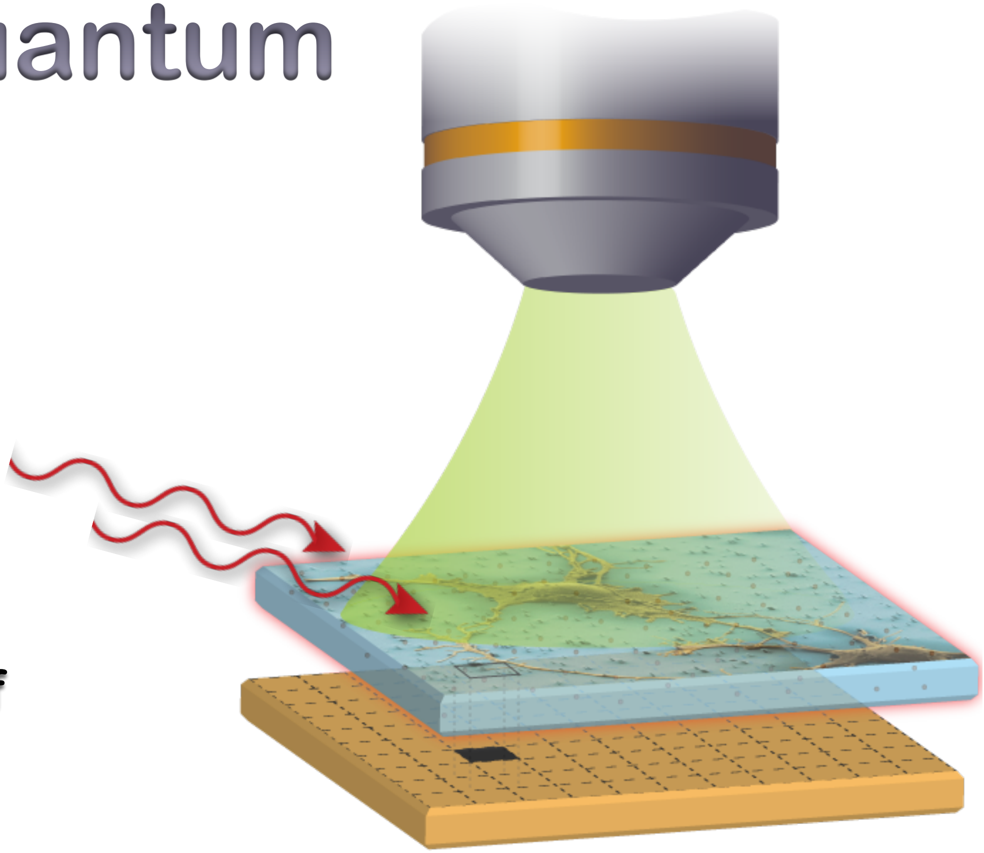
Control of quantum sensors



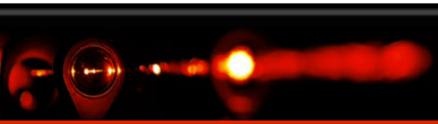
Paola Cappellaro

Massachusetts Institute of Technology

Limits and goals of qt. control

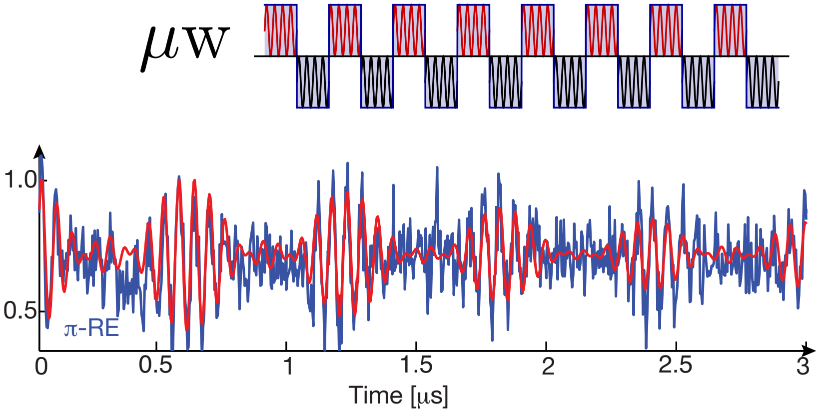
- Quantum information processing requires universal quantum control
- Control of quantum sensors has different goals and constraints
  - Less stringent requirements
  - New challenges:

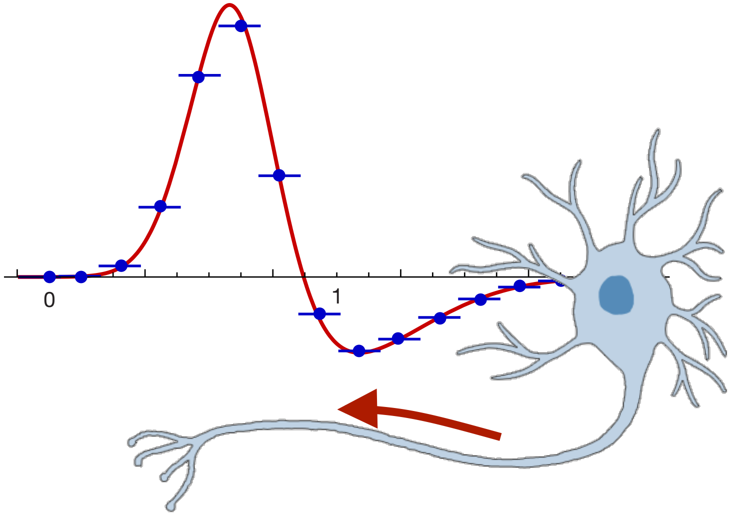
    e.g. compromise between noise refocusing and external field sensing



Control of quantum devices

- Continuous decoupling magnetometry

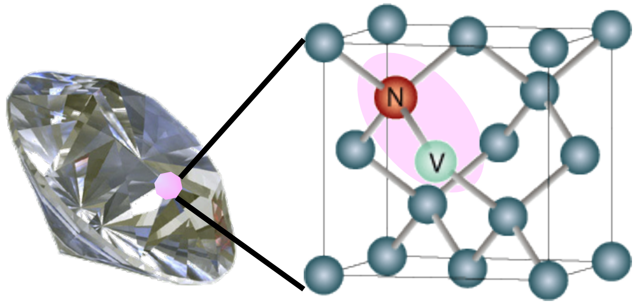




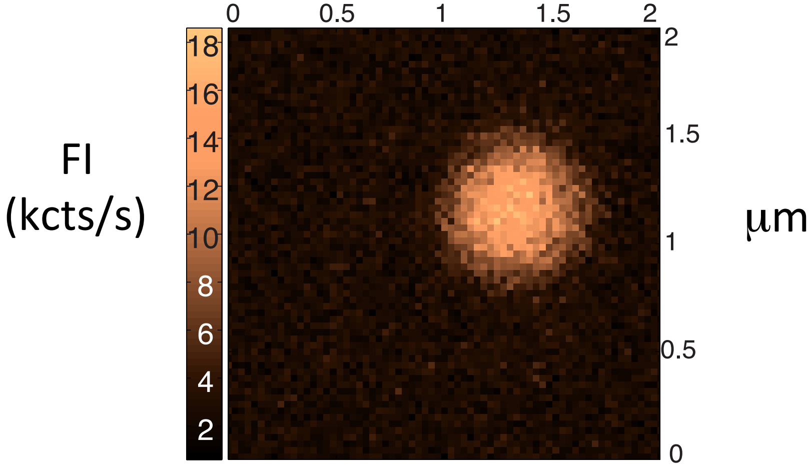
- Reconstruction of time-dependent magnetic fields

NV Center Spin

- Isolated defect in diamond with electronic spin 1

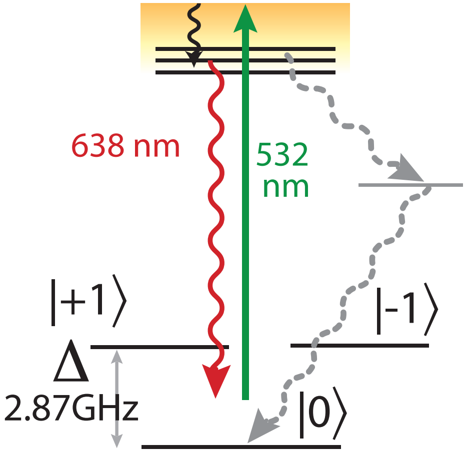


- ODMR in a confocal microscope



NV Center Spin

- Electronic spin 1



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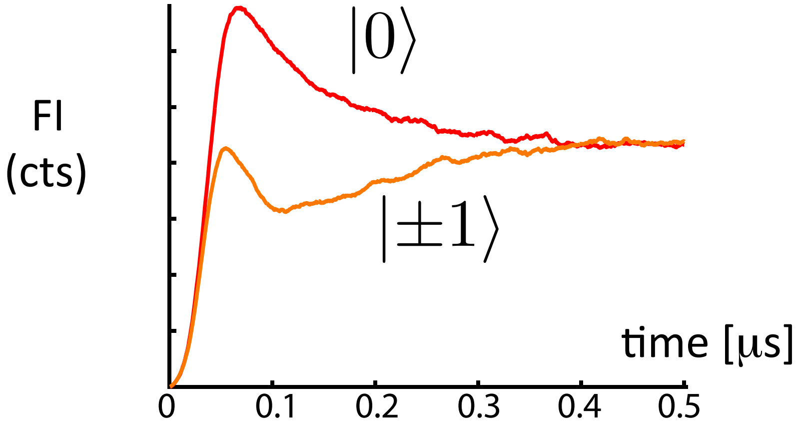
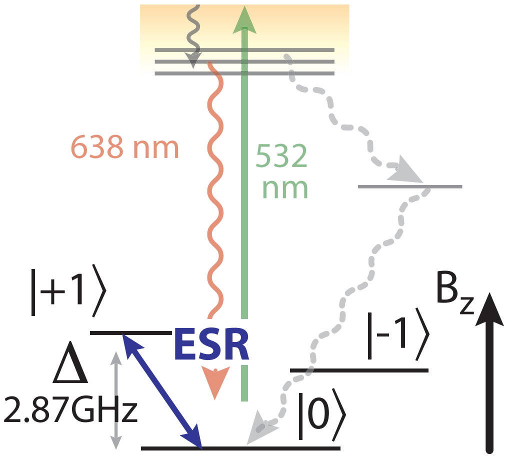


- Single-spin state detection
  - Fluorescence intensity (FI)
- Optical polarization
  - mK at room temperature

NV Center Spin

- Electronic spin 1



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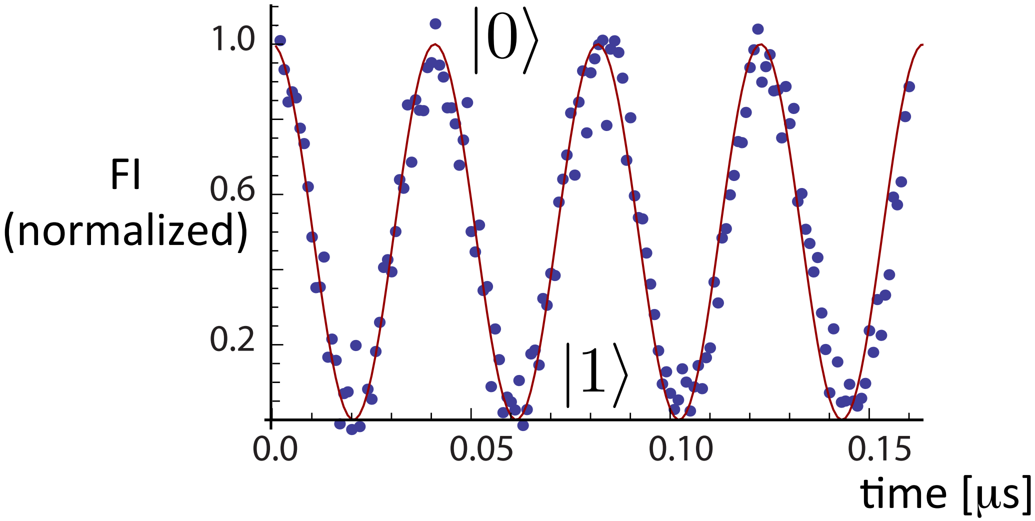
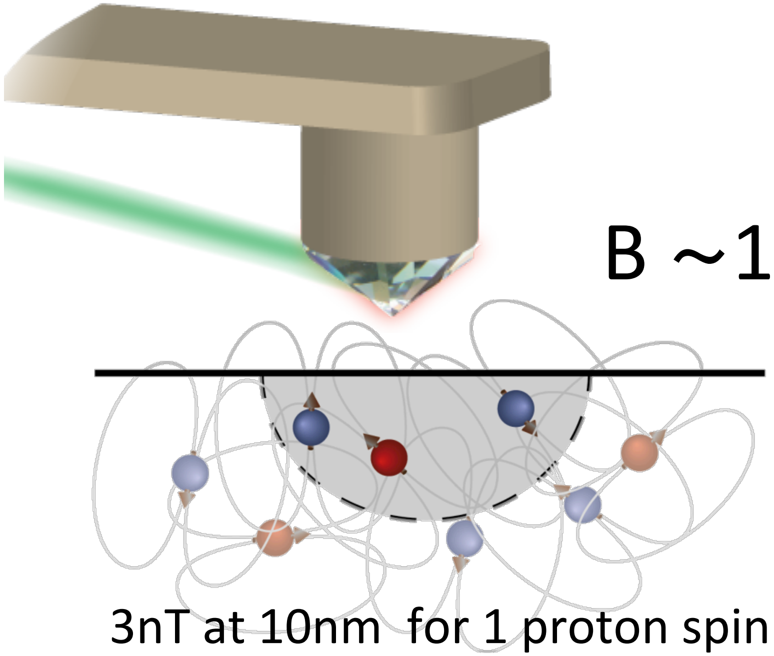


- Single-spin state detection
  - Fluorescence intensity (FI)
- Optical polarization
- Precise control
  - Manipulation via resonant microwave

Spin magnetometer

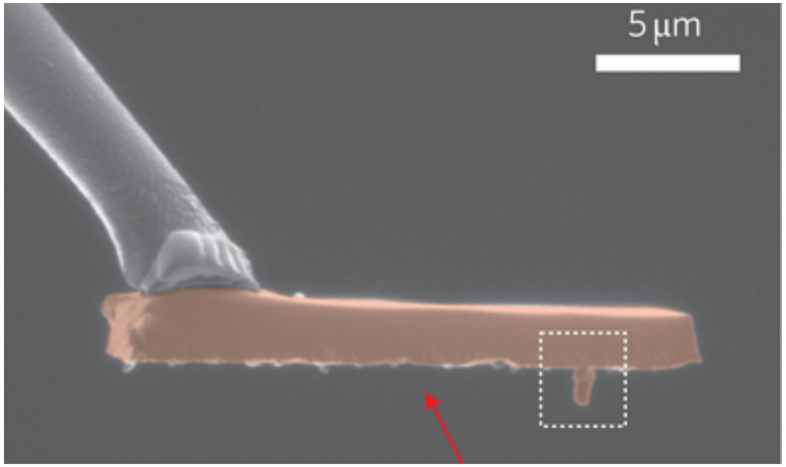
- Control + localization

  → sensitivity & spatial resolution



$B \sim 1/r^3$

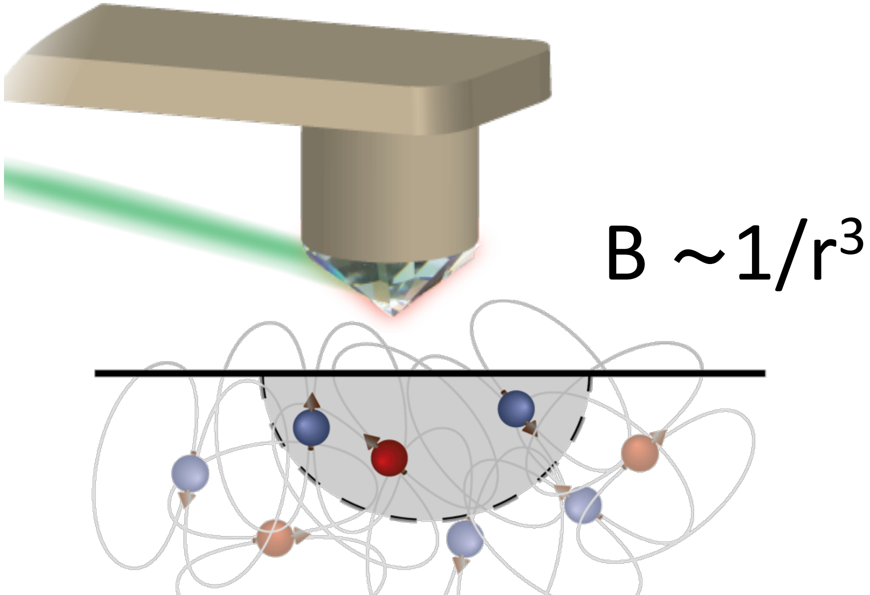
3nT at 10nm for 1 proton spin



A. Yacoby

Spin magnetometer

- Control + localization
  → sensitivity & spatial resolution

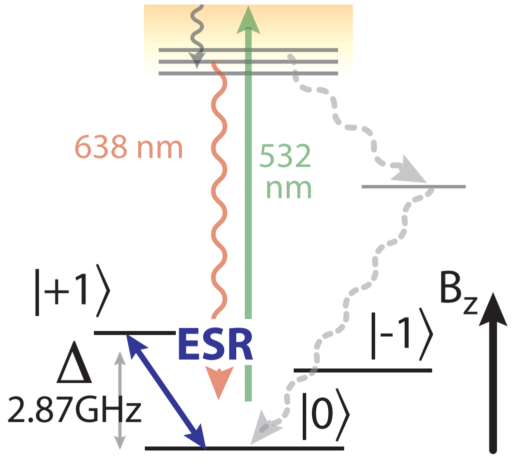


3nT at 10nm for 1 proton spin

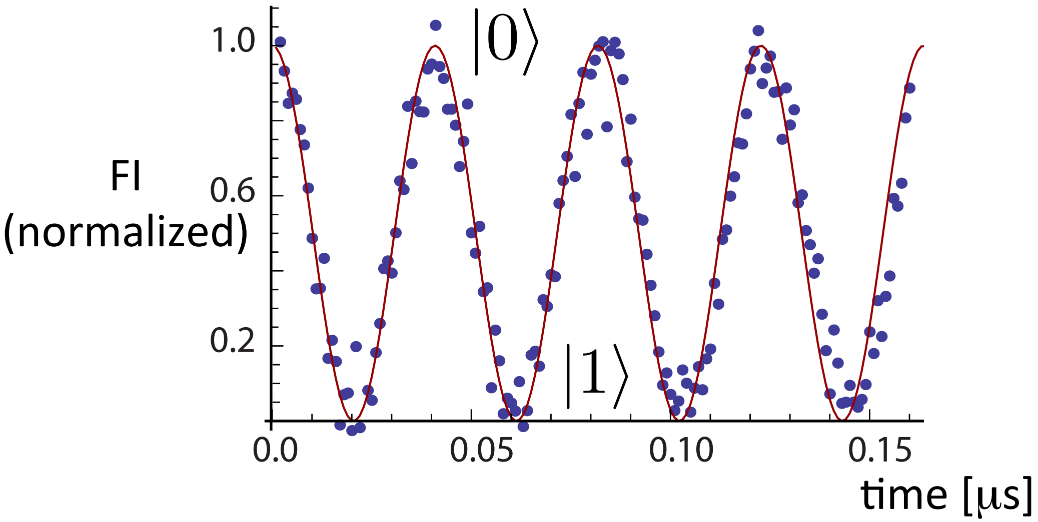
H.-C. Chang

NV Center Spin

- Electronic spin 1



- ODMR in a confocal microscope



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- Optical polarization
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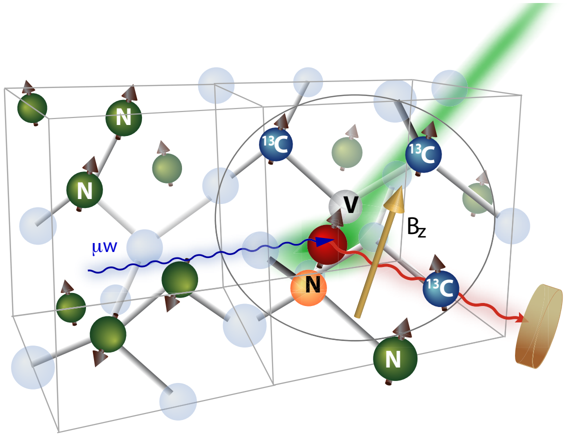
NV Center Spin

- Electronic spin 1



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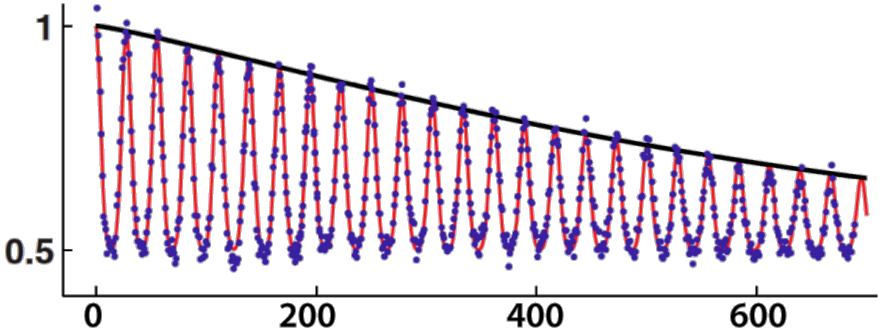
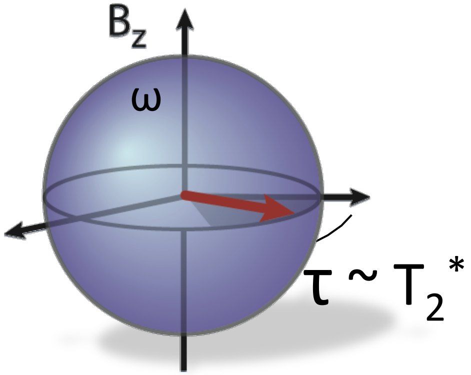


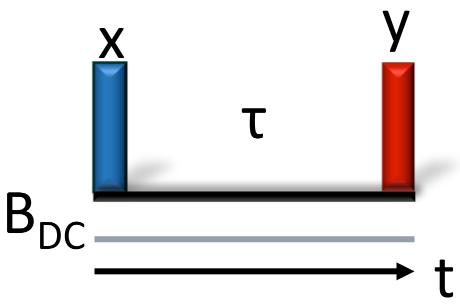
- Single-spin state detection
  - Fluorescence intensity (FI)
- Optical polarization
- Precise control
  - Manipulation via resonant microwave

- Exceptional coherence time
  - Up to ms, allows many operations
- Complex environment
  - Nuclear spins
  - Electronic Nitrogen spins

Single-spin magnetometer

- Detect magnetic field with Ramsey-type experiment





- Shot-noise limited sensitivity (minimum resolvable field)

$$\delta B \sim C \frac{\hbar}{g\mu_B} \frac{1}{\sqrt{T_2^*}}$$

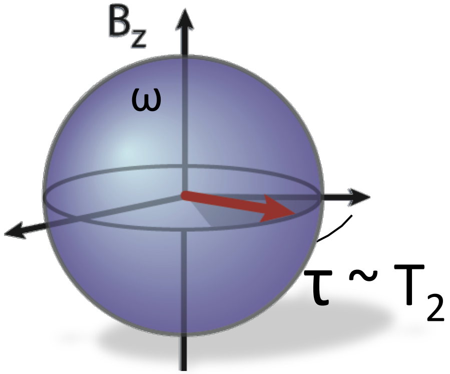
[T Hz$^{-1/2}$]

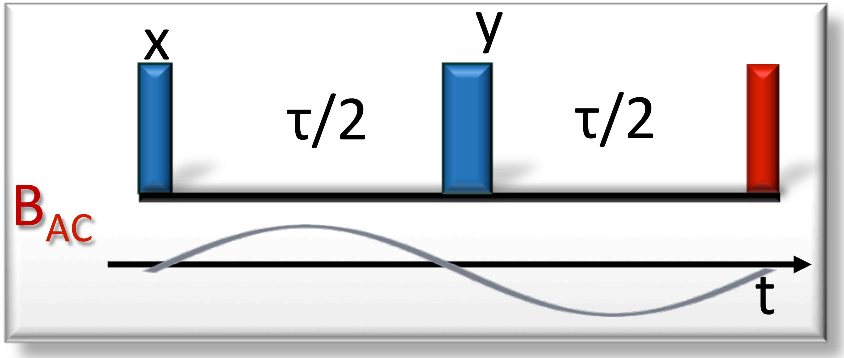
  - Noise limits the evolution time to $\tau \lesssim T_2^*$

J. Taylor, P.C. et *al*., Nature Phys 2008

Single-spin magnetometer

- Detect magnetic field with Ramsey-type experiment





- Shot-noise limited sensitivity (minimum resolvable field)

$$\delta B \sim C \frac{\hbar}{g\mu_B}\frac{1}{\sqrt{T_2}} \qquad [\mathrm{T\ Hz^{-1/2}}]$$

  - Limited by dephasing time → Spin echo
  - **No sensing of DC-field, limited by pulse errors**

CONTINUOUS DECOUPLING MAGNETOMETRY

A. Aiello, M. Hirose, P.C. Nature Comm. **4**, 1419 (2013)
M. Hirose, A. Aiello, P.C. Phys. Rev. A. **86**, 062320 (2012)

DC magnetometry

- Detection of static magnetic fields

Ramsey

(high sensitivity, short T_2)

DC magnetometry

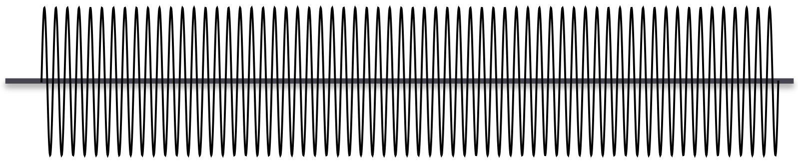
- Detection of static magnetic fields

Ramsey

(high sensitivity, short T_2)

Rabi*

(long T_2, low sensitivity)



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*Fedder *et al.*, Appl Phys B **102**, 497–502 (2011)

DC magnetometry

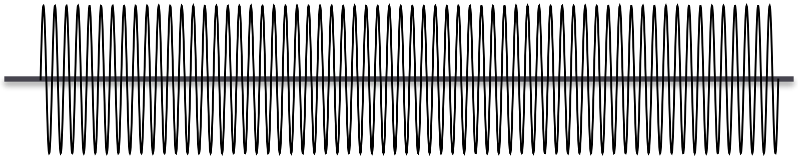
- Detection of static magnetic fields

Ramsey

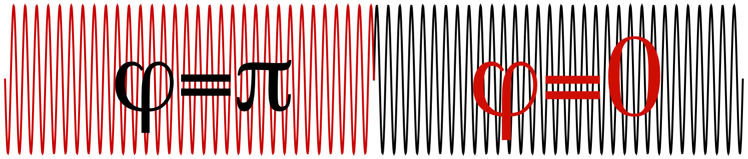
(high sensitivity, short T_2)

Rabi*

(long T_2, low sensitivity)



Example: Rotary Echo



I. Solomon (1958)

DC magnetometry

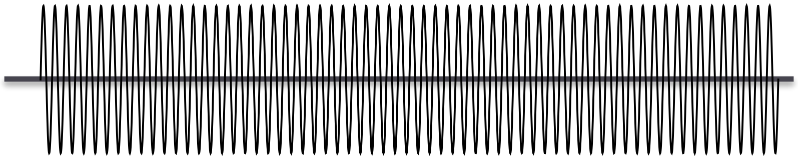
- Detection of static magnetic fields

Ramsey

(high sensitivity, short T_2)

Rabi*

(long T_2, low sensitivity)



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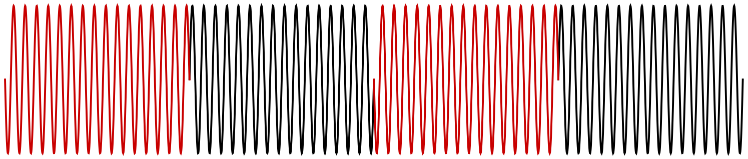


DC magnetometry

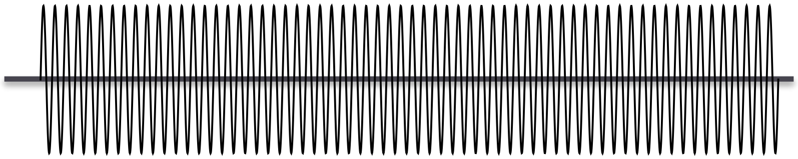
- Detection of static magnetic fields

Ramsey

(high sensitivity, short T_2)

Rabi*

(long T_2, low sensitivity)



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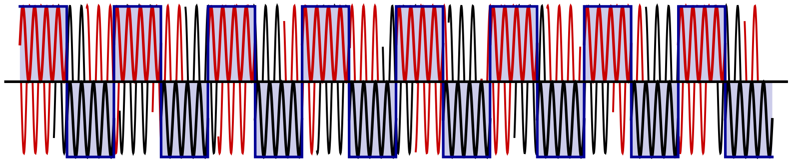
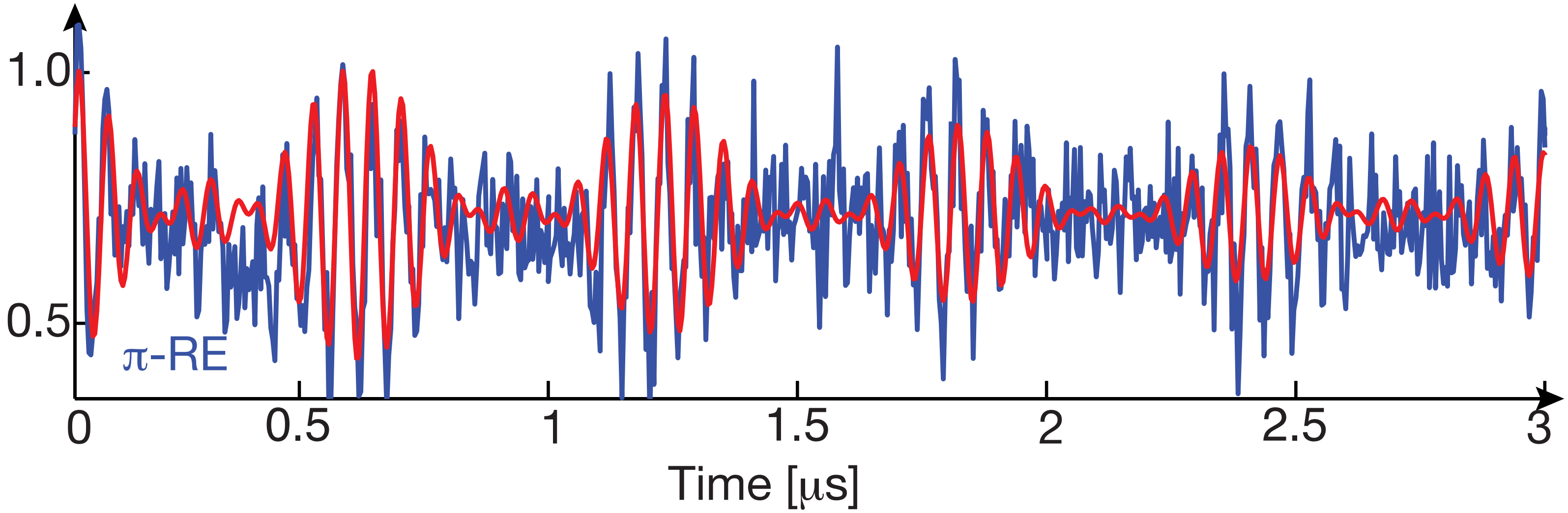
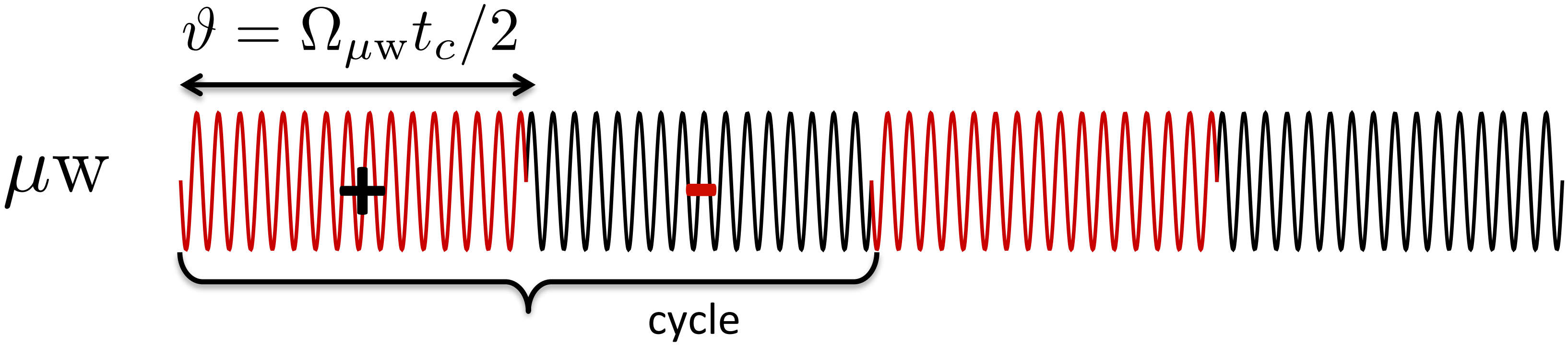


- Compromise:
  - Longer T_2 than Ramsey, higher sensitivity than Rabi
- Corrects for μw instability

Rotary Echo

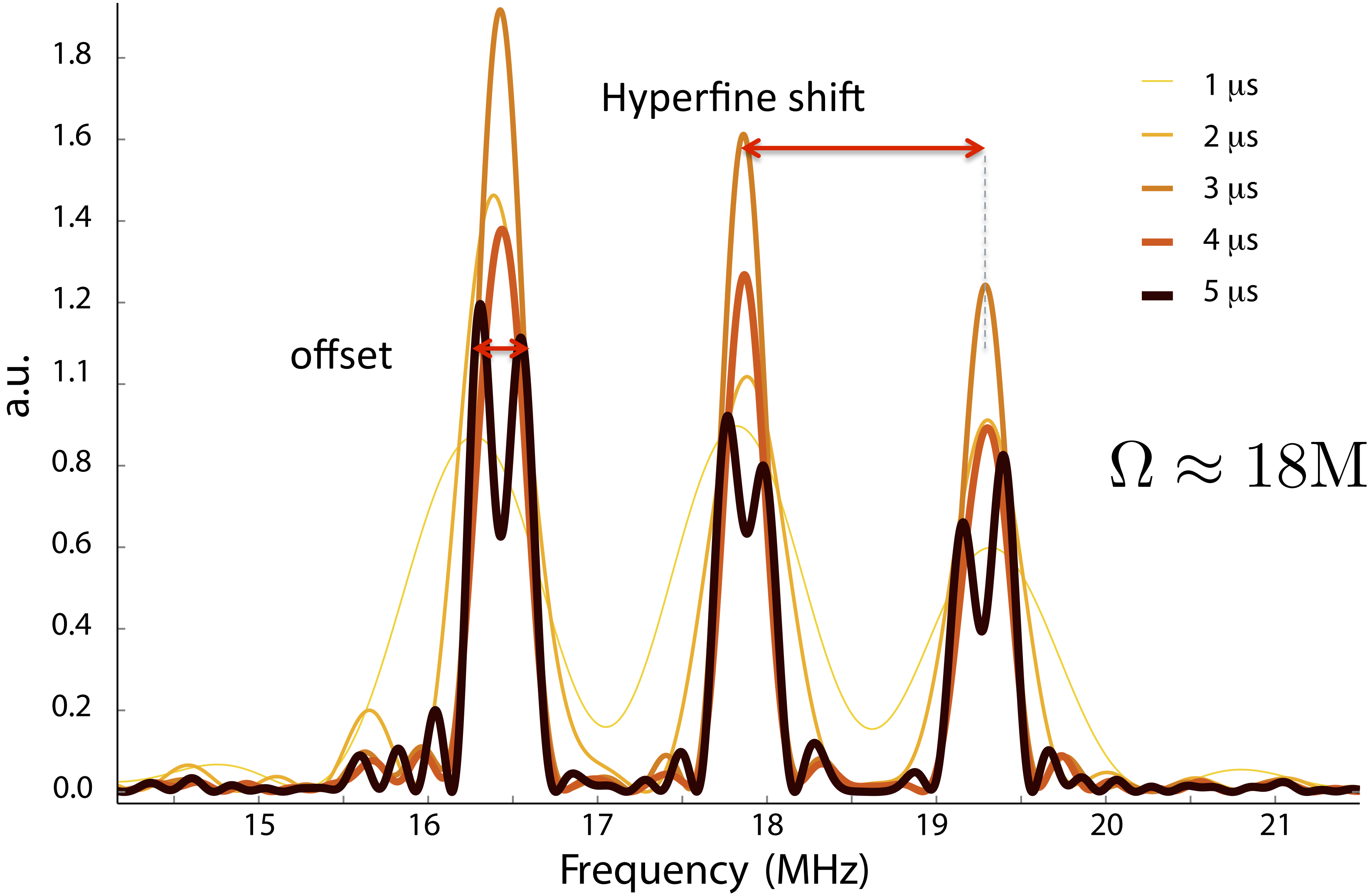
- Intermediate (variable) T_2 and sensitivity





$$\vartheta = \Omega_{\mu \mathrm{w}} t_c/2$$

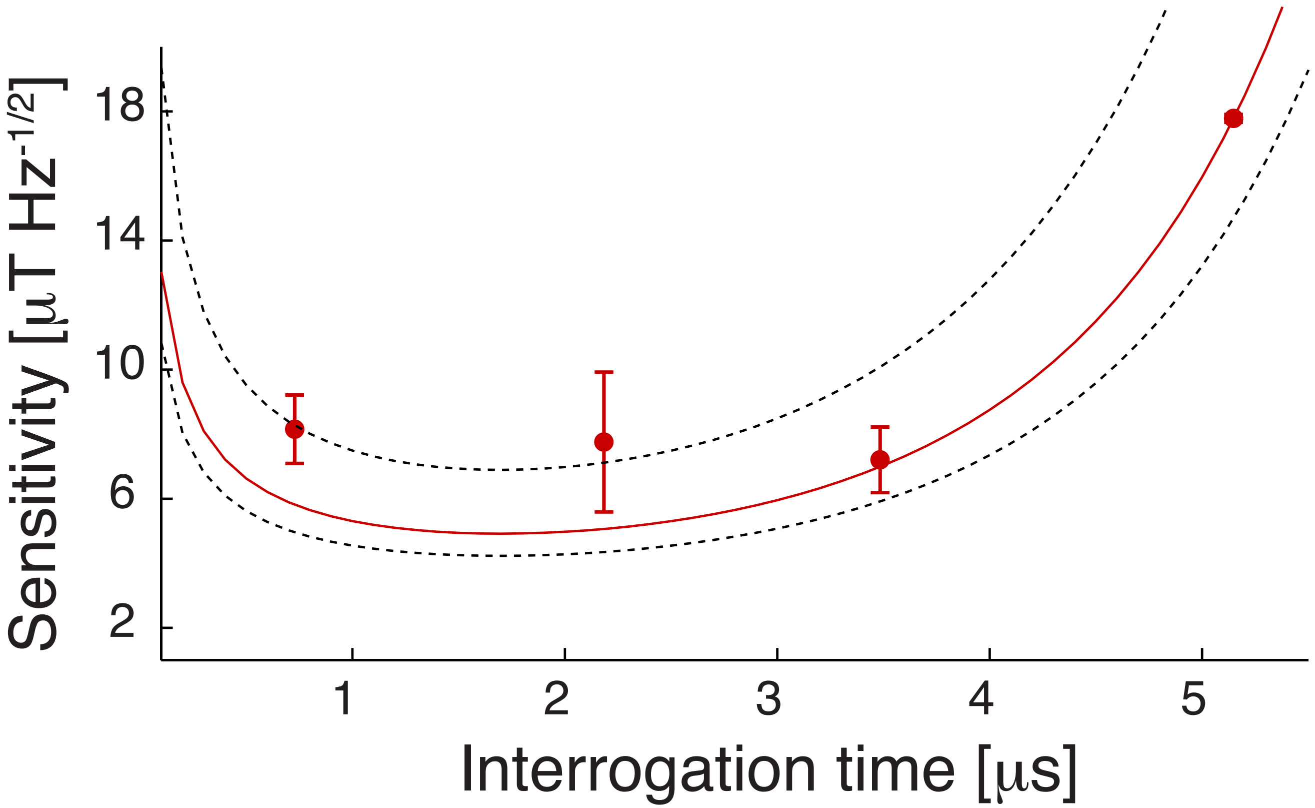
Rotary Echo Magnetometry



$$\Omega \approx 18\text{MHz}$$

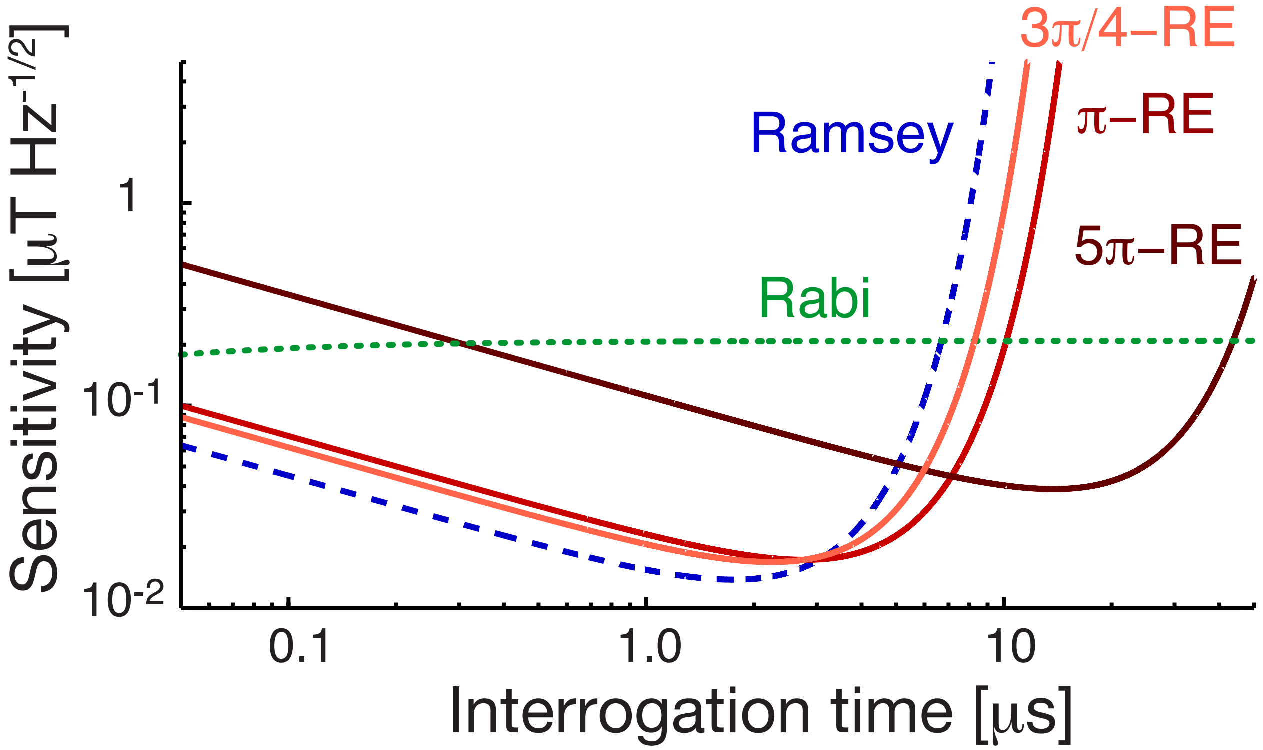
Sensitivity

- Experimental results with 1 NV center



Sensitivity

- Higher sensitivity, robust against μw noise

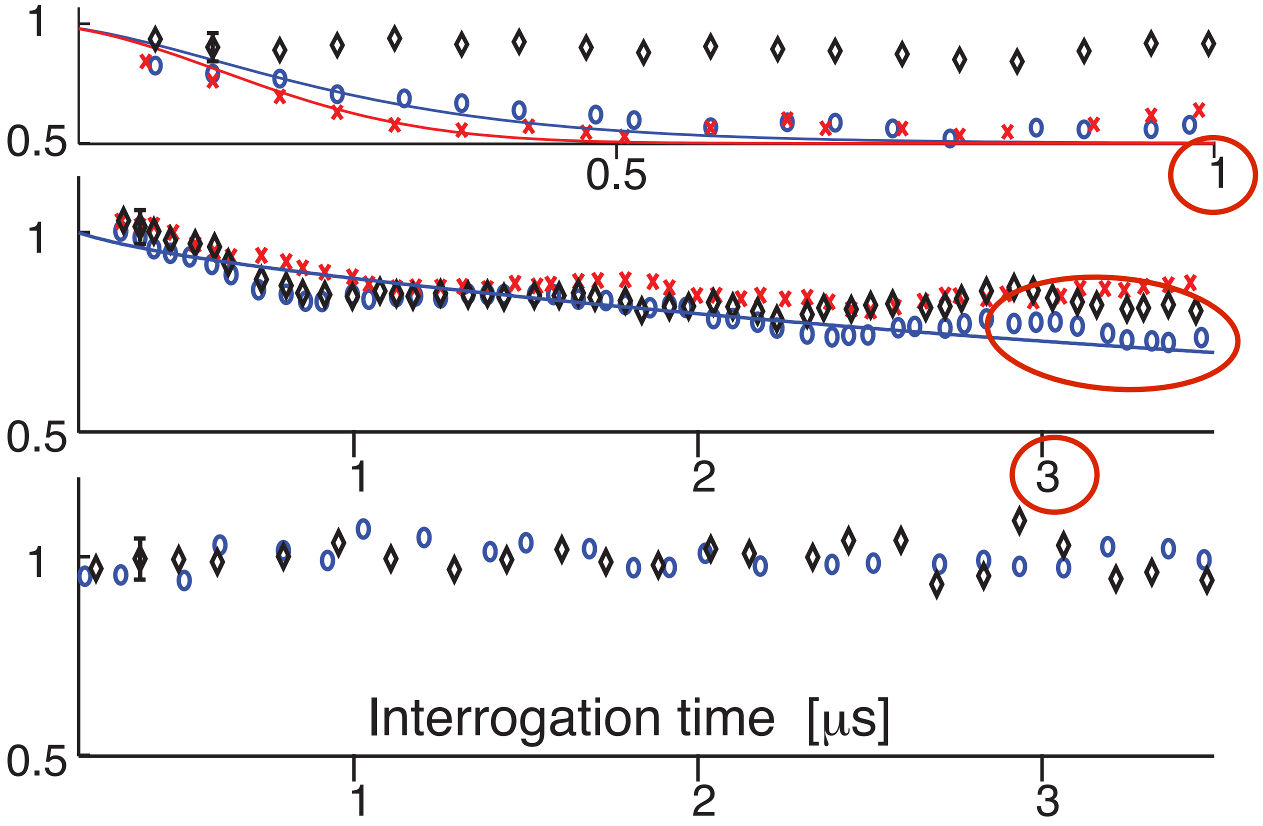


$S \propto b$

$S \propto b^2$

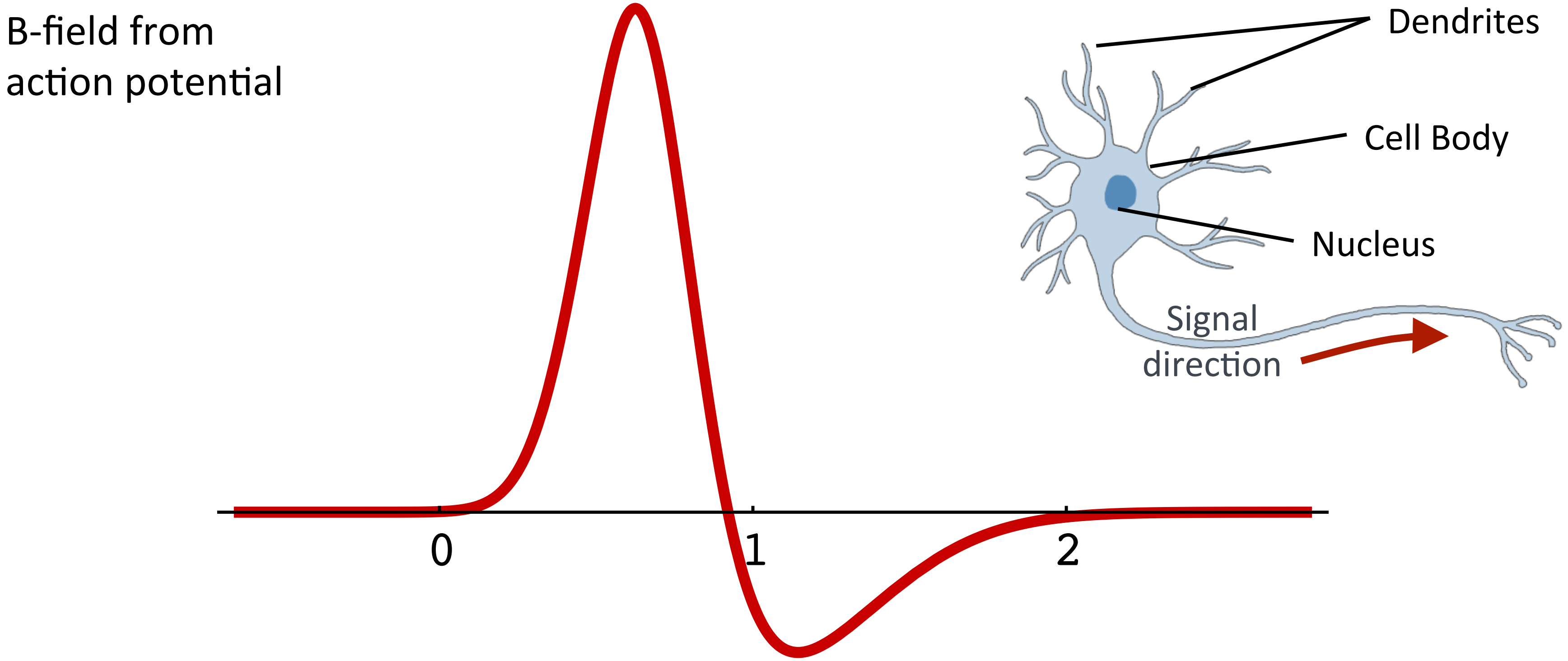
Advantage: Robustness

- Rotary Echo corrects for driving fluctuations
  - – Experiments (added noise)



Advantage: Flexibility

- Adjustable coherence time
  - match external constraints, avoid overhead times



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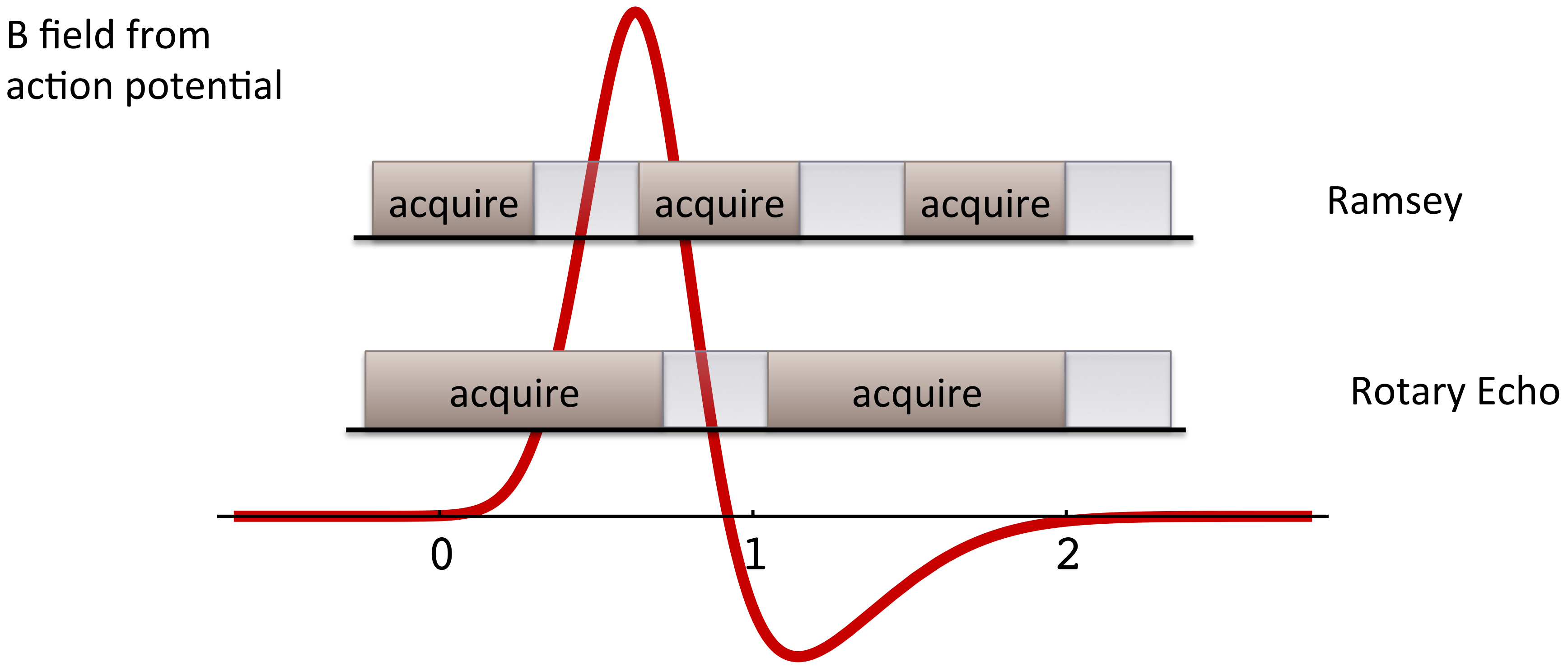

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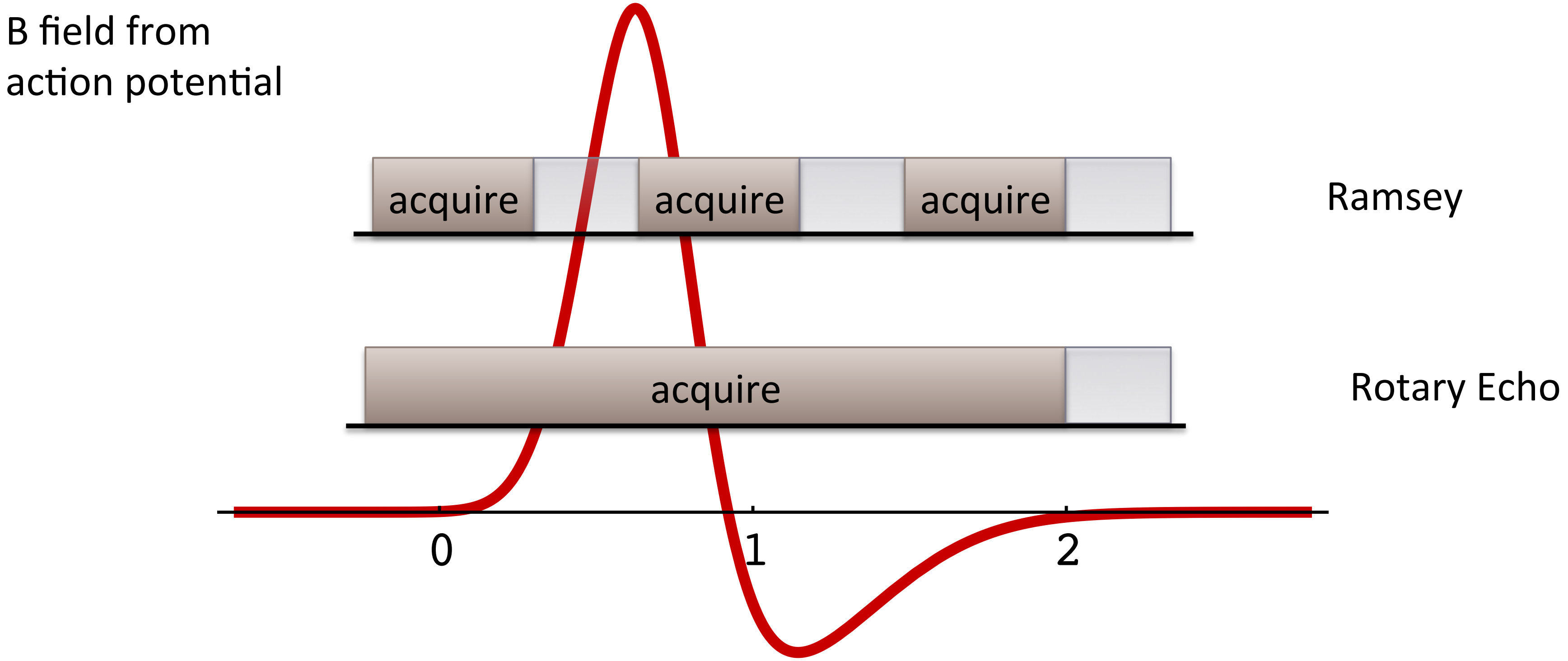

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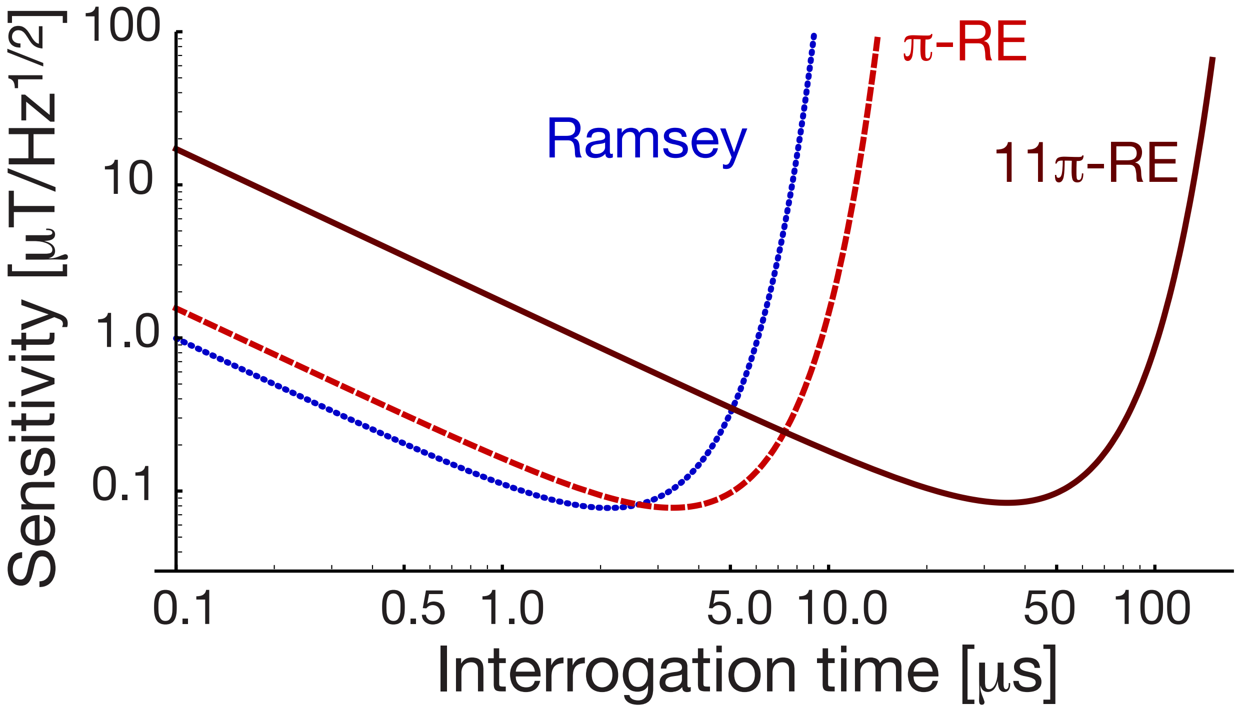
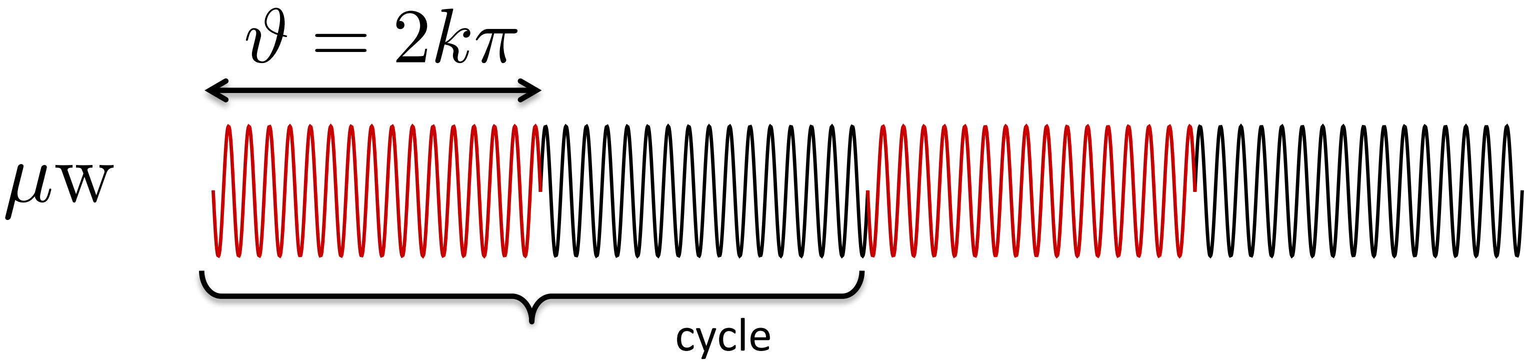


AC Magnetometry

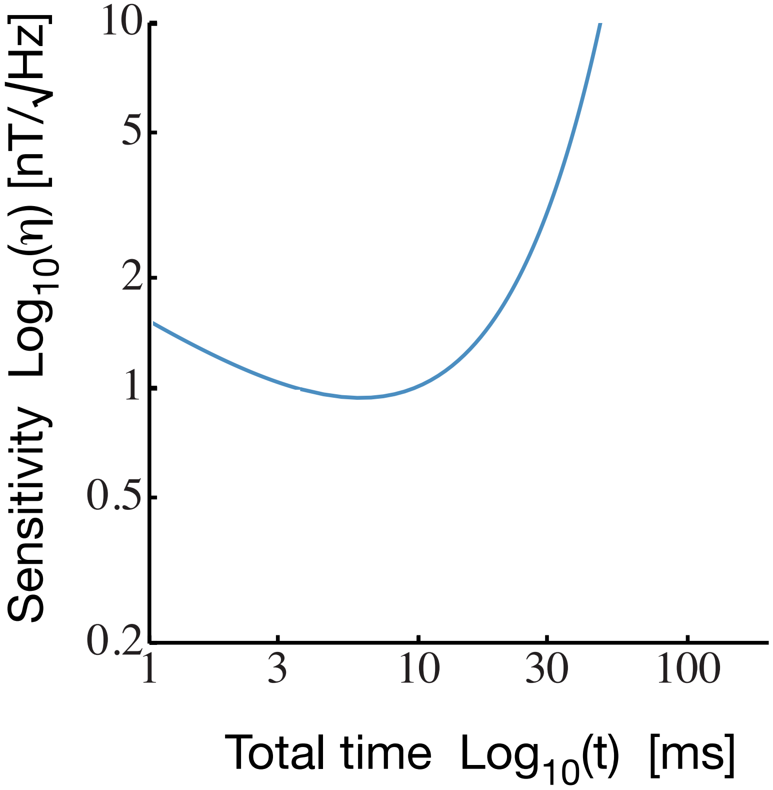
- Pulsed and continuous Dynamical Decoupling allow measuring AC fields

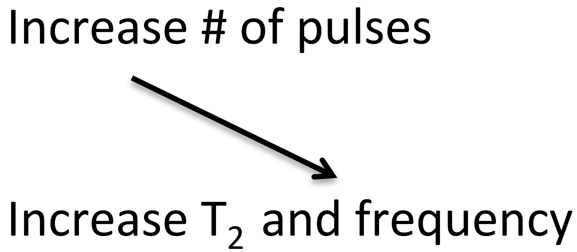


- cDD allows more flexibility than PDD
  - Compromise between decoupling efficiency and bandwidth

Compromise: T_2 vs. ω

Rotary Echo



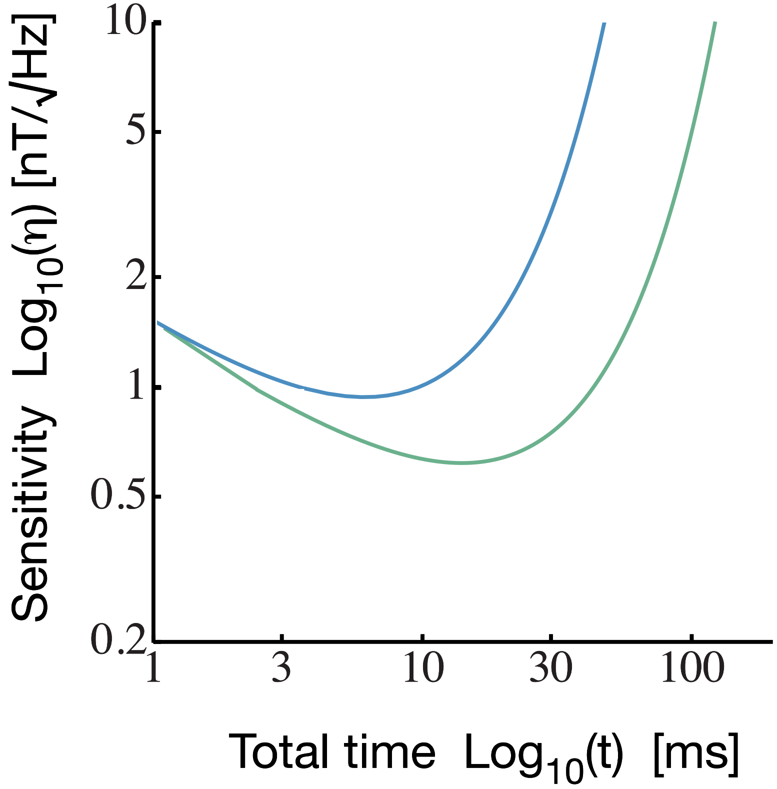


Increase # of pulses

Increase T_2 and frequency

Compromise: T_2 vs. ω

Rotary Echo



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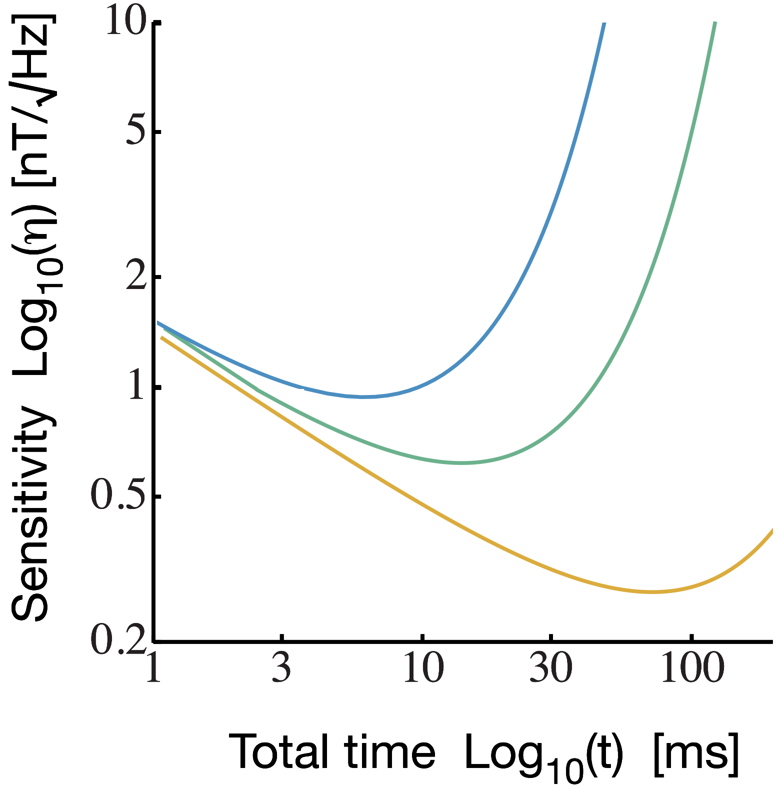

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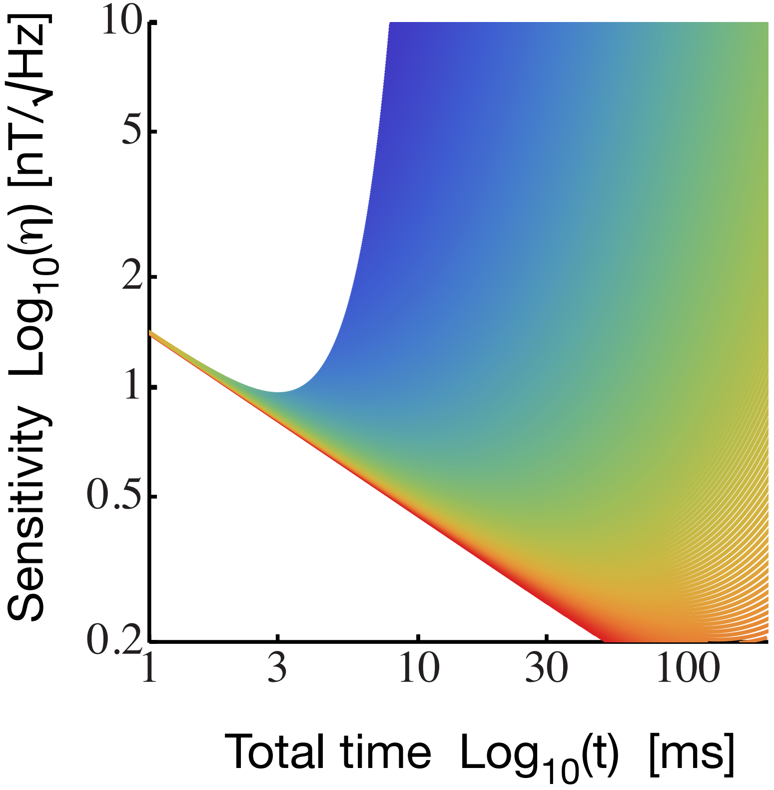

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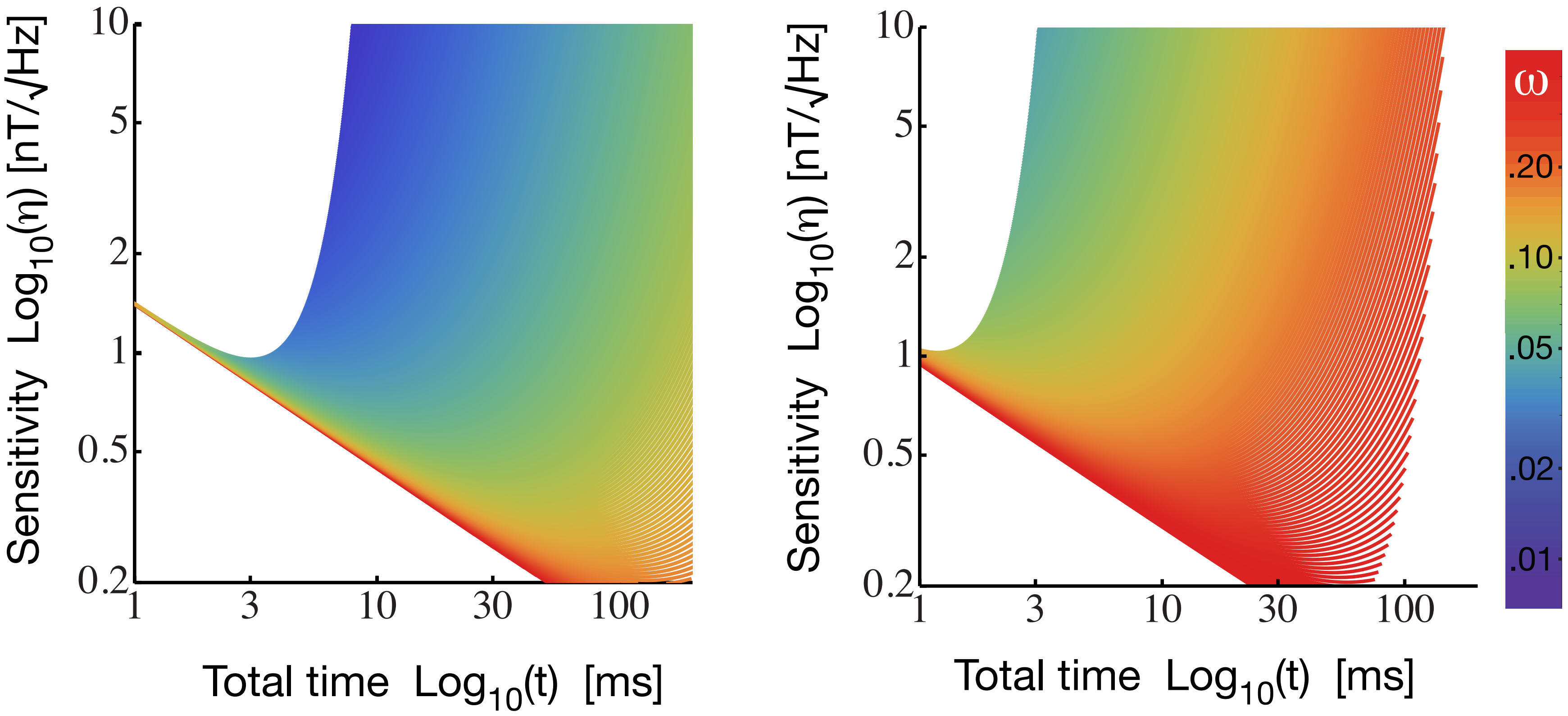
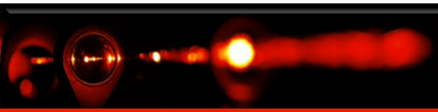


Spectroscopy

- Frequency selectivity can be varied by pulse cycle and Rotary Echo angle
  - Acquired phase is weighted by DD evolution:

$$\overline{B} = \frac{1}{t}\int_0^t b(t)F_{\mathrm{DD}}(t)dt = \overline{B}_{\max}W_{\mathrm{DD}}(\omega)$$



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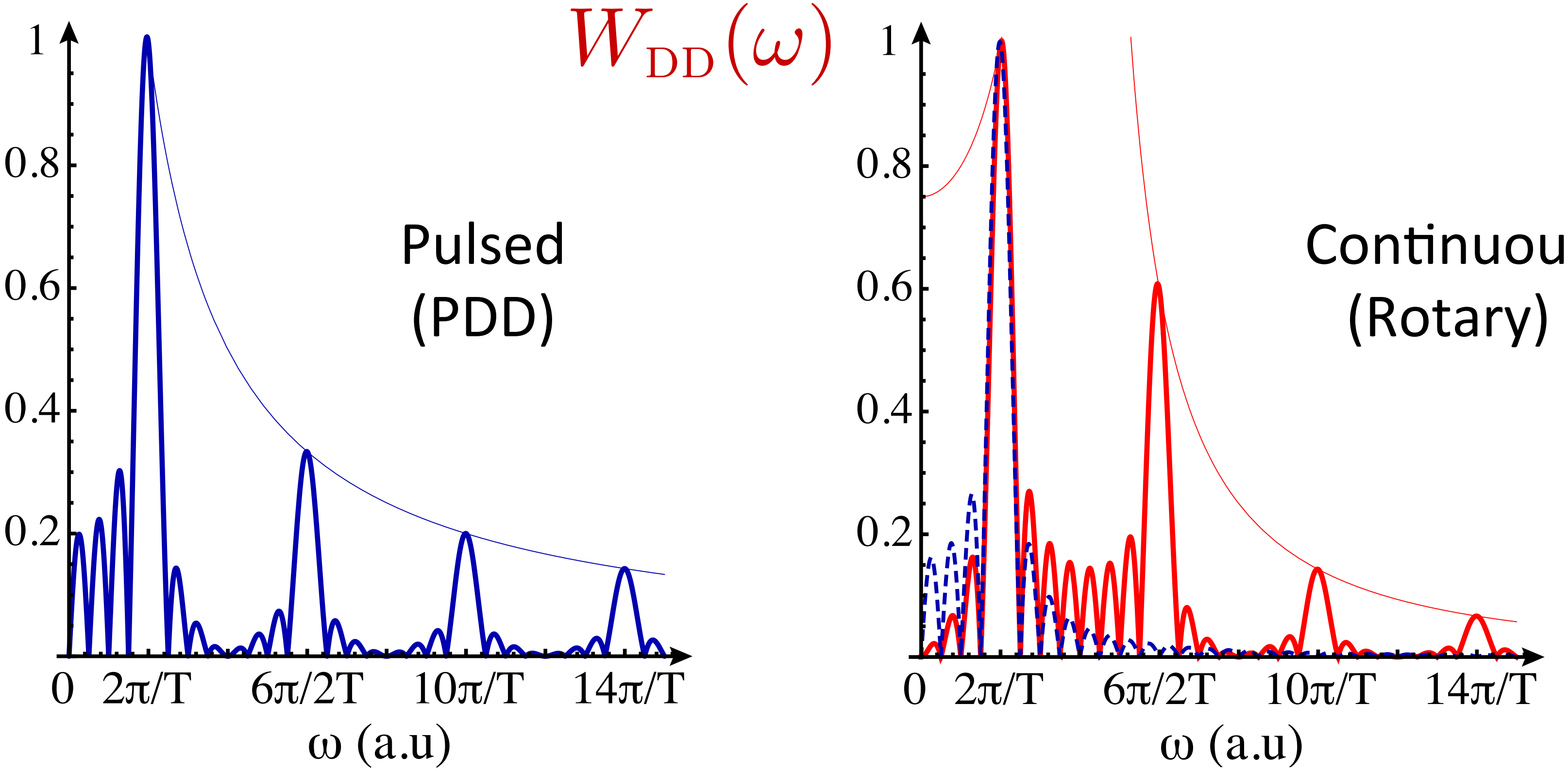
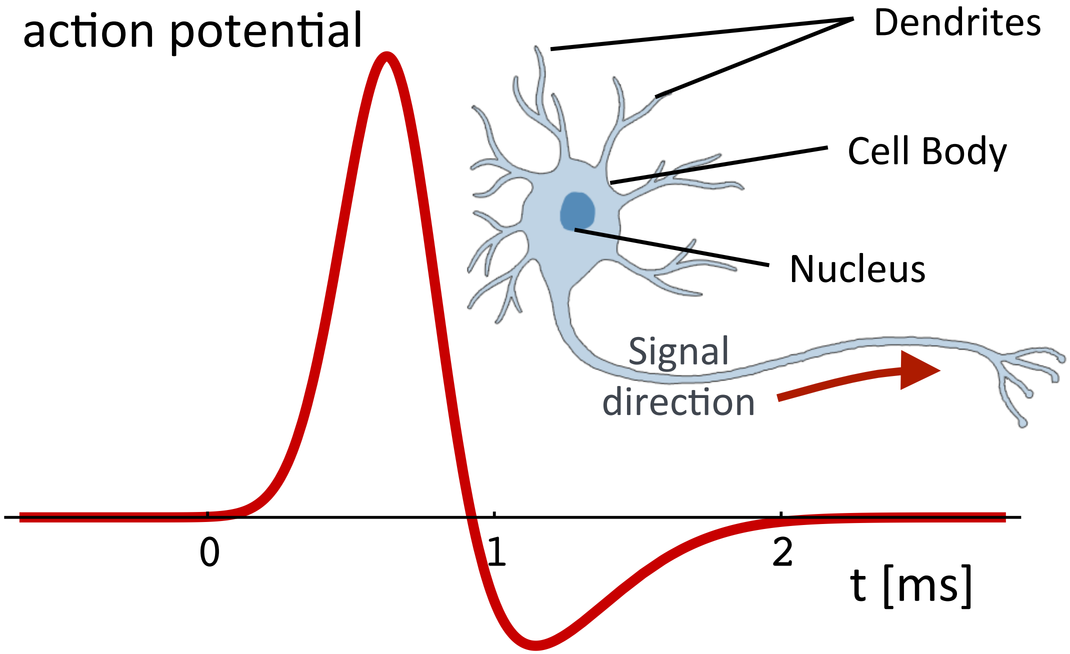


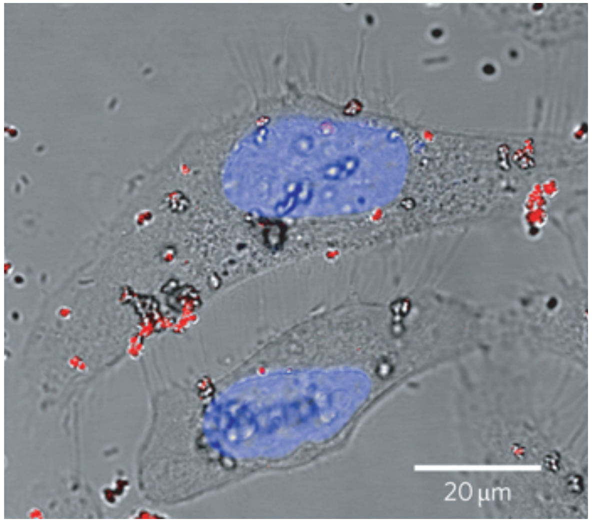
WAVEFORM RECONSTRUCTION

Waveform reconstruction

- Magnetic fields from biological activities

B-field from
action potential



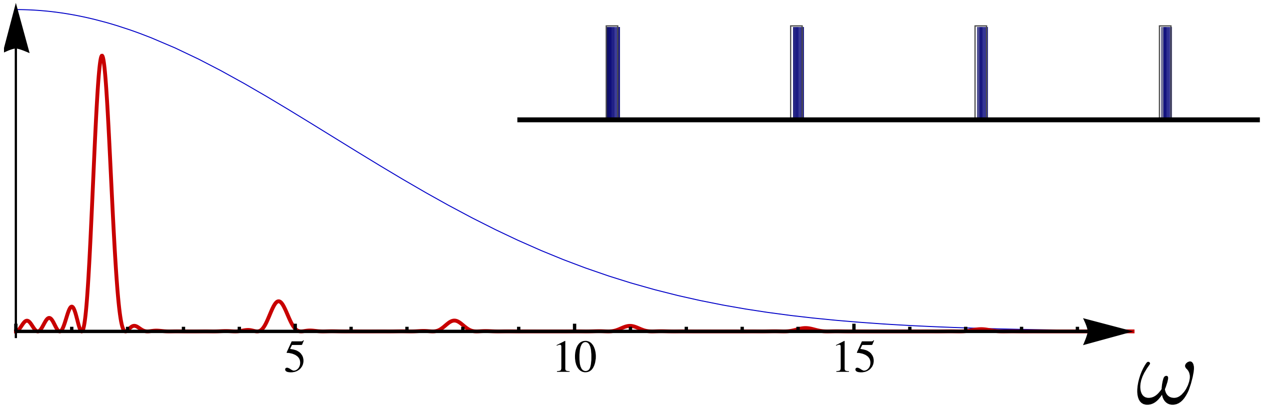


Magnetic activities
in He-La cells

L. P. McGuinness *et al.*, Nature Nanotechnology 6, 358–363 (2011)

Spectroscopy via DD

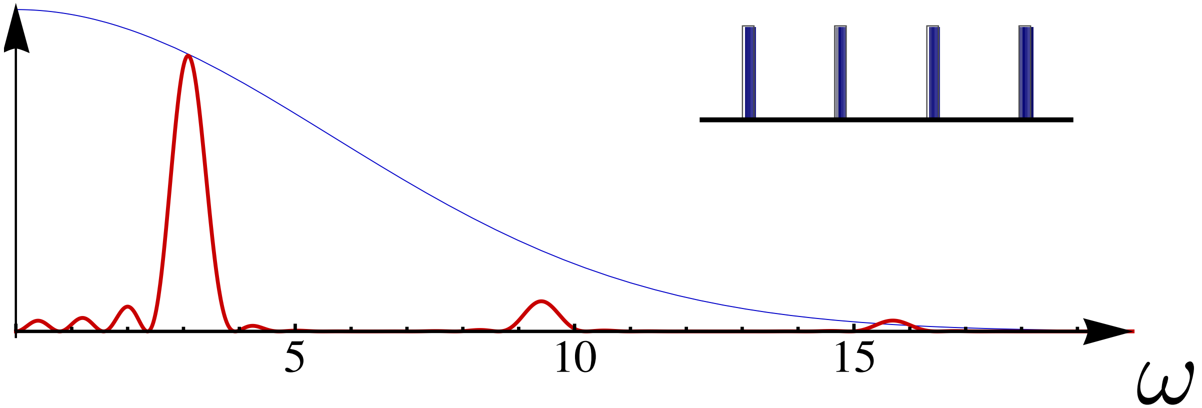
- CPMG sequences → frequency filters



Change pulse spacing

Spectroscopy via DD

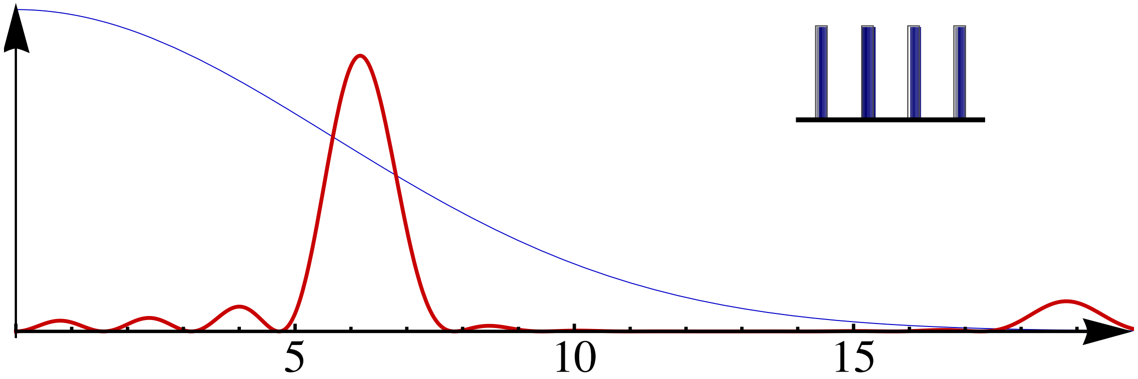
- CPMG sequences → frequency filters



Change pulse spacing

Spectroscopy via DD

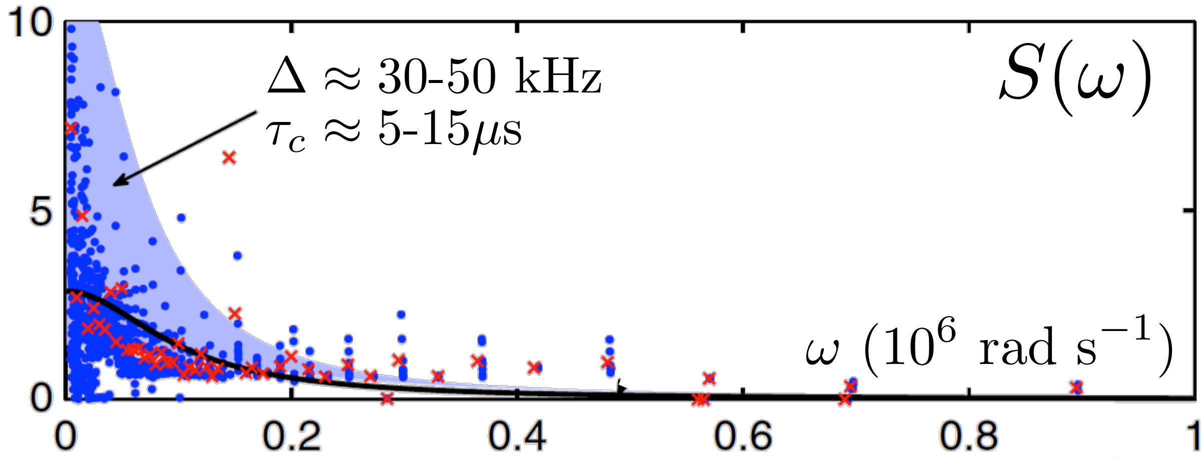
- CPMG sequences → frequency filters



Change pulse spacing

Spectroscopy via DD

- CPMG sequences ➞ frequency filters

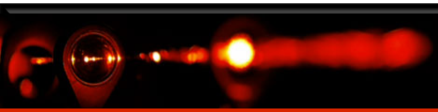


N. Bar-Gill, Nat. Comm. 3:858 (2012)

- Limitations:
  - – Inefficient reconstruction
  - – Cannot reconstruct general time-dependence
  - – Increasing pulse number, variable decoupling, …

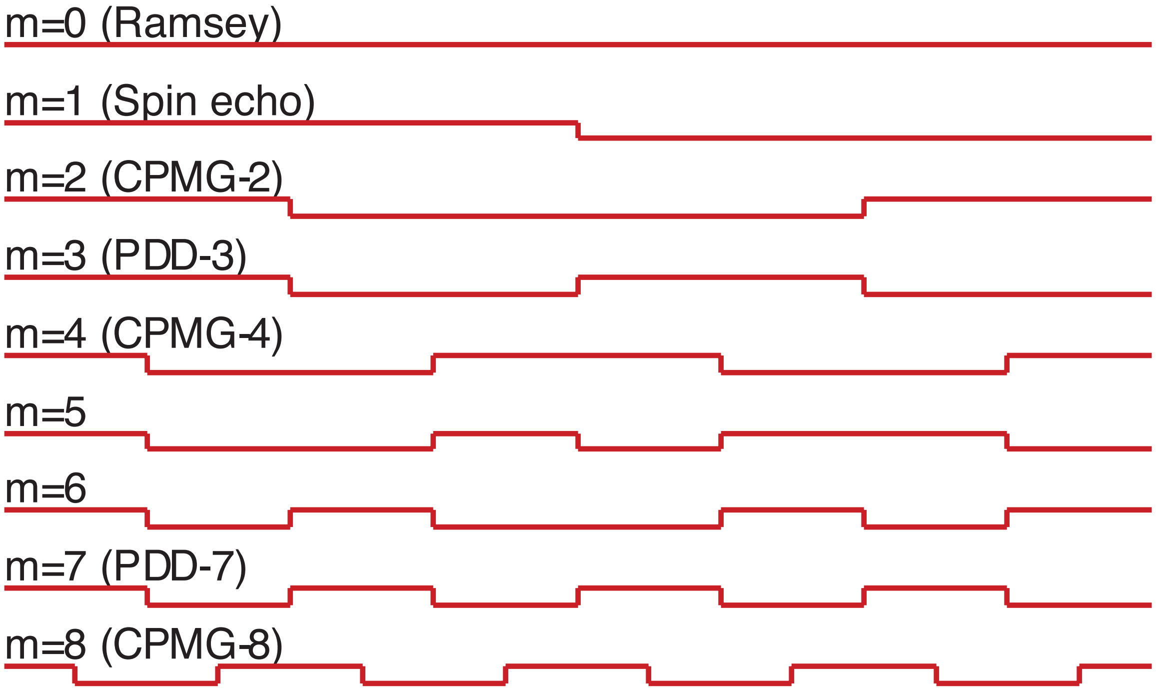
Waveform reconstruction

- Arbitrary waveform reconstruction with a complete (Walsh) transform
  - Complete set of orthonormal filters generated by pulsed control
  - Digital sampling reconstruction, systematic and efficient
  - Still achieves noise refocusing



Walsh Functions

- Complete basis (with increasing precision @ higher order)



Walsh Functions

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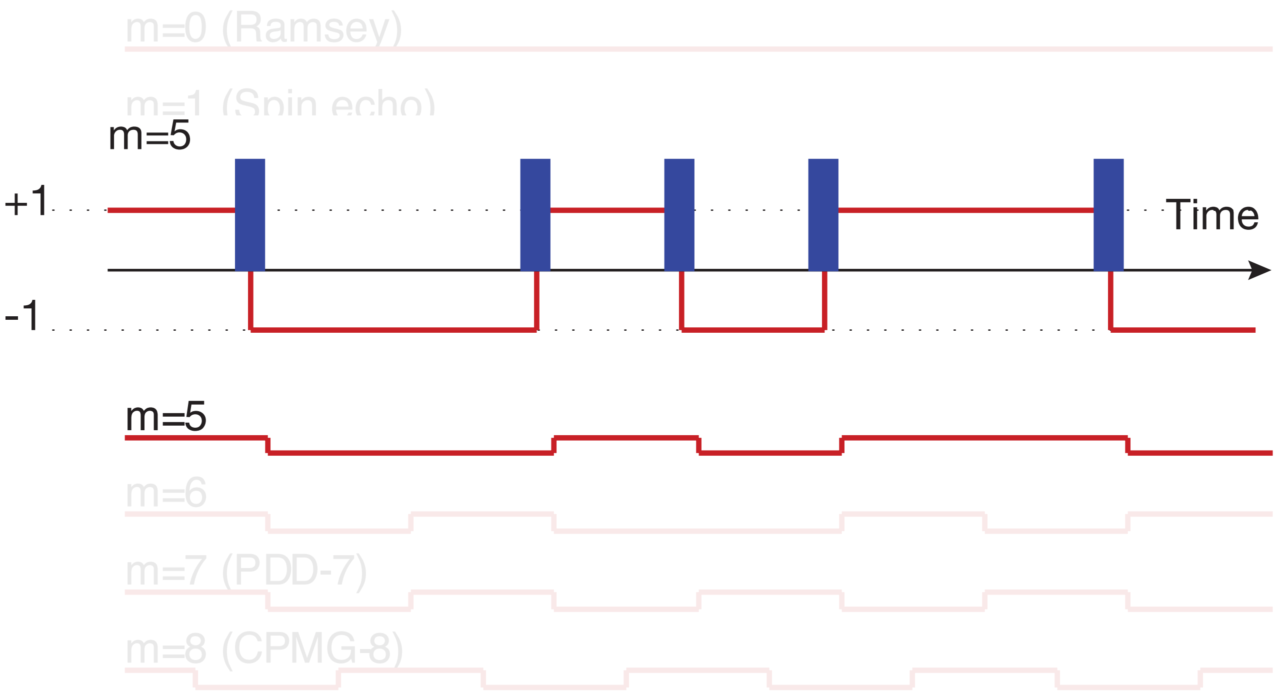


- CPMG (PDD) are a subset of Walsh

Walsh Reconstruction

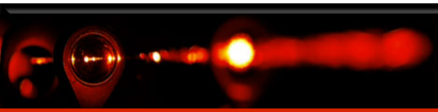
- Acquired phase depends on field and Walsh:

$$\varphi_m(T) = \gamma_e \int_0^T b(t) W_m(t/T) dt = \gamma_e \hat{b}_T(m)$$

- Field obtained from Walsh transform

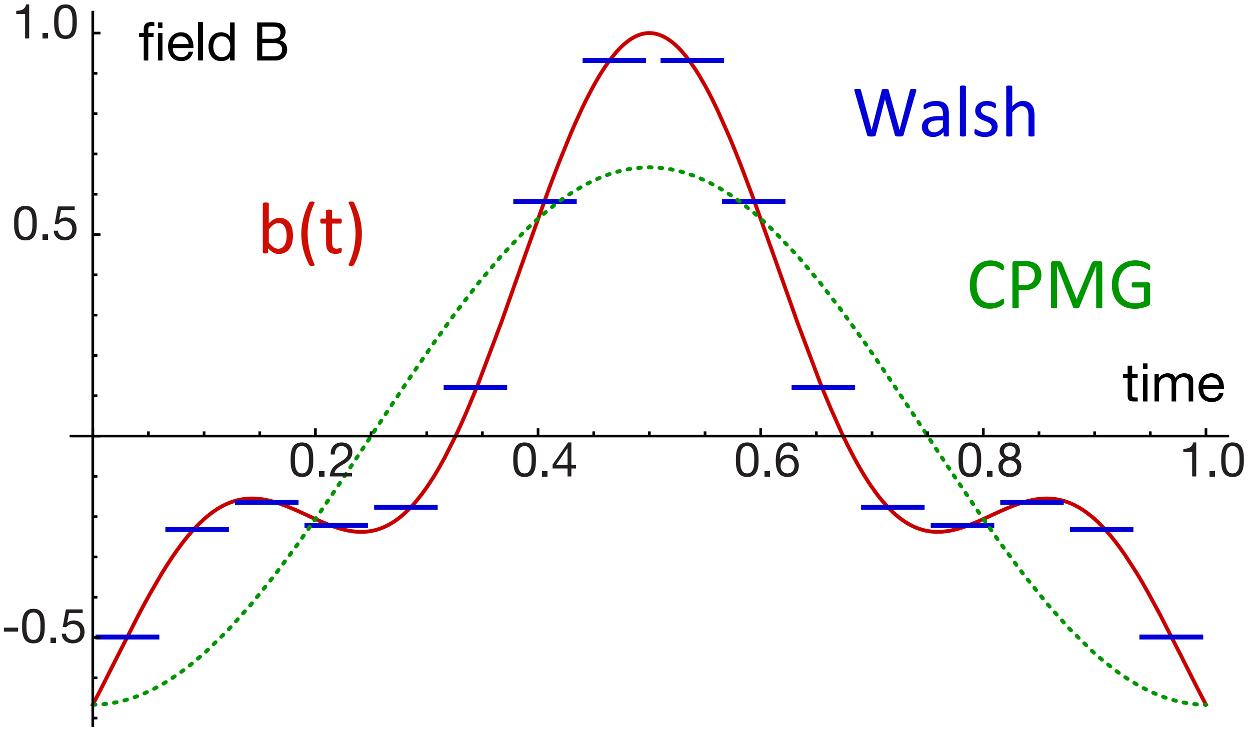
$$\tilde{b}_N(t) = \frac{1}{N} \sum_{m=0}^{N-1} \hat{b}_T(m) W_m(t/T)$$

- Accurate reconstruction (minimal error)



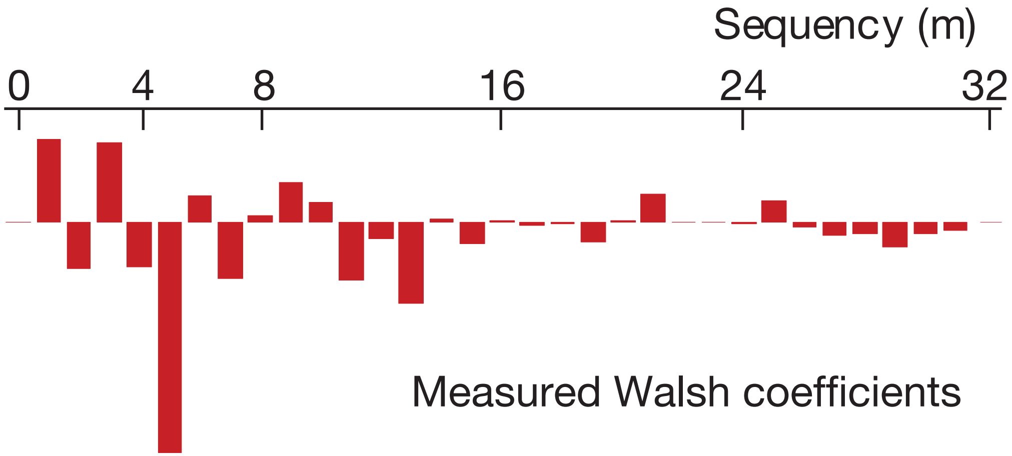
Walsh vs. CPMG

- Reconstruction of polychromatic, asymmetric wave: $b(t) = a_1 \sin(\omega_1 t) + a_2 \sin(\omega_2 t + \varphi)$



Preliminary results

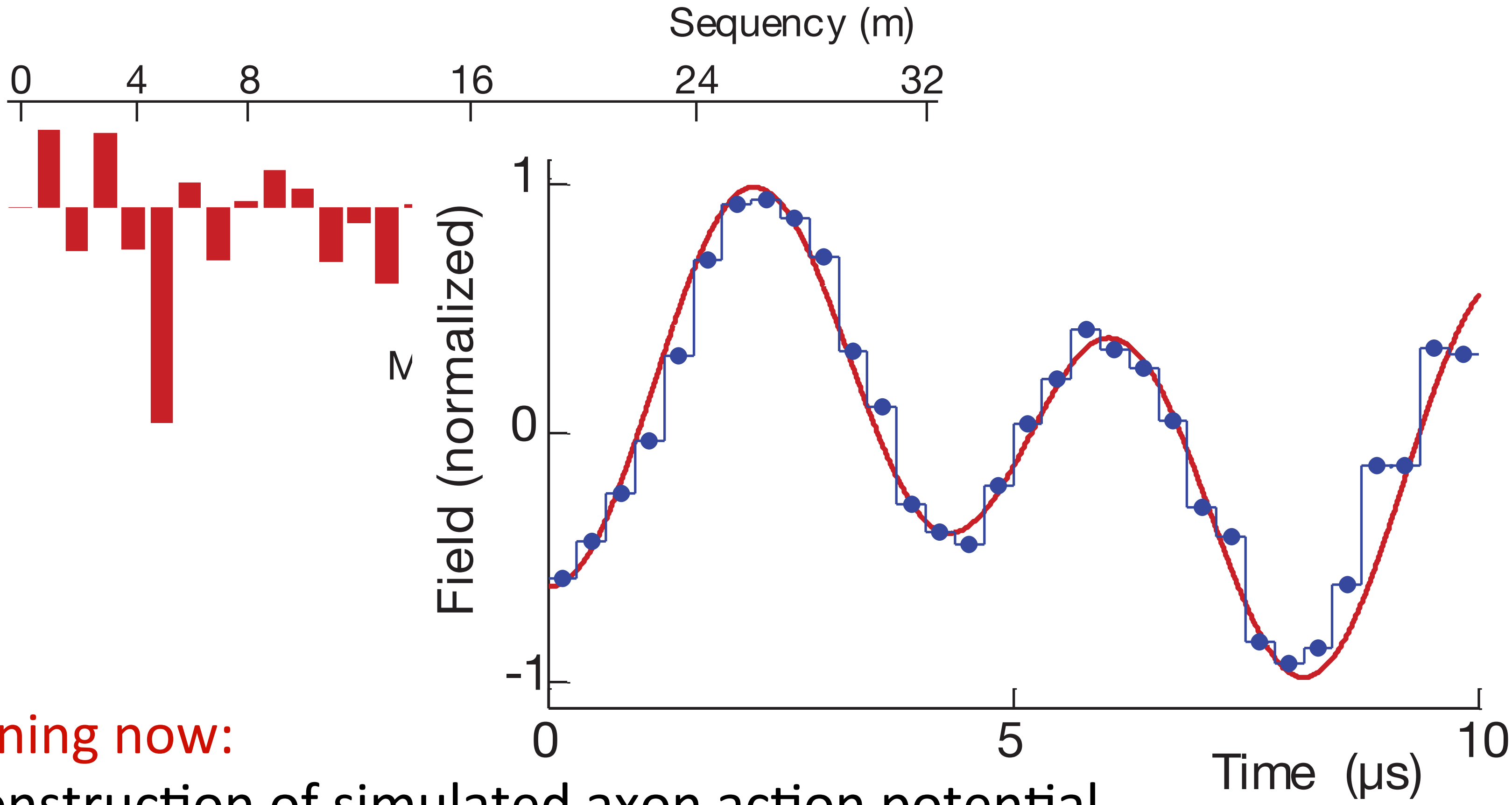
- Experimental reconstruction $b(t) * \mathrm{Amp}$



Measured Walsh coefficients

Preliminary results

- Experimental reconstruction $b(t) * \mathrm{Amp}$



Running now:
reconstruction of simulated axon action potential

Outlooks

- General scheme, applicable to other measurements (e.g. temperature)
- Noise spectroscopy for random fields
- Optimization
  - Optimal subset of Walsh, given prior information
  - Compressive sensing

Conclusions

- Quantum sensors introduce new challenges and opportunities in quantum control
  - Devise control strategies to achieve flexible quantum sensors
  - Quantum probe manipulation extract field information efficiently

Thanks!

Alex Cooper

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Ken Wang

Easwar Magesan

Quantum Engineering Group - MIT