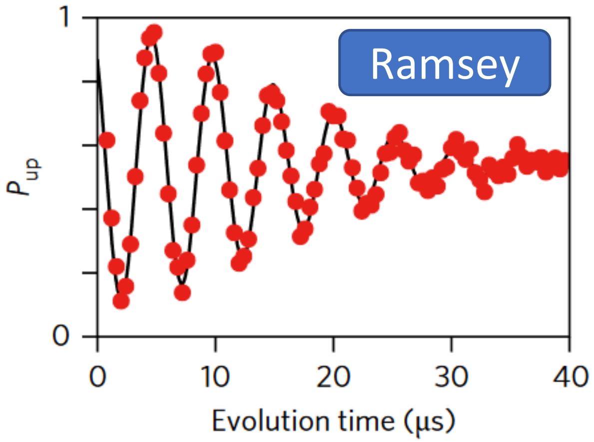
- Electron spin qubit in ^{28}Si/SiGe heterostructure
- Micro-magnet for spin-electric coupling
- Single-shot readout via charge sensing
- T2* ~ 20us
- F_Rabi ~ 20MHz
- Q-factor (#operations/coherence time) ~ 900
- 99.9% single gate fidelitiy

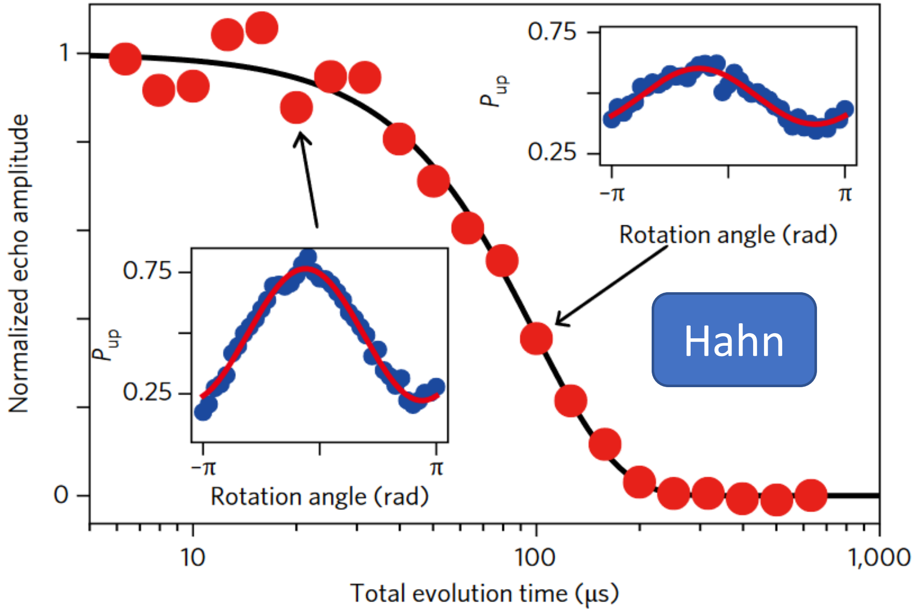


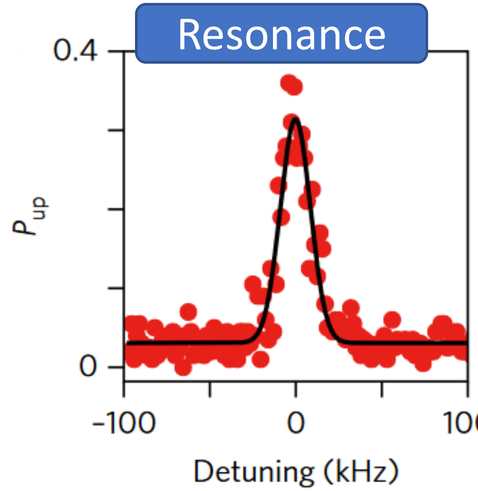
„Standard“ qubit experiments

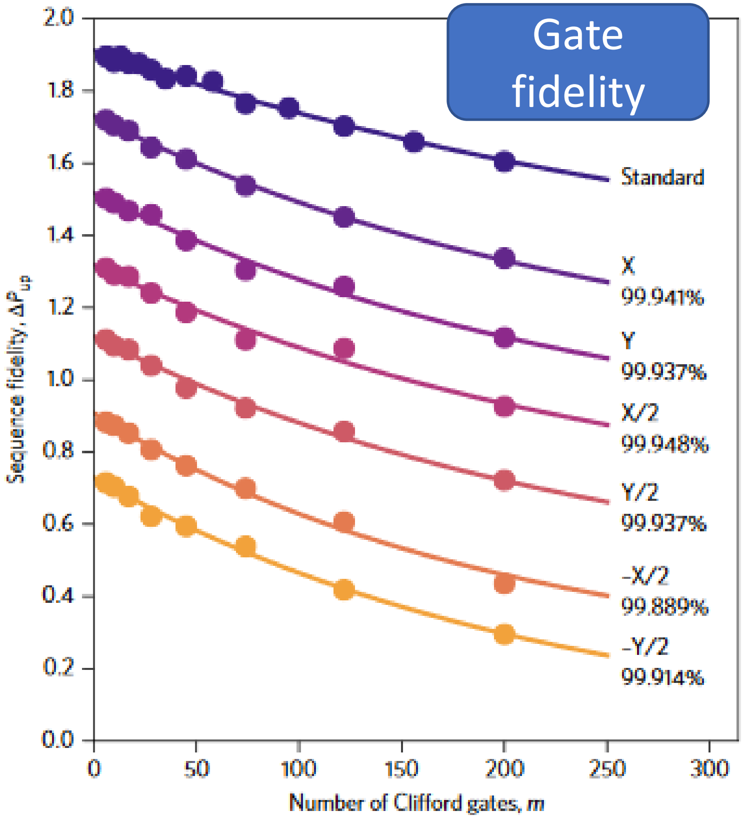






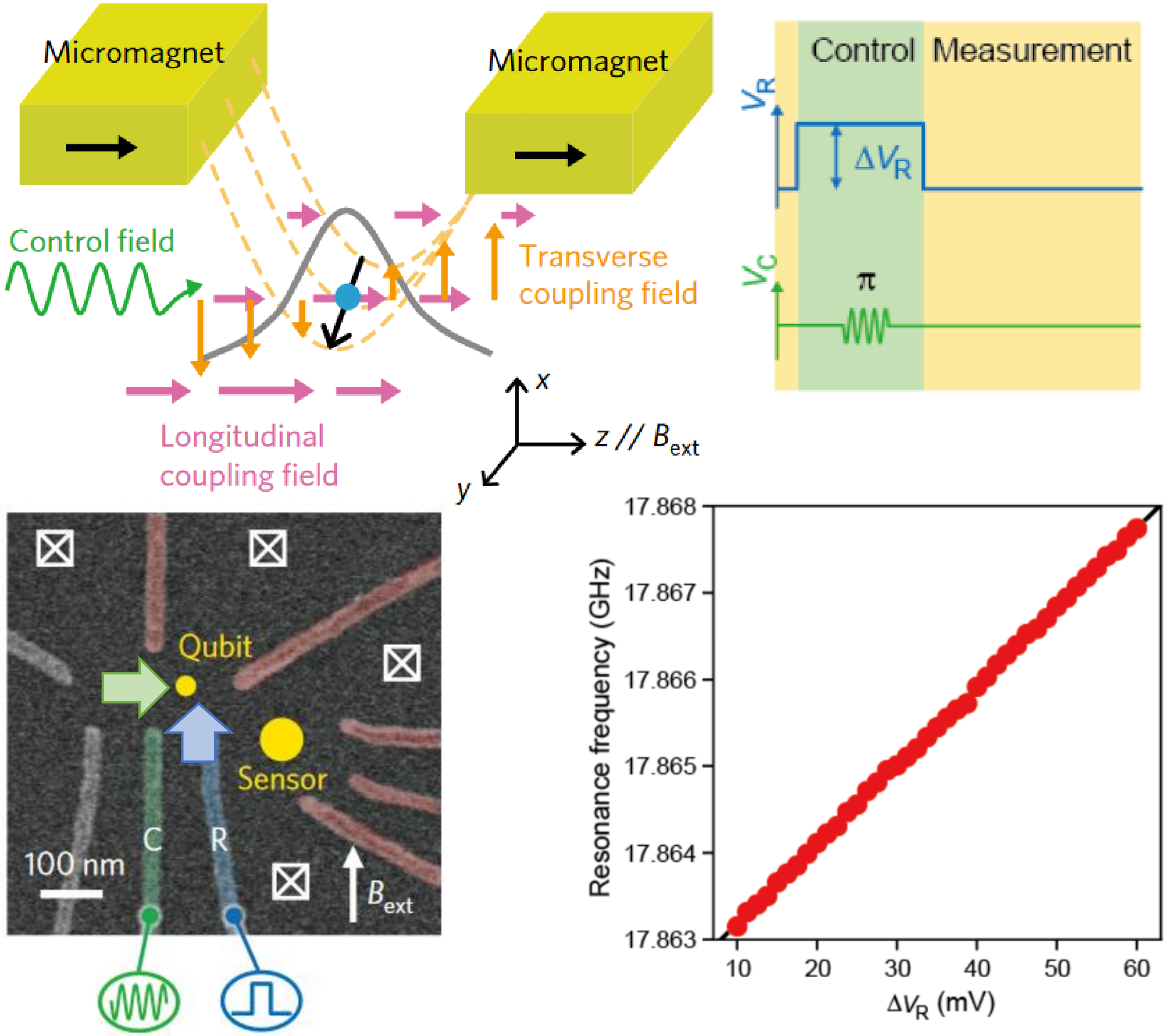






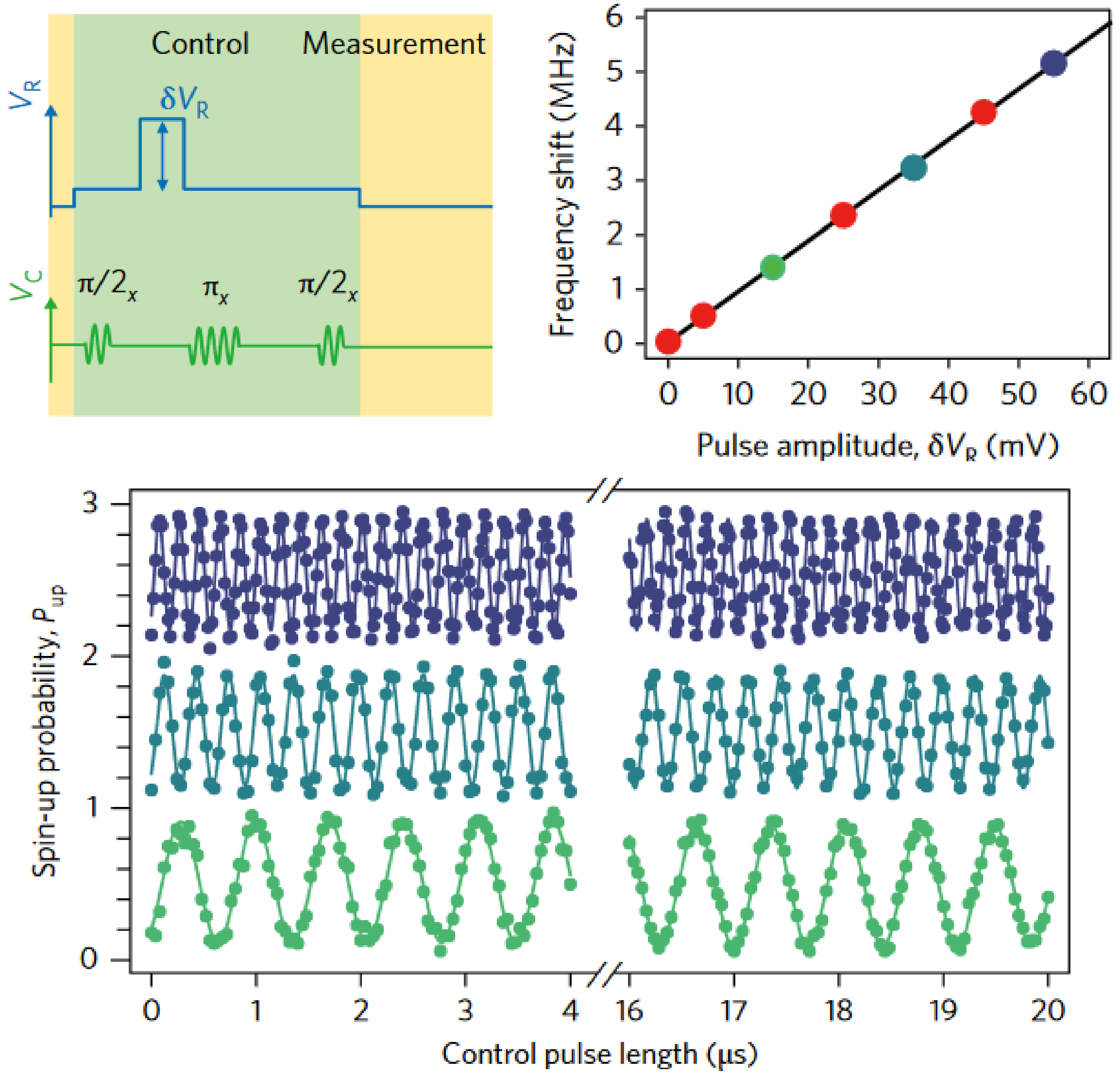
Electric tuning of qubit frequency

- Micromagnet induces transverse and longitudinal spin-electric coupling
- RF -> transverse
- Coulomb pulse -> longitudinal
- Coulomb pulse amplitude tunes resonance frequency



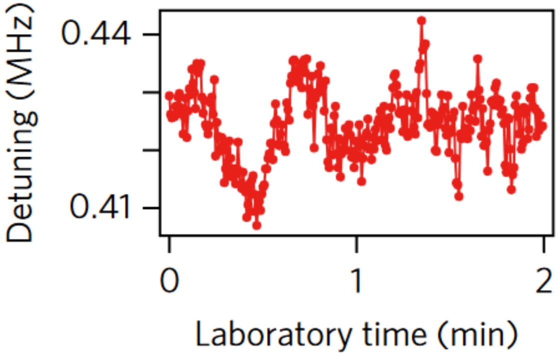
Real-time modulation of V_R

- δV_R-pulse rapidly shifts resonance frequency
- Phase shift in qubit depends linearly on pulse amplitude
- Z-gate/phase-gate



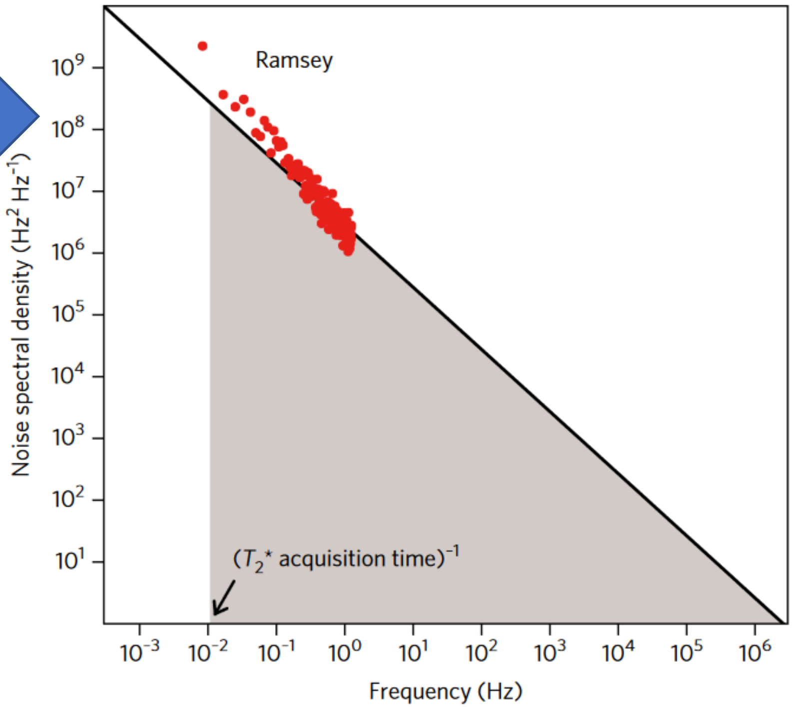
Low-frequency noise

- observe the resonance frequency shift over time -> Fourier transform gives low-frequency noise
- Ramsey is very sensitive to frequency shifts
- Noise frequency limits:
    - upper: minimum acqusition time
    - lower: measurement duration



$$S(\mathrm{f}) = \frac{1}{\mathrm{T}} \left| \int_0^T dt\, e^{2\pi i f t} \delta(t) \right|^2$$

for T -> ∞



unpublished Data

High-frequency noise

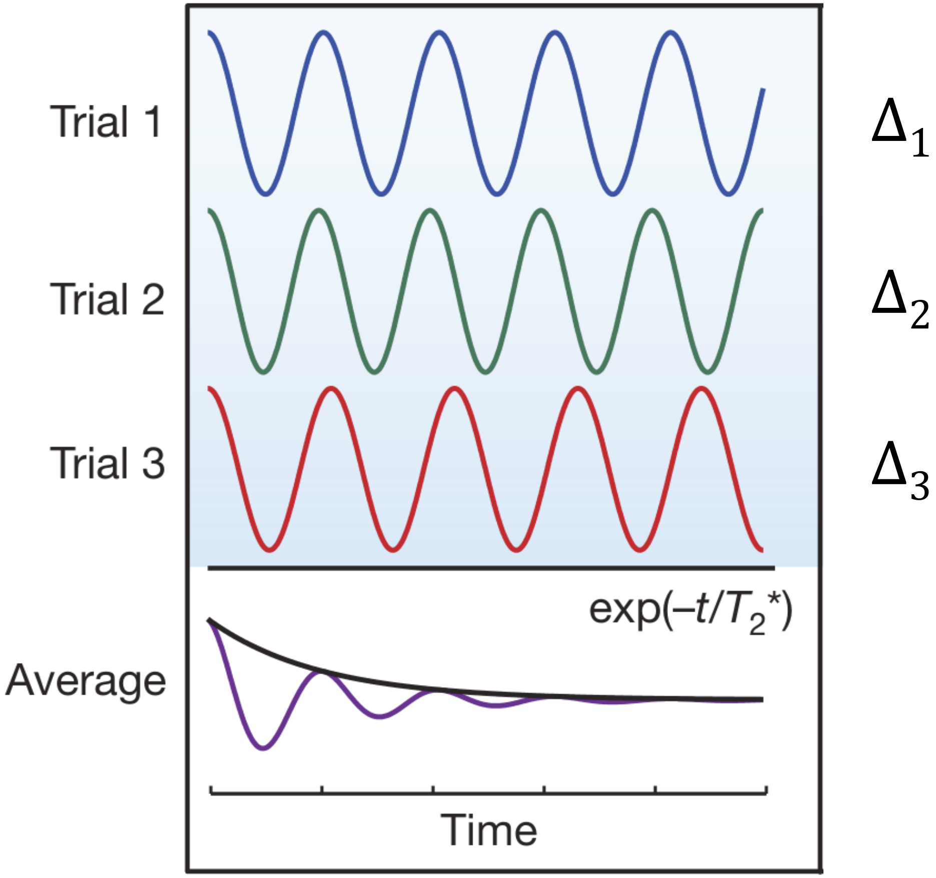
- Dynamical decoupling eliminates low-frequency noise
  -> is used to analyise high-frequency noise
- Therefore:

A short digression into dynamical decoupling (DD)

DD digression

Classical noise -> Dephasing

- small variations in detuning Δ lead to decay of average signal
- average signal decays with $e^{-\eta(t)}$ with $\eta(t) = c \cdot \int_{-\infty}^{\infty} d\omega \, S(\omega) \frac{F(\omega t)}{\omega^2}$



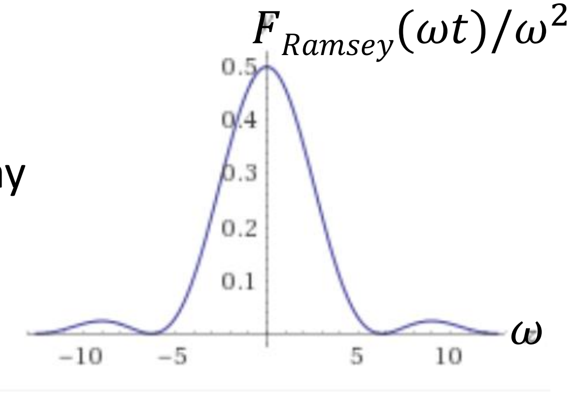
from Christoph Klöffel‘s lecture on spin-based quantum computing

Ladd et al., Nature **464**, 45 (2010)

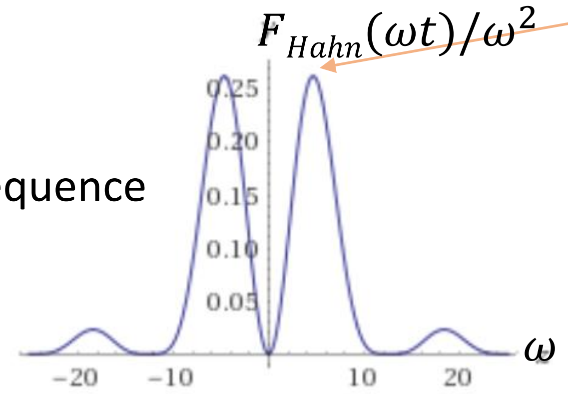
Filter function

- Decay with $\eta(t) = c \cdot \int_{-\infty}^{\infty} d\omega\, S(\omega)\, \frac{F(\omega t)}{\omega^2}$
- spectral function of noise $S(\omega)$ is improved by:
  - active feedback, spin pumping, minimizing noise in setup, etc.
- filter function $\frac{F(\omega t)}{\omega^2}$ gives sensitivity to noise of certain frequency, can be shifted by DD sequences to higher frequencies
- usually $S(\omega) \propto 1/f^{\alpha}$ with $\alpha > 0$

Ramsey decay



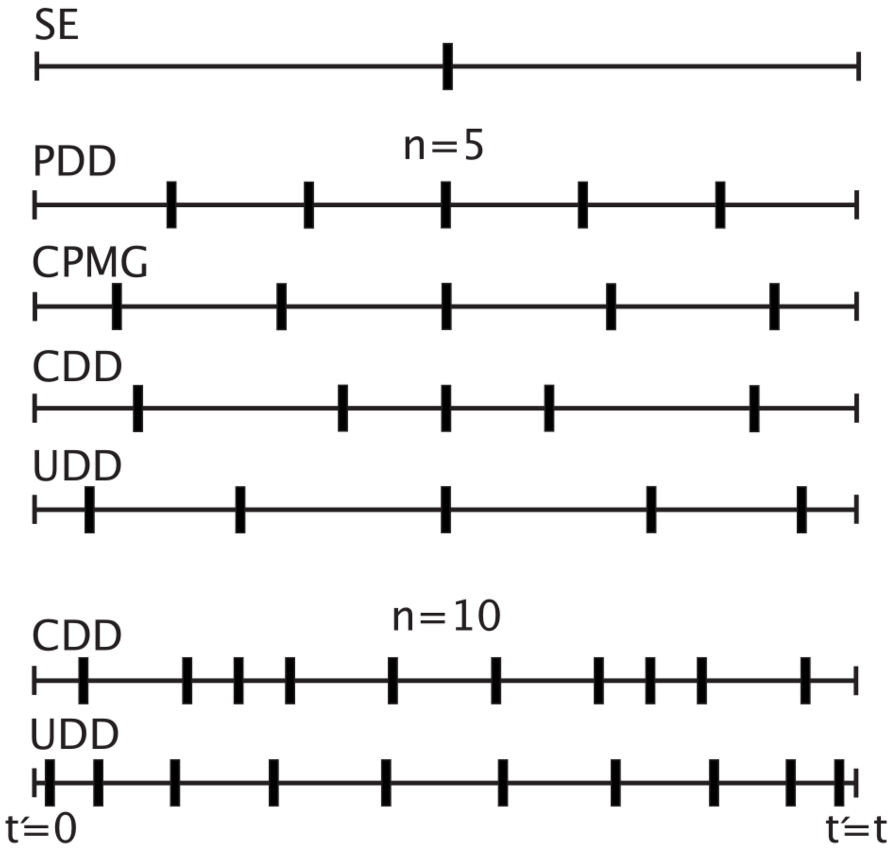
Hahn echo sequence



highest sensitivity shifted to higher frequency -> smaller $\eta(t)$

DD digression

Filter functions for some DD sequences



Sequence	$F(z)$
FID	$2\sin^2\frac{z}{2}$
SE	$8\sin^4\frac{z}{4}$
PDD (odd n)	$2\tan^2\frac{z}{2n+2}\sin^2\frac{z}{2}$
CPMG (even n)	$8\sin^4\frac{z}{4n}\sin^2\frac{z}{2}/\cos^2\frac{z}{2n}$
CDD	$2^{2l+1}\sin^2\frac{z}{2^{l+1}}\Pi_{k=1}^{l}\sin^2\frac{z}{2^{k+1}}$
UDD	$\frac{1}{2}\lvert\Sigma_{k=-n-1}^{n}(-1)^k\exp[\frac{iz}{2}\cos\frac{\pi k}{n+1}]\rvert^2$

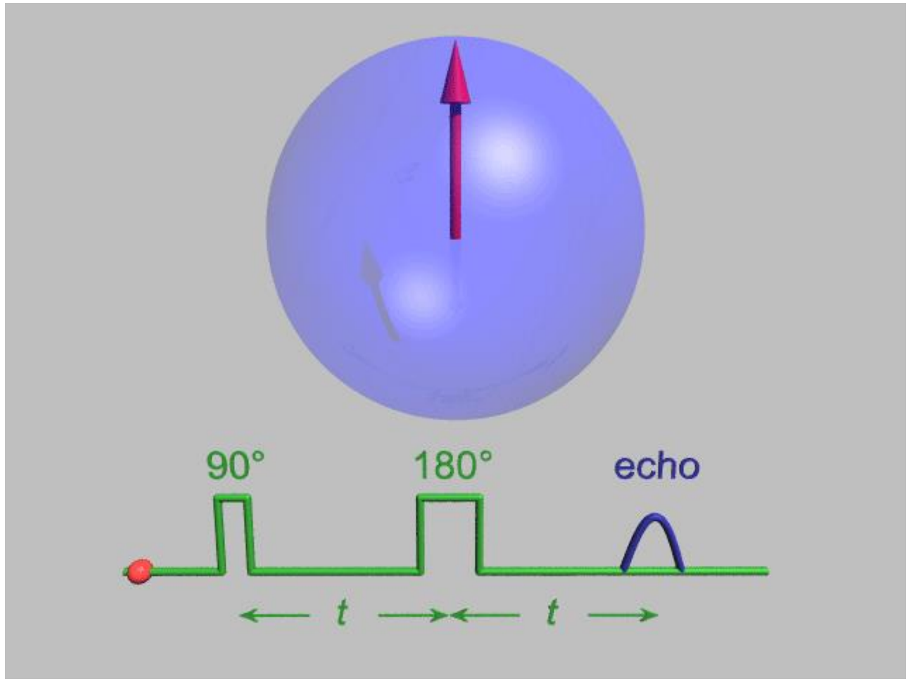
L. Cywinski et al., Phys. Rev. B **77**, 174509 (2008)

Spin-Echo/Hahn-Echo sequence

- X – t/2 – **X^2** – t/2 – X

- X/Y = Pi/2 pluse around X/Y-axis
- X^2/Y^2 = Pi pulse
- t = waiting time

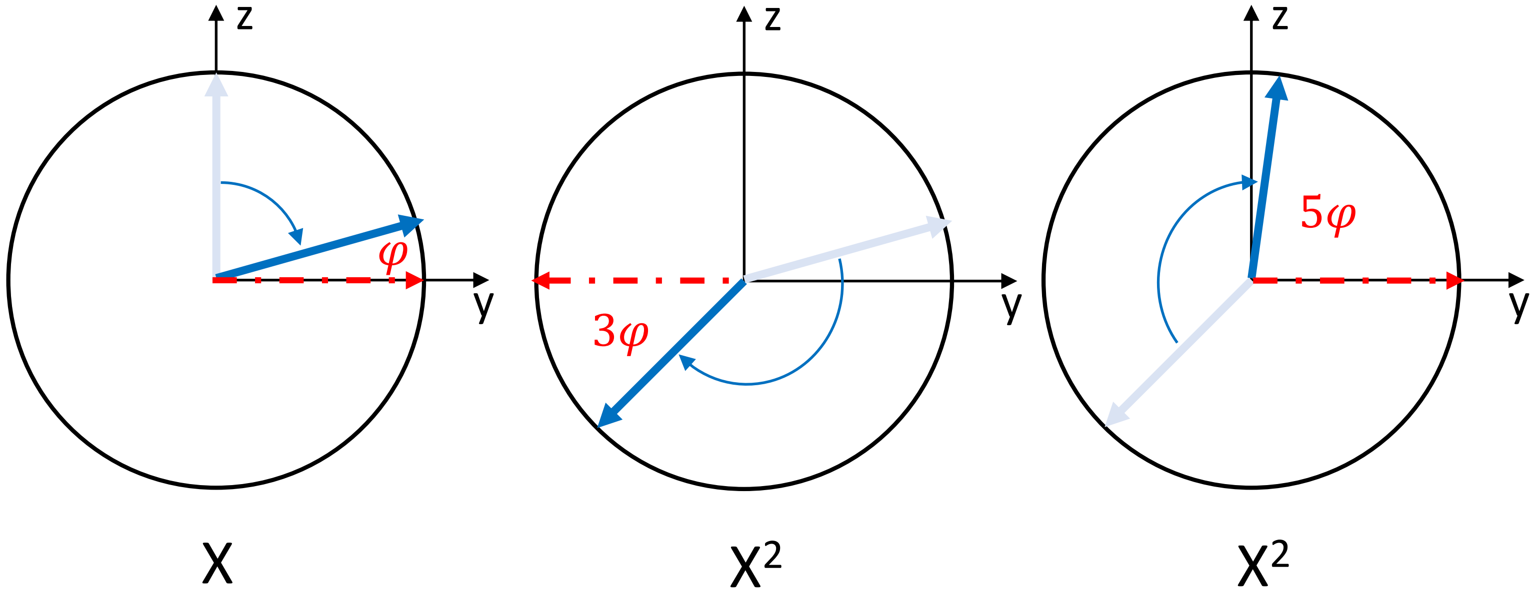
- **Problem:** only removes quasi-static noise



by Gavin W Morley

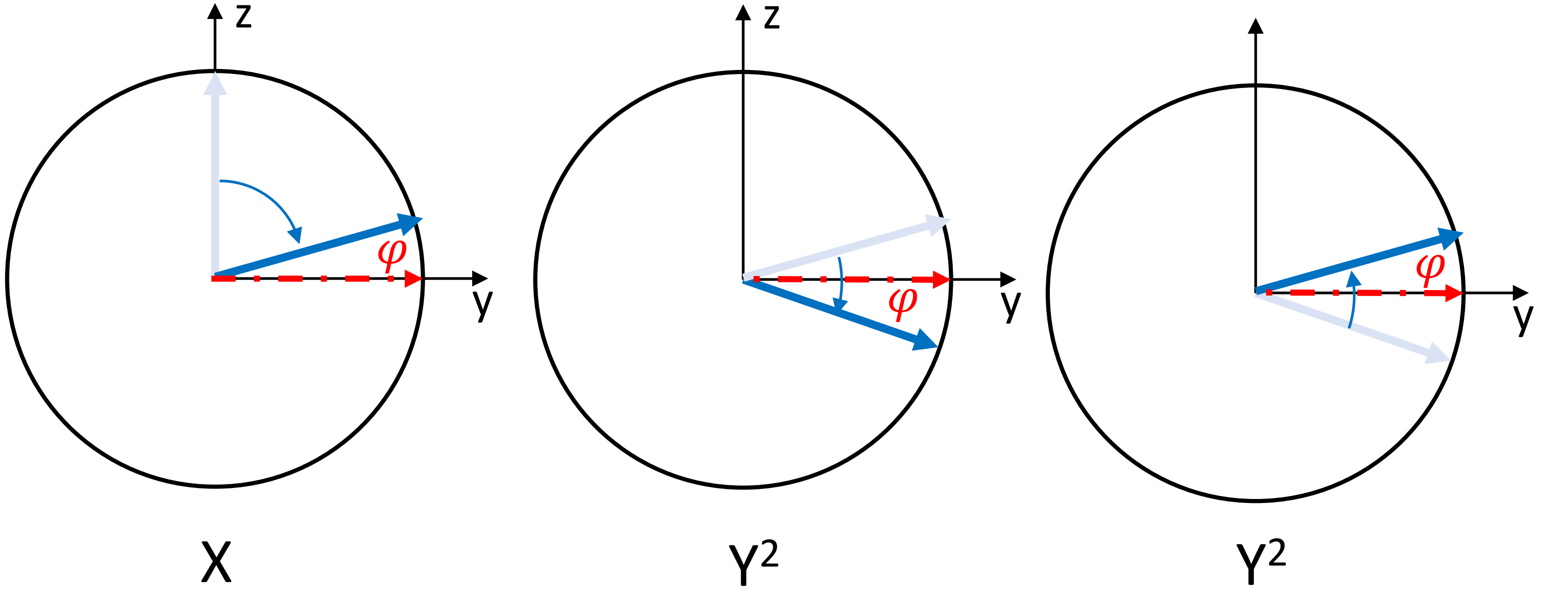
CP sequence (Carr- Purcell)

- CP-N:
  X – t/2 – **X²** (– t – **X²**)^N-1 – t/2 – X
- similar, but worse at small N: PDD
- **Problem:** pulsing errors accumulate fast (e.g. too short pulse)



CPMG sequence (Carr- Purcell-Meiboom-Gill)

- CPMG-N:
  X – t/2 – **Y²** (– t – **Y²**)^n-1 – t/2 – X



errors in Y-pulse length accumulate slower if the qubit is close to the y-axis

- **Problem:** very effective for „longitudinal states“, poor for „transversal states“

DD digression

XY-4

- XY-4:
  X – t/2 – $\mathbf{X^2}$ – t – $\mathbf{Y^2}$ – t – $\mathbf{X^2}$ – t – $\mathbf{Y^2}$ – t/2 – X
- better compensation of pulsing errors (on average) than CPMG

A lot more:

XY-8

PDD XY

SDD XY

CDD_n

…

DD sequences overview

Hahn-Echo:	$X – X^2 – X$	removes quasi-static noise
CP:	X (- X^2 -)^n X	pulsing errors accumulate fast
CPMG:	X (- Y^2 -)^n X	reduces pulsing error accumulation
XY-4:	X (- $X^2 – Y^2 – X^2 – Y^2$ -) X	eliminates some pulsing errors completely
XY-8:	X (- $X^2 – Y^2 – X^2 – Y^2$ -) (- $Y^2 – X^2 – Y^2 – X^2$ -) X	
PDD XY:	X (– $X^2 – Y^2 – X^2 – Y^2$) X	
SDD XY:	X (– $X^2 – Y^2 – X^2 – Y^2$) (Y^2– $X^2 – Y^2 – X^2$ –) X	
CDD_n:	concatenations of XY-4 (see Souza et al.)	

- = tau/2
– = tau
X = pi/2 pulse
X^2 = pi pulse

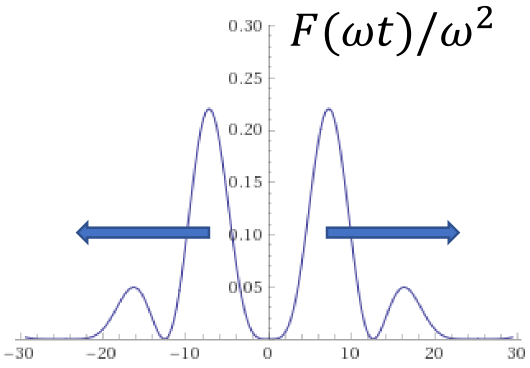
A. Souza et al. *Phil. Trans. R. Soc. A* **370**, 4748–4769 (2012)
Z.-H. Wang et al. *Phys. Rev. B* **85**, 155204 (2012)

DD digression

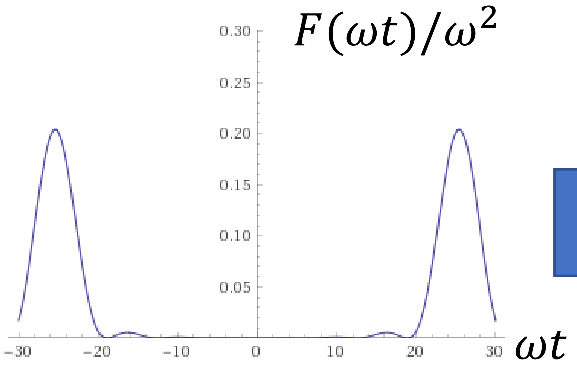
CPMG with different number of pulses n

Filter function:

$$8\sin^4\left(\frac{z}{4n}\right)\sin^2\left(\frac{z}{2}\right) / \cos^2\left(\frac{z}{2n}\right)$$



n = 2



n = 8

For increasing n the sensitivity shifts to higher frequencies, acts like adjustable band-pass filter

Decay of CPMG signal can be used to gain information on the noise spectral density S(f) at the „sensitive“ frequency (from Yoneda et al.):

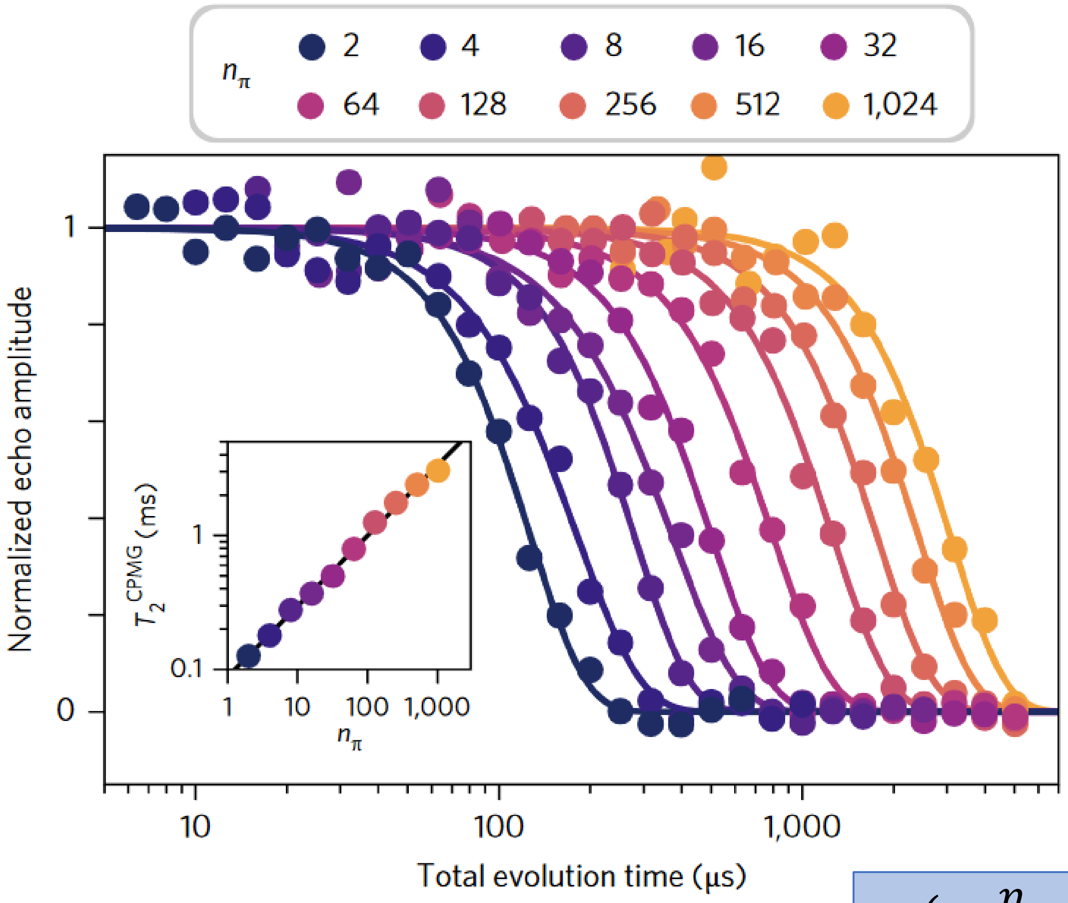
$$S\left(\frac{n}{2 \cdot t_{wait}}\right) = -\ln(A_{CPMG})/2\pi^2 t_{wait}$$

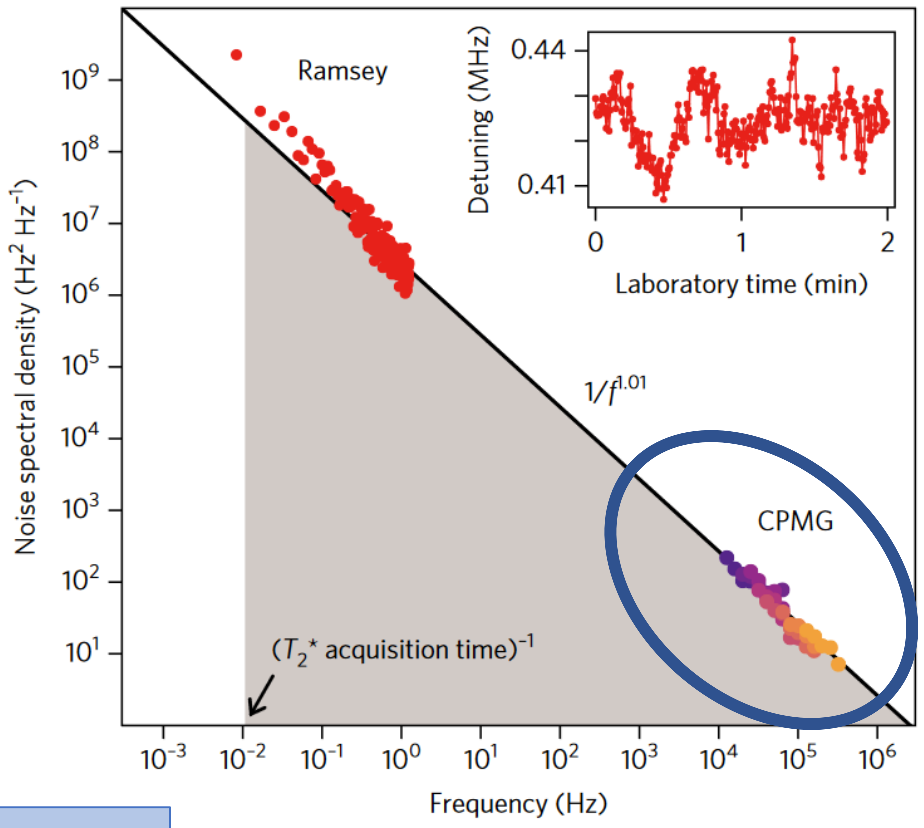
t_{wait} = free evolution time between CPMG pulses

A_{CPMG} = spin-up probability

valid for gaussian noise and n > 8

High-frequency noise from CPMG

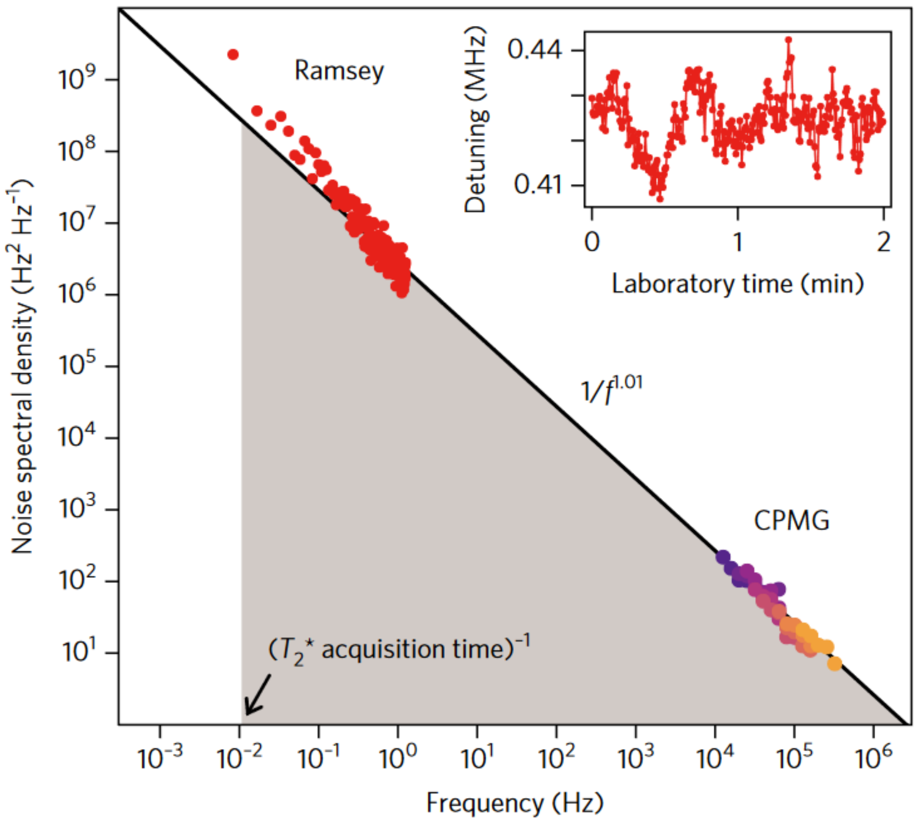




$$S\left(\frac{n}{2 \cdot t_{wait}}\right) = -\ln(A_{CPMG})/2\pi^2 t_{wait}$$

Noise spectrum

- S(f) ~ 1/f^1.01 over 7 orders of magnitude (!)
- 1/f dependence of noise indicates charge noise as main source



Conclusion

- High-quality electron qubit in ^{28}Si
- High single-qubit gate fidelity > 99.9%
- Charge noise identified as main (only?) dephasing mechanism