Quantum Techniques for Precision Measurements with NV-Diamond

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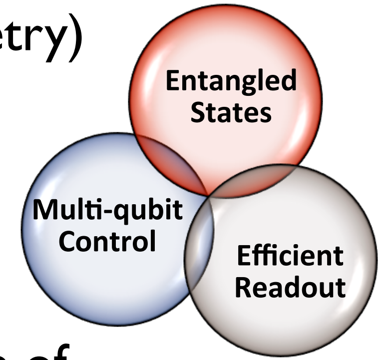
Harvard University, Department of Physics

Outline

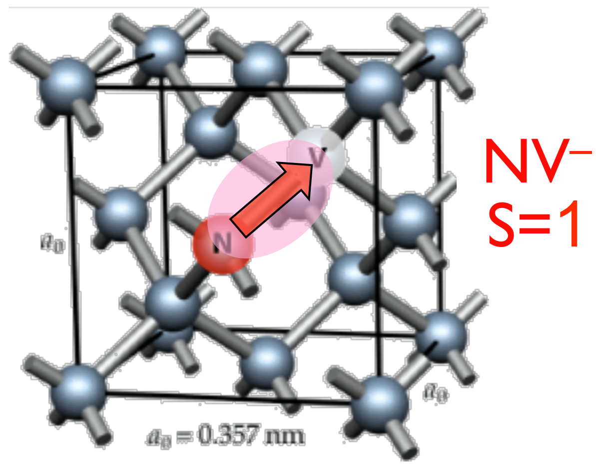
- A little background on NV-diamond physics & precision spin measurements (magnetometry)

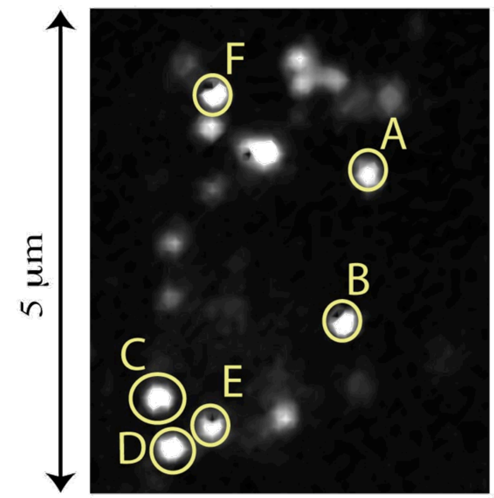


- My group's role as part of QuISM team
- Some recent results:
  - Successful application of dynamic decoupling to wide range of NV-diamond samples => T_2>2 ms, improved magnetometry FOM
  - Identified suppression of electronic (N) spin-bath dynamics by nuclear (^{13}C) spin impurities => unexpectedly long NV T_2
  - Side-collection technique => NV optical collection efficiency >50%
  - AR-coating of diamond => improved NV excitation/detection efficiency

Nitrogen Vacancy (NV) color centers in diamond

Atom-like defect with special properties:

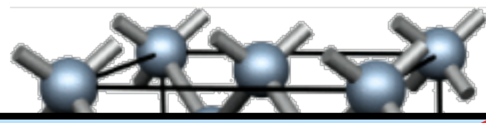


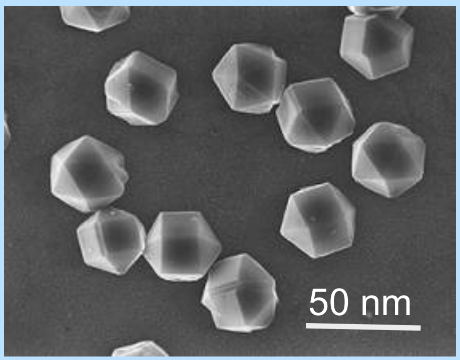


Confocal: individual NVs in diamond

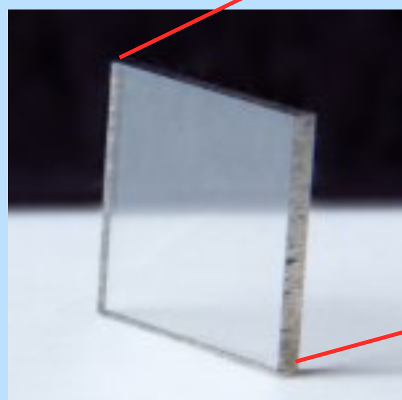
- NV$^-$: localized electronic spin state (S=1) with T_2 ~ ms, large Zeeman shift
- Optical pumping => spin-state preparation
- Coherent spin manipulation with microwave pulses
- Optical read-out of spin-state
- Diamond: transparent, robust solid; stiff lattice; small spin-orbit
- NV density ~ 10^{12} - 10^{18} cm^{-3}

Nitrogen Vacancy (NV) color centers in diamond

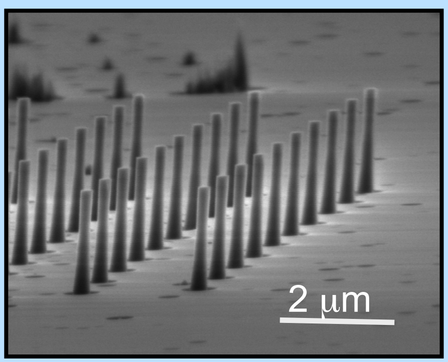




Diamond nanocrystals

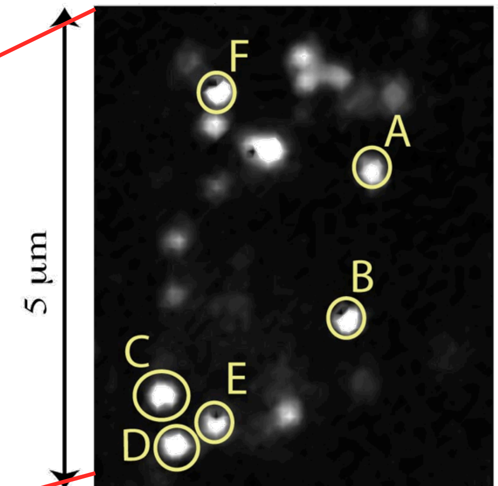


Single crystal diamond



Diamond nanopillars

NV centers created by ion implantation & annealing; also CVD techniques

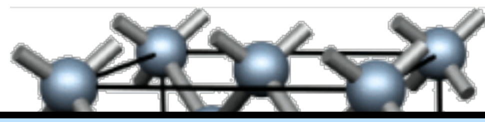


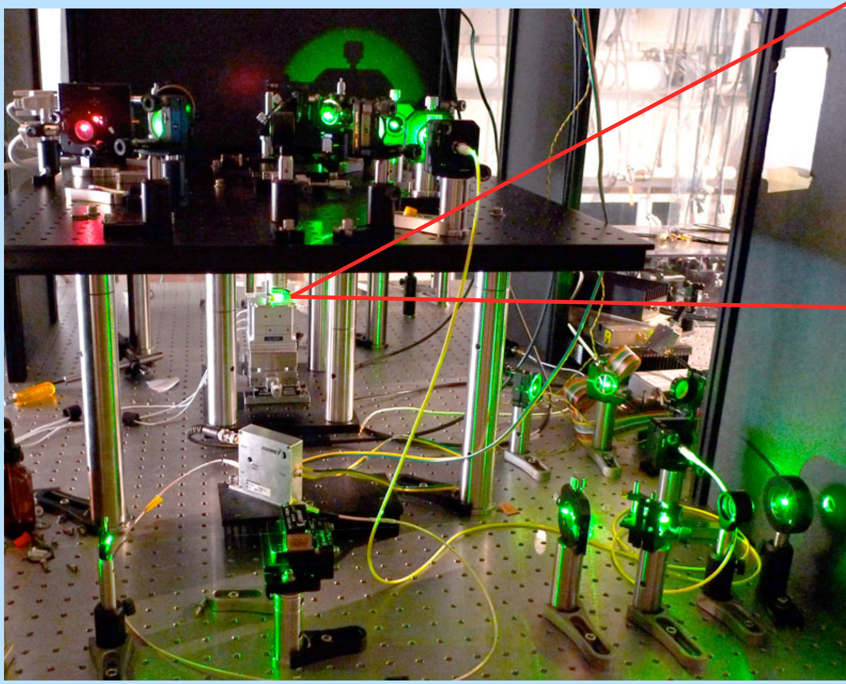
Confocal: individual NVs in diamond

ms, large Zeeman shift

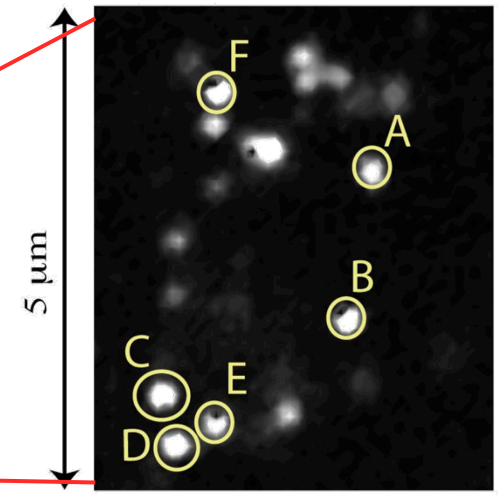
l spin-orbit

Nitrogen Vacancy (NV) color centers in diamond





Relatively simple apparatus (confocal)



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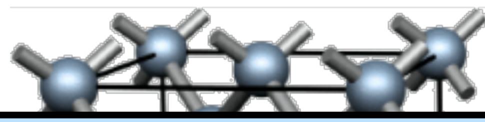
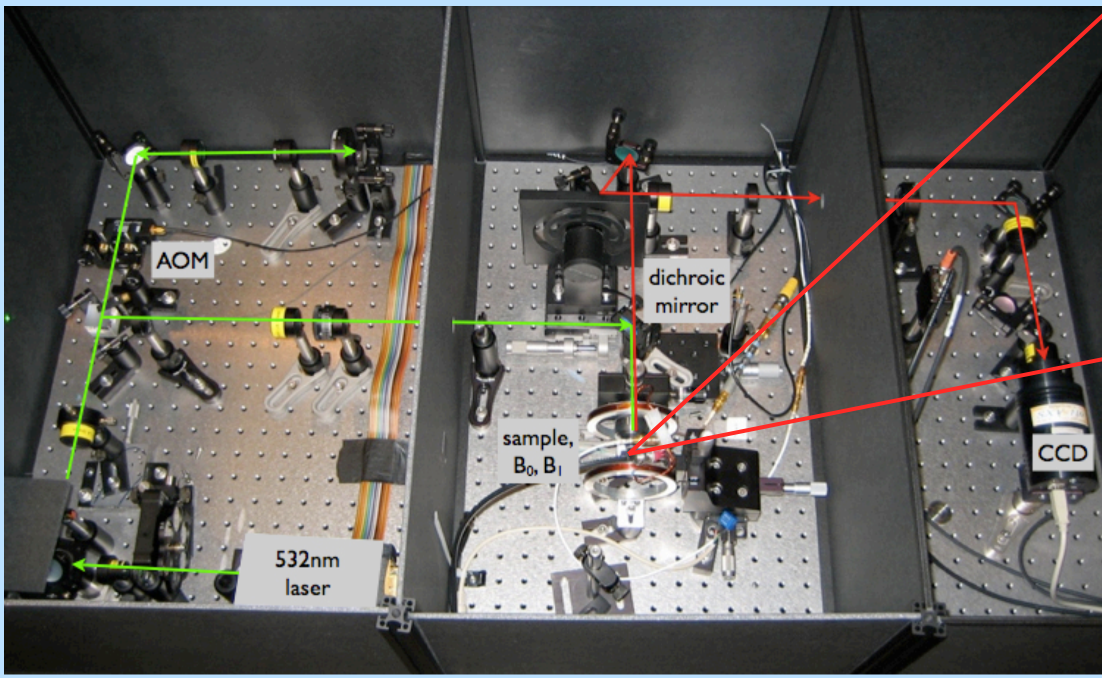
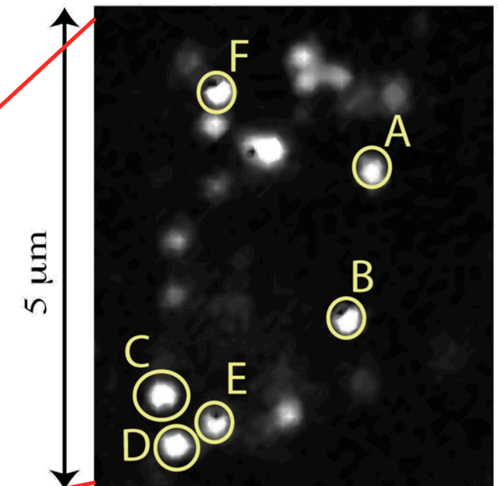




Relatively simple apparatus (CCD imager)



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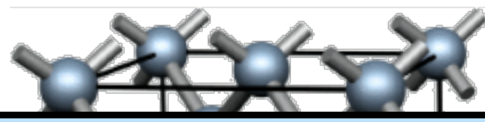
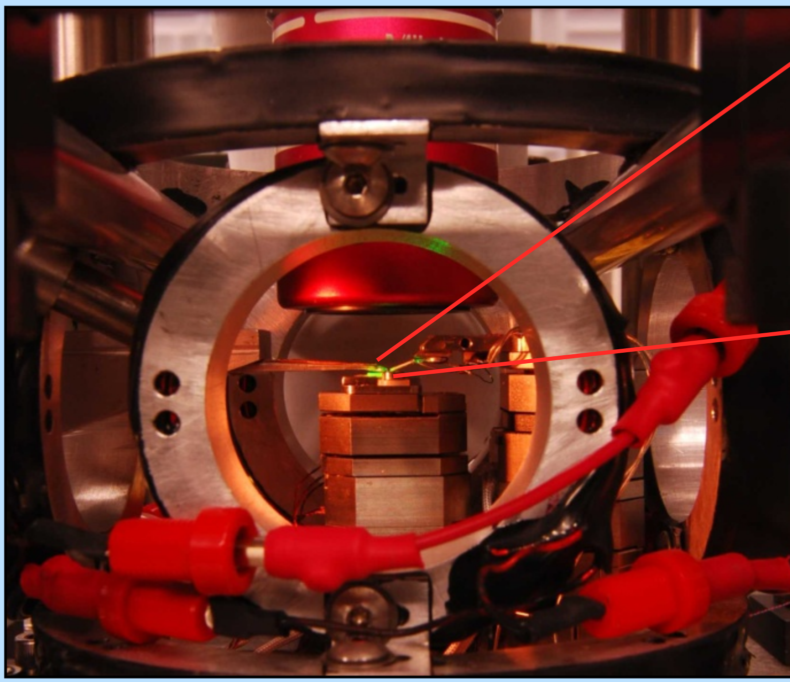
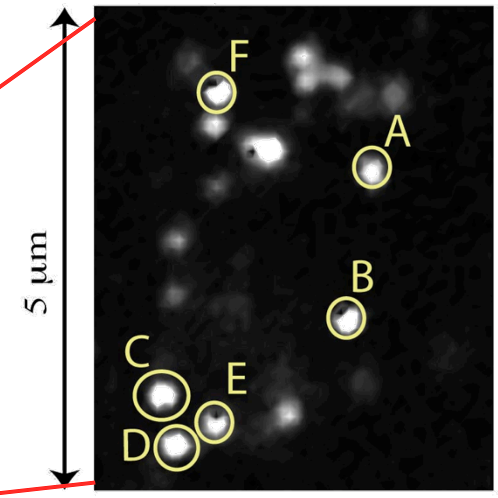




Less simple… (confocal + AFM)



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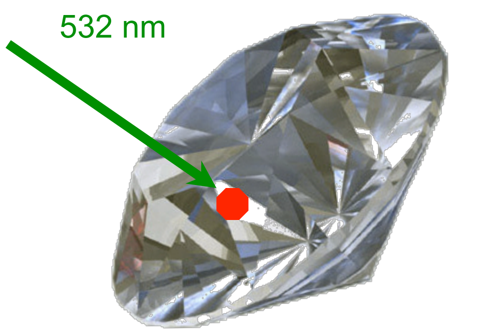
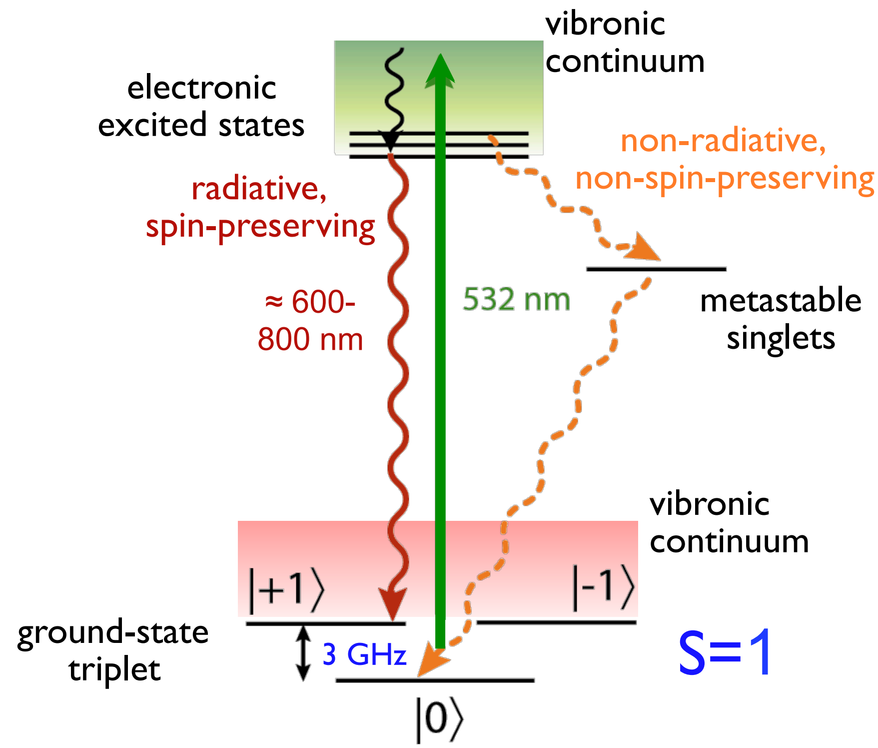
Coherent spin manipulation in NV-diamond





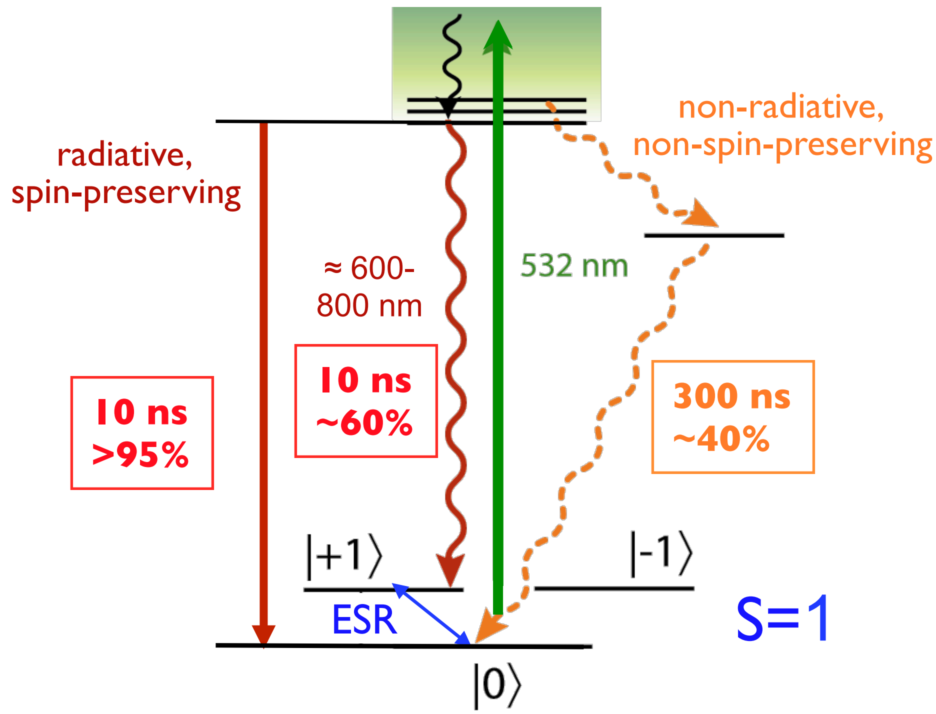
- Atom-like energy levels coupled by strong optical transitions
- Ground-state hyperfine & Zeeman structure with long ESR coherence times (T_2 ~ 1 ms)
- Spin-state dependent fluorescence & decay

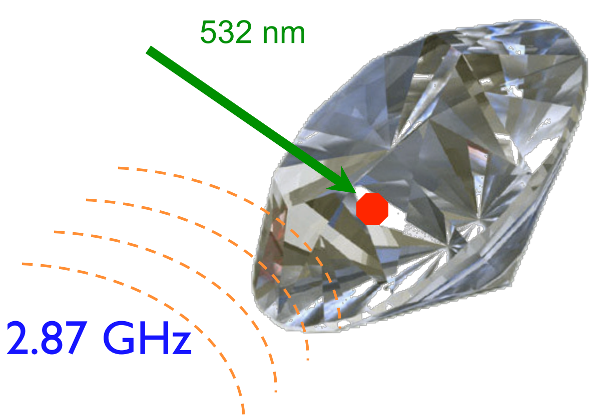
Coherent spin manipulation in NV-diamond

1) Spin-polarization (into m_S=0) by optical pumping (>95%)

2) Spin coherence control with ESR

3) Spin-state optical read-out





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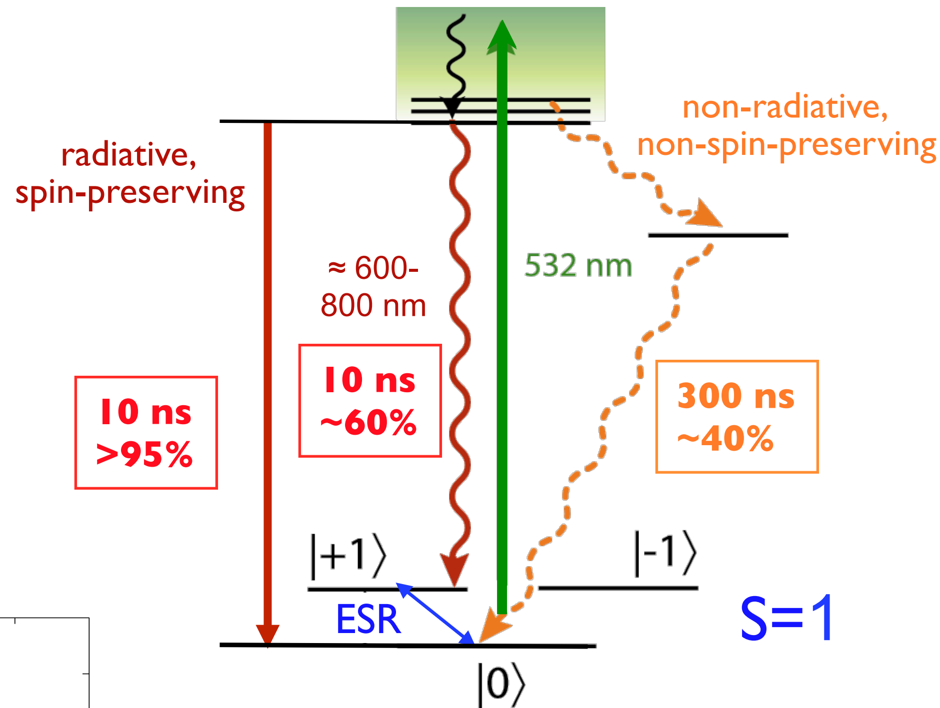

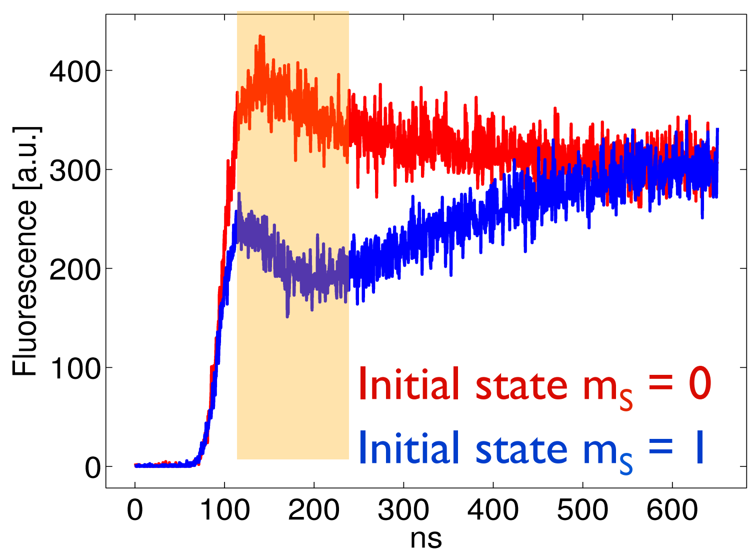

Typical single NV fluorescence data

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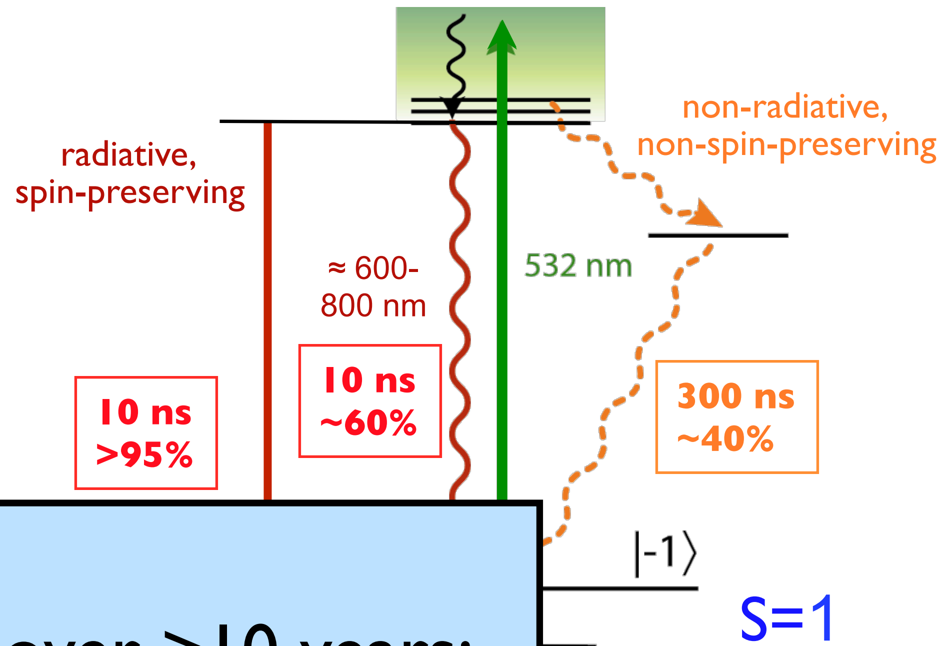

Large amount of work over >10 years:

N. Manson	T. Kennedy
S. Rand	P. Grangier
F. Jelezko	J.F. Roch
J. Wrachtrup	S. Prawer
P. Hemmer	D. Awschalom

Coherent spin manipulation in NV-diamond

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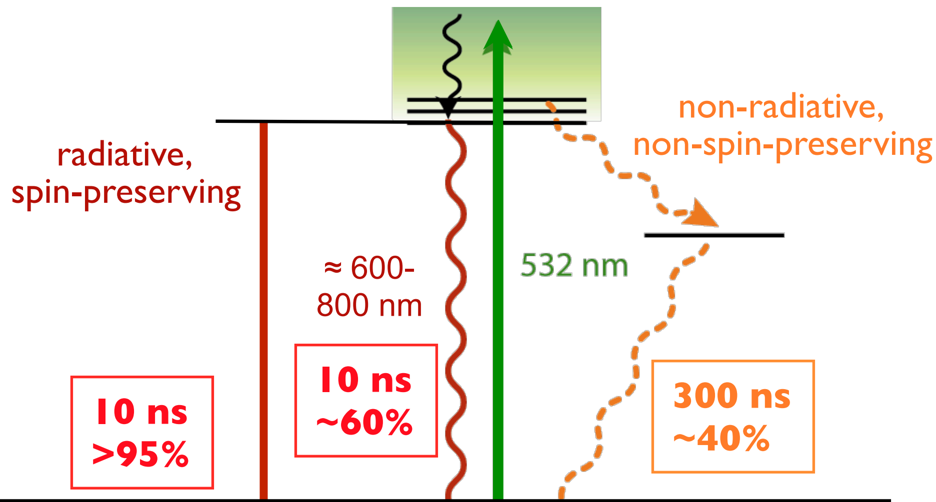


Other important issues:

Composite spin environment: N, ^{13}C

=> NV decoherence

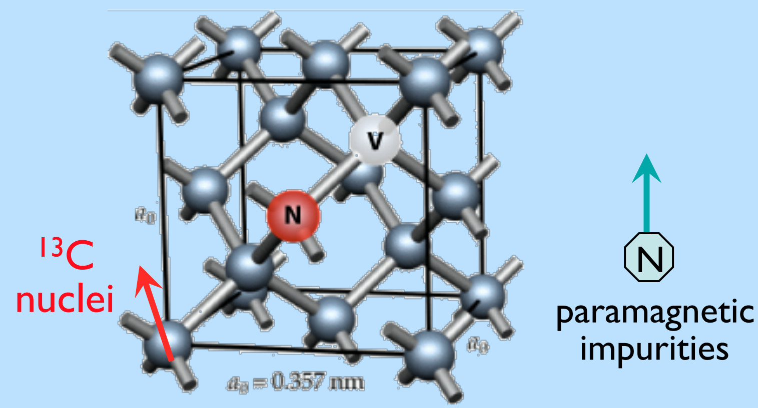
Environment-enhanced metrology?

4 crystal axes

Optical ionization to NV^0

Sample geometry & fabrication

Surface chemistry

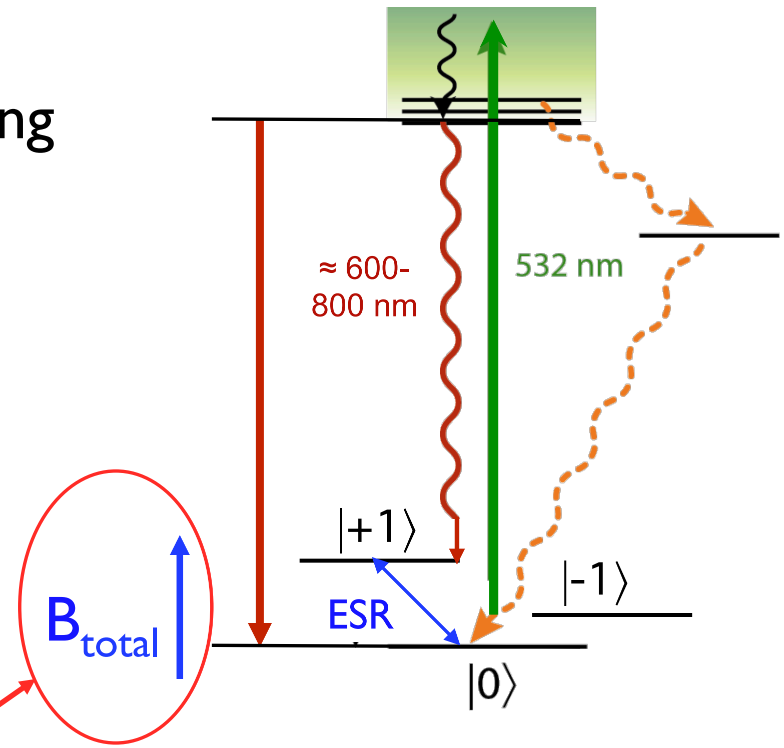


NV-diamond magnetometry

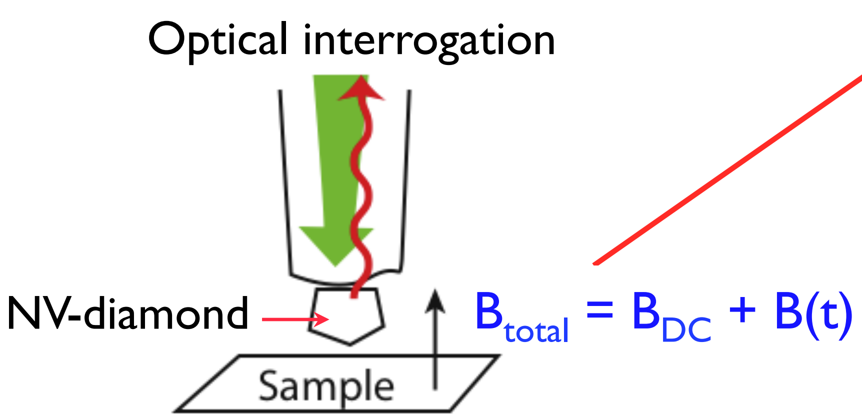
1) Spin-polarization by optical pumping

2) Spin coherence control with ESR
   & B field to be sensed

3) Spin-state optical read-out

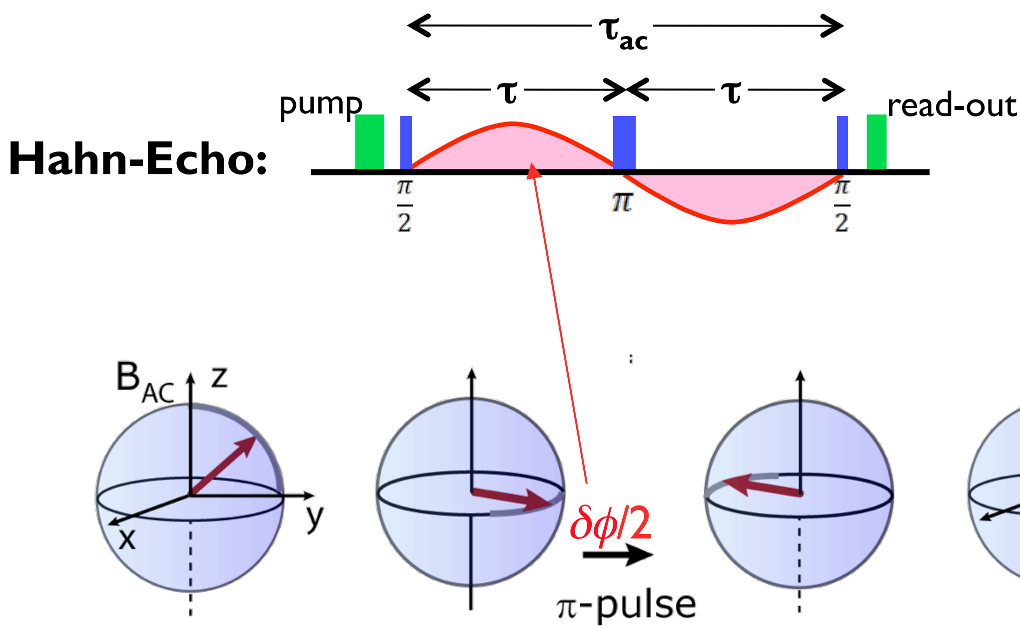


Bohr magneton
Zeeman shift



Maze et al., Nature (2008)
Balasubramanian et al., Nature (2008)
Taylor et al., Nature Physics (2008)

Echo-based NV magnetometry

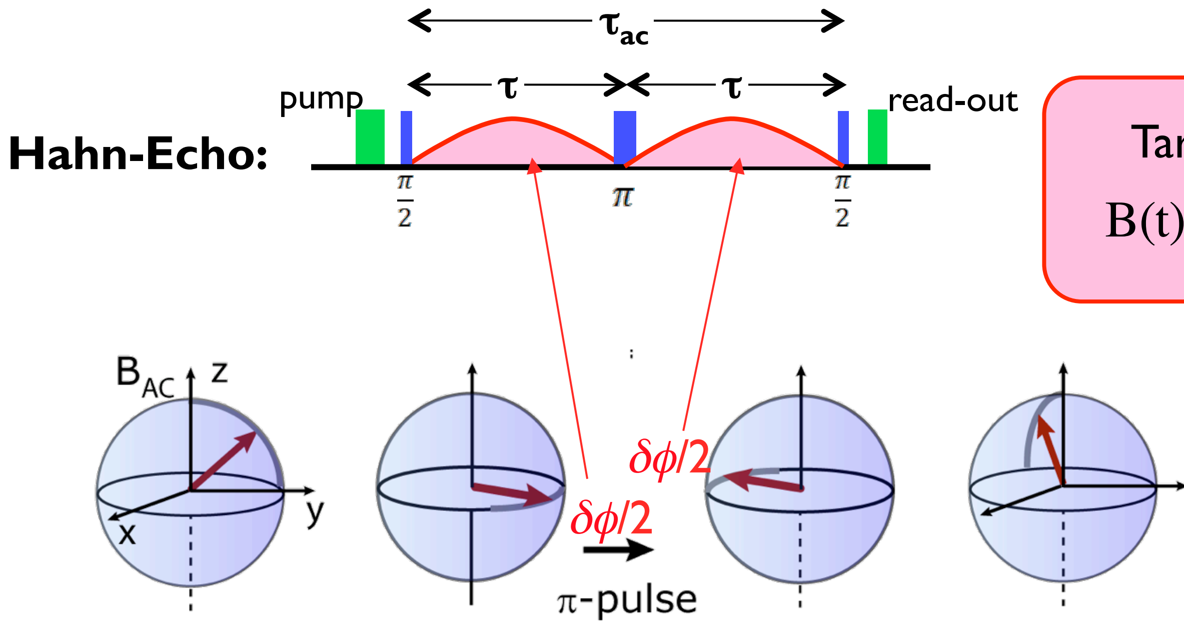


Target ac magnetic field:

$$B(t) = B_{ac} \sin[(2\pi f_{ac})t + \phi]$$

Echo also decouples NV spin from static inhomogeneities in local environment => T_2 limit

Echo-based NV magnetometry



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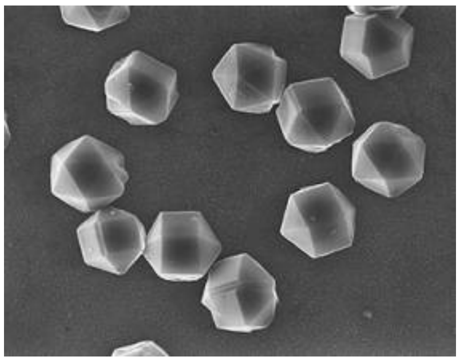
NV fluorescence signal ~ $\delta\phi \approx \gamma_{NV} B_{ac} \tau$

Shot-noise sensitivity

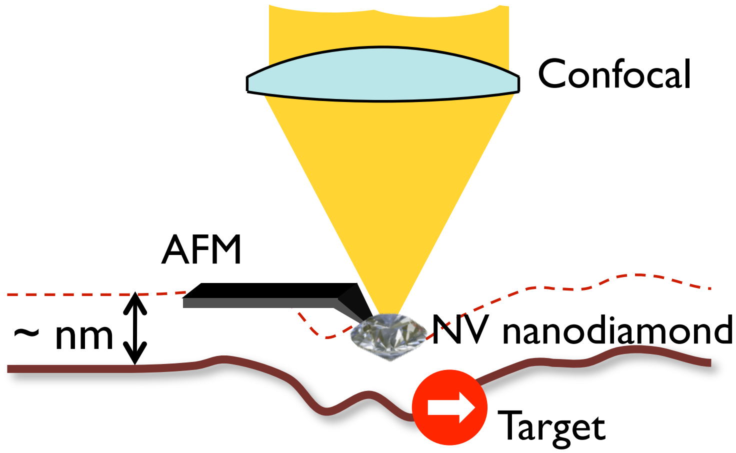
$$\frac{\delta B_{ac}}{\sqrt{\text{Hz}}} \sim \frac{1}{\gamma_e \sqrt{T_2 n}}$$

NVs in sensor volume

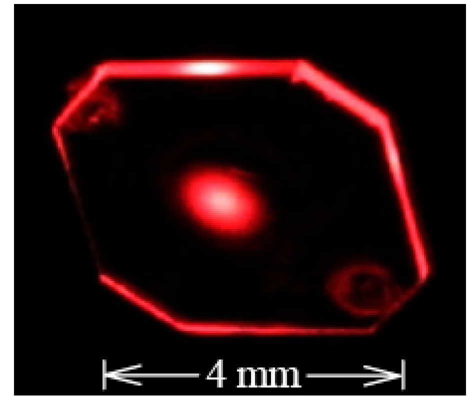
NV-diamond magnetometry: complementary modalities



NV nanodiamonds

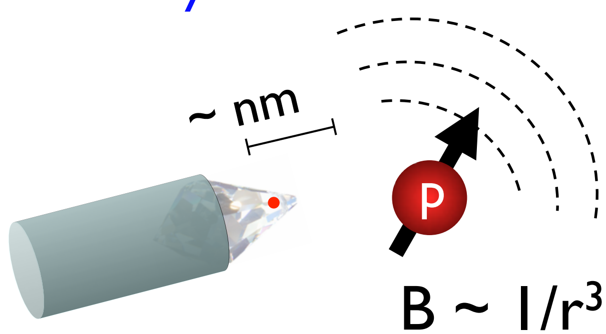


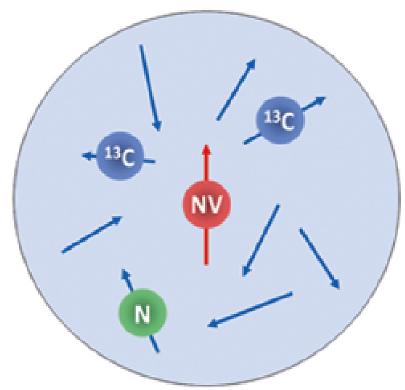
Scanning diamond-AFM



Bulk diamond

Proximity to field source

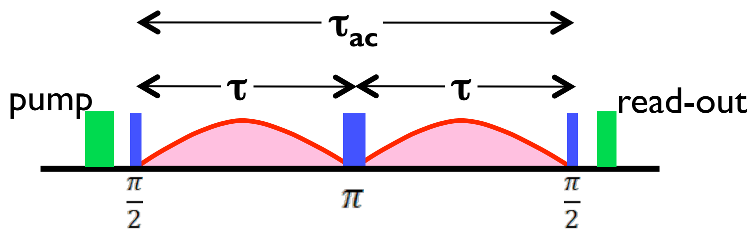




Composite spin environment

Best single-NV magnetometry: 4 nT/Hz$^{1/2}$

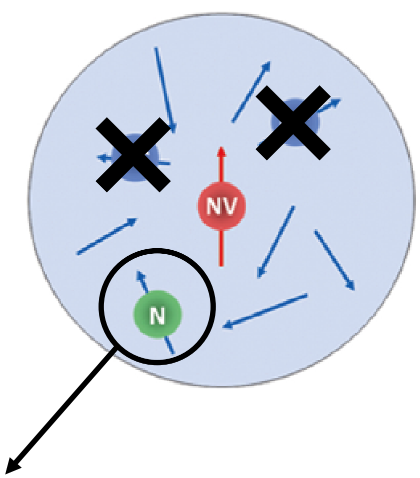
Hahn-Echo:

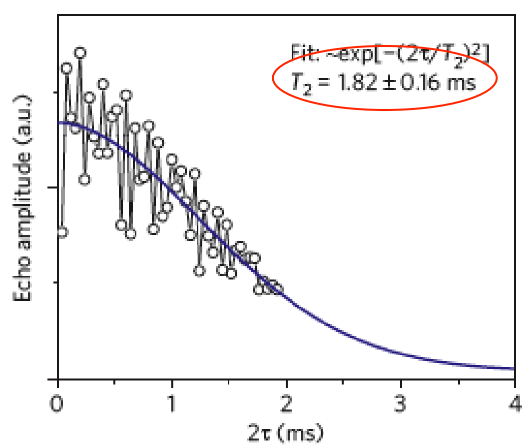


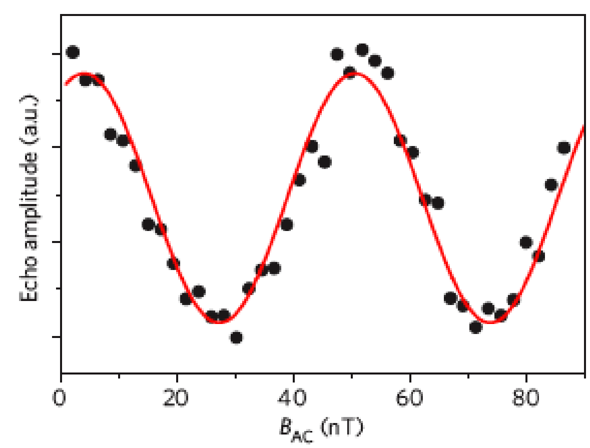
Target ac magnetic field:

$$B(t) = B_{ac}\sin[(2\pi f_{ac})t + \phi]$$

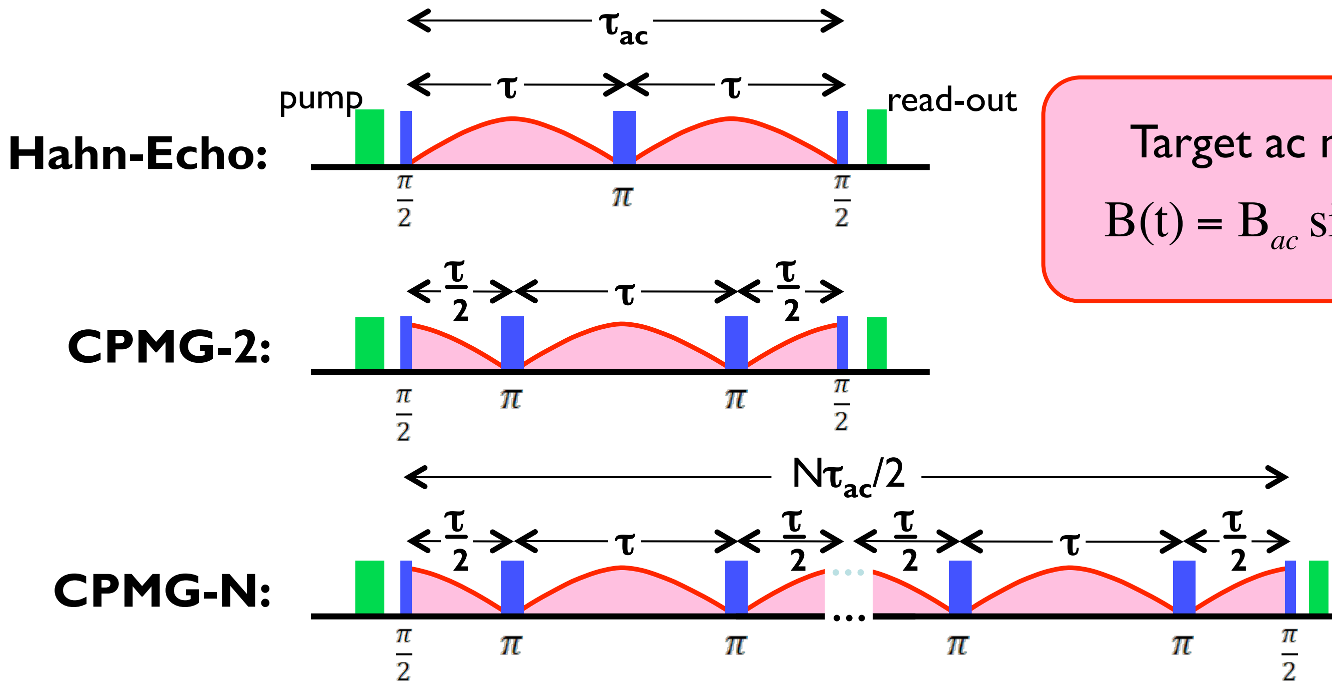
Isotopically purified CVD diamond: $^{13}C \approx 0.3\%$
[N] <10^{13} cm^{-3}
Balasubramanian et al., Nature Materials (2009)







Progress toward NV magnetometry <1 nT/Hz$^{1/2}$



Target ac magnetic field:

$$B(t) = B_{ac}\sin[(2\pi f_{ac})t + \phi]$$

1) Use N-pulse dynamic decoupling sequence:

$$T_2 \Rightarrow T_2 N^s$$

$$\tau_{ac} \Rightarrow N\tau_{ac} / 2$$

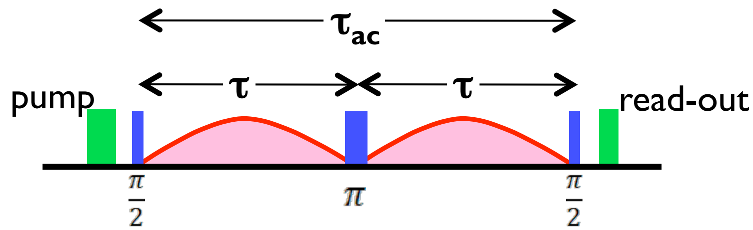
Shot-noise sensitivity:

$$\frac{\delta B_{ac}}{\sqrt{\text{Hz}}}$$

$$\eta_{ac}^{\text{CPMG-N}} \approx \frac{\pi\hbar}{2g\mu_B}\frac{1}{C}\sqrt{\frac{2}{N\tau_{ac}}}\exp\left[\left(\frac{N^{(1-s)}\tau_{ac}}{2T_2}\right)^p\right]$$

Progress toward NV magnetometry <1 nT/Hz$^{1/2}$

Hahn-Echo:



Target ac magnetic field:

$$B(t) = B_{ac}\sin[(2\pi f_{ac})t + \phi]$$

3) Maximize $C = \alpha\sqrt{\beta n}$

α = Spin-state-dependent signal contrast

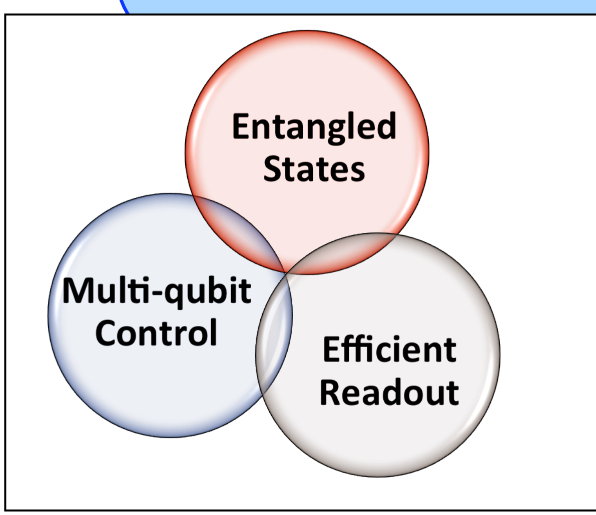
β = # photons collected per NV per measurement

n = # sensing NVs (and ancilla spins) in detection volume

1) Use N-pulse dynamic decoupling sequence:

$$T_2 \Rightarrow T_2 N^s$$

$$\tau_{ac} \Rightarrow N\tau_{ac}/2$$

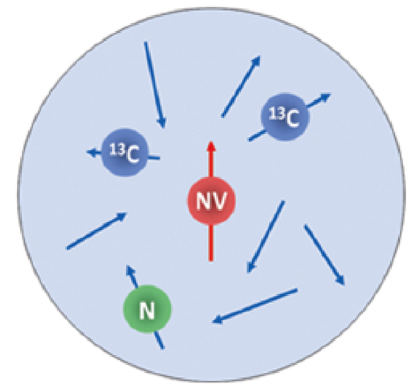


$$\eta_{ac}^{\text{CPMG-N}} \approx \frac{\pi\hbar}{2g\mu_B}\frac{1}{C}\sqrt{\frac{2}{N\tau_{ac}}}\exp\left[\left(\frac{N^{(1-s)}\tau_{ac}}{2T_2}\right)^p\right]$$

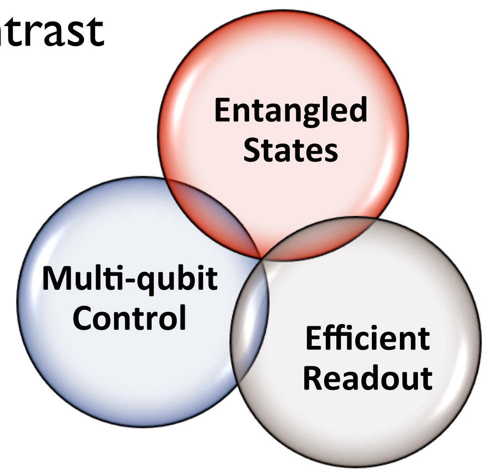
2) Maximize bare T_2 => control spin environment

Our role on QuISM team

- **NV-diamond as testbed for:**
  – Physics of many-body composite-spin systems
  – Optimal environmental control (dynamic decoupling)
  – Environment-enhanced metrology:
    e.g., ancilla sensing spins (N) & storage spins (^{13}C)
  – Creation & application of novel quantum states

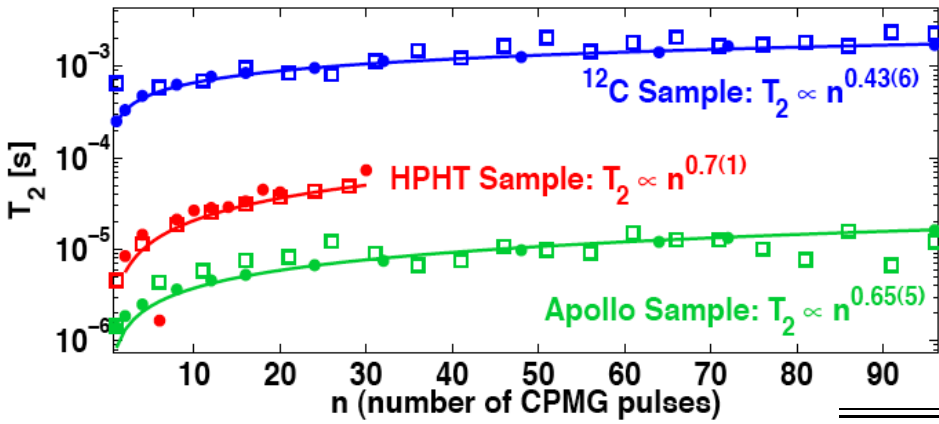


- **Technical optimization of NV-diamond spin measurements:**
  – T_1, T_2, T_2^*
  – Optical collection efficiency & NV spin-state signal contrast
    => SNR, single-shot NV read-out
  – Diamond material properties & control techniques
  – Single NV vs. ensembles
  – Bulk diamond vs. thin NV layers vs. nanodiamonds
  – NV electronically excited, metastable & dark states
  – NV^- vs. NV^0



- **Physics interactions with other team members**

Recent results: Dynamic decoupling to increase NV T_2



CPMG sequence applied to a wide array of NV-diamond samples => T_2 increased by ~10x

$$\delta\phi \propto \frac{1}{\sqrt{n_{NV} T_2}} \equiv \frac{1}{\sqrt{FOM}}$$

Spin coherence Figure-of-Merit

	^{12}C	HPHT	Apollo
Meas. technique	ensemble	confocal	ensemble
N concentration	~ 1 ppm	~ 50 ppm	~ 100 ppm
NV density	$\sim 10^{14}[\mathrm{cm}^{-3}]$	$\sim 10^{12}[\mathrm{cm}^{-3}]$	$\sim 10^{16}[\mathrm{cm}^{-3}]$
^{13}C concentration	0.01%	1.1%	1.1%
Echo (1-pulse) T_2	240(6) μs	5(1) μs	2(1) μs
T_2 scaling	$n^{0.43(6)}$	$n^{0.7(1)}$	$n^{0.65(5)}$
Max. achieved T_2	2.2 ms	35μs	20μs
Δ (expected)	≈ 60 kHz	≈ 3 MHz	≈ 6 MHz
Δ (measured)	30(10) kHz	1(1) MHz	7(3) MHz
τ_c (expected)	≈ 15 μs	≈ 0.34 μs	≈ 0.17 μs
τ_c (measured)	10(5) μs	10(5) μs	3(2) μs
FOM [ms/cm^3]	2×10^{14}	10^{10}	2×10^{14}

Largest FOM in any solid-state spin system => improved NV magnetometry

N. Bar-Gill et al. (2011)

Recent results: Dynamic decoupling to increase NV T_2

Comparative study of CPMG decoupling applied to E6 CVD samples with 0.01% ^{13}C and variable (low) N content.

General Information

ID: 61

Substrate #:

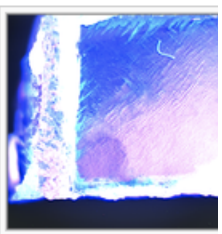
Run #: 1173101-02

Ext Sample #: 1173101-02

Brief Description: 99.99% 12C layer on electronic grade diamond.

E6 Comments:

- Sample unpolished, 1
- The sample has a var do with the way N is i variation is mostly ca will be a thickness de precise numbers on t that we could eliminat DiamondView (broadb clearly shows the vari



DiamondView

General Information

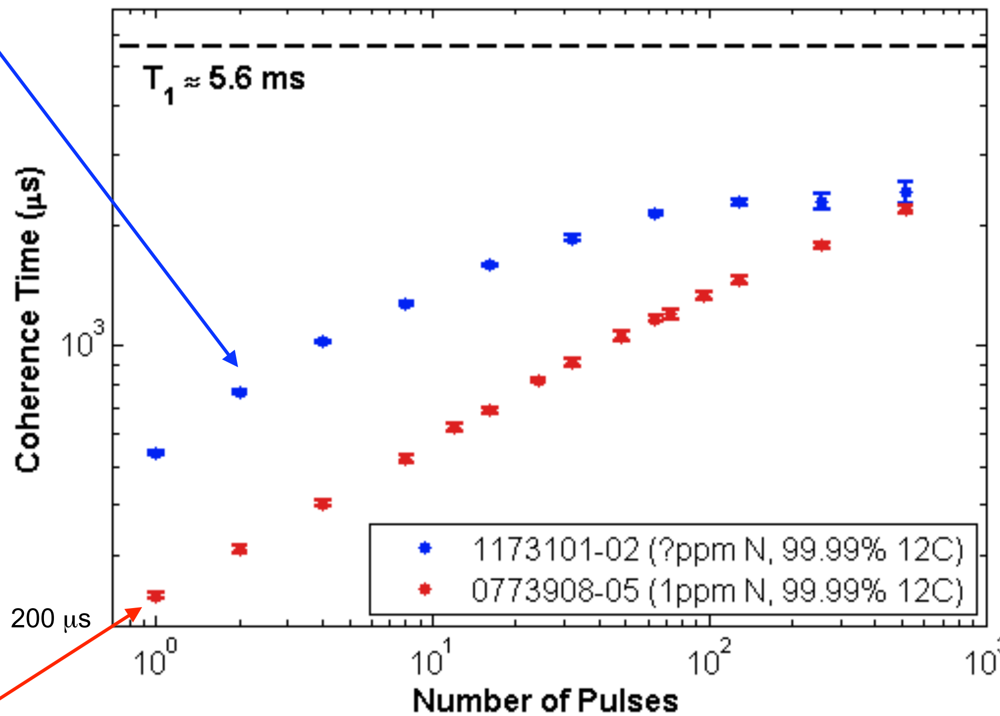
ID: 31

Substrate #:

Run #: 0773908-05

Ext Sample #: 0773908-05

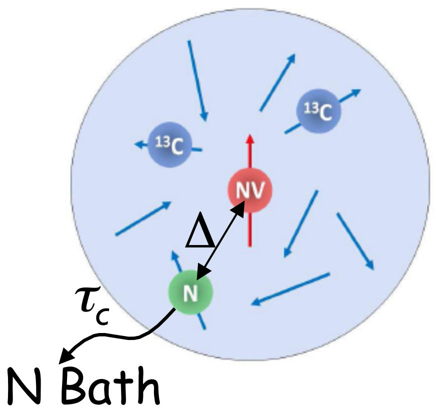
Brief Description: 0.6mm growth 99.99% 12C with 1ppm N2 CVD layer on HPHT sample



All samples reach $T_2 \approx 2.5$ ms, with $T_1 \approx 5.6$ ms

L. Pham et al. (2011)

Recent results: Probe/control spin-bath spectrum



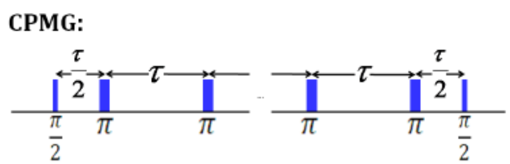
Spectral decomposition: Measure NV coherence decay as a function of # of CPMG pulses & time
=> fit to determine N spin-bath spectrum parameters

Δ = NV-N dipolar coupling ~ N density

τ_c = N spin-bath correlation (flip-flop) time ~ (N density)$^{-1}$

Lorentzian N spin-bath

$$S(\omega) = \frac{\Delta^2 \tau_c}{\pi} \frac{1}{1 + (\omega \tau_c)^2}$$



	^{12}C	HPHT	Apollo
Meas. technique	ensemble	confocal	ensemble
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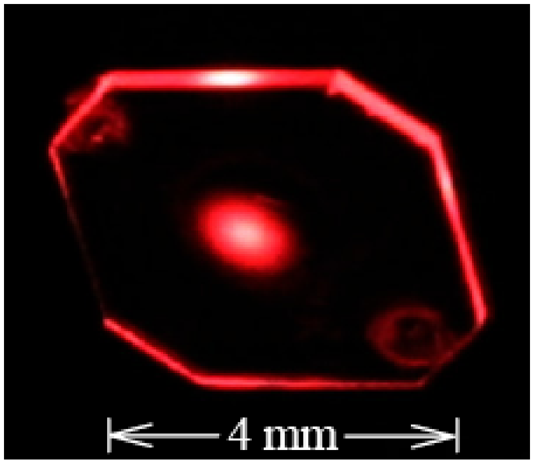
T_2 scaling	$n^{0.43(6)}$	$n^{0.7(1)}$	$n^{0.65(5)}$
Max. achieved T_2	2.2 ms	35μs	20μs
Δ (expected)	≈ 60 kHz	≈ 3 MHz	≈ 6 MHz
Δ (measured)	30(10) kHz	1(1) MHz	7(3) MHz
τ_c (expected)	≈ 15 μs	≈ 0.34 μs	≈ 0.17 μs
τ_c (measured)	10(5) μs	10(5) μs	3(2) μs
FOM [ms/cm^3]	2×10^{14}	10^{10}	2×10^{14}

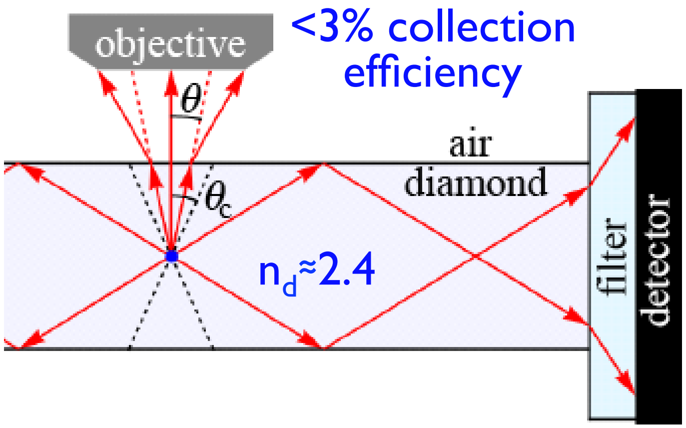
Suppression of N bath flip-flops by random Overhauser field from proximal ^{13}C spins

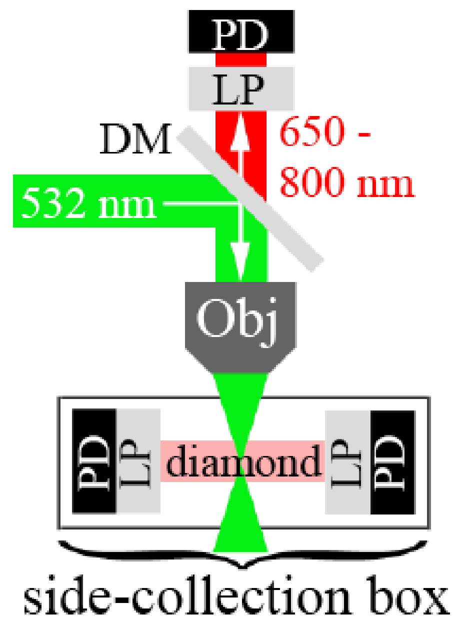
N. Bar-Gill et al. (2011)

Recent results: Side-collection technique

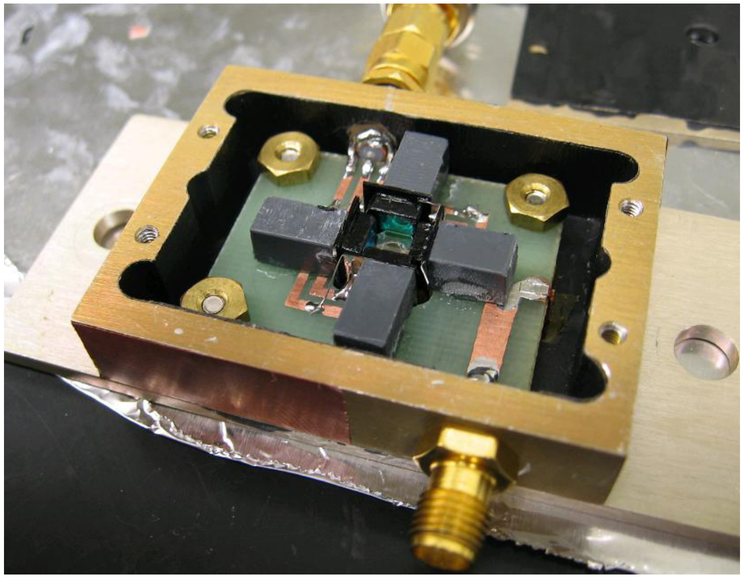


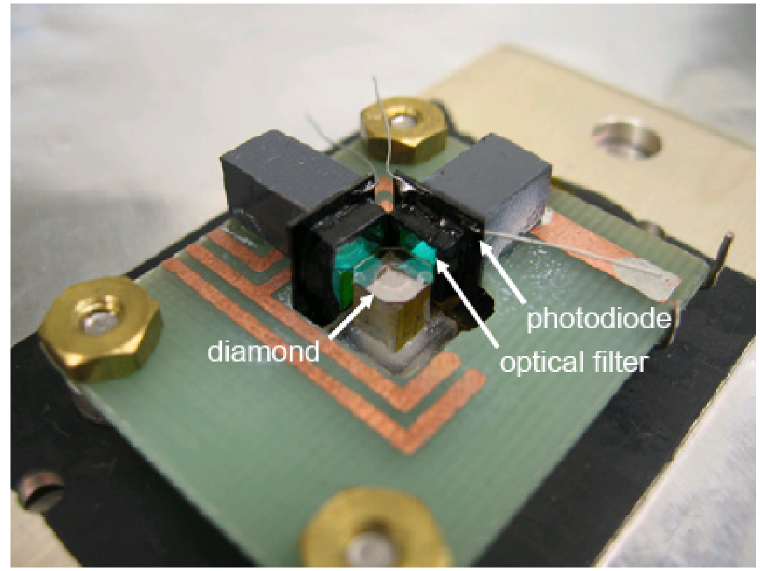
>90% of NV fluorescence leaves via the side (rim) of a diamond chip

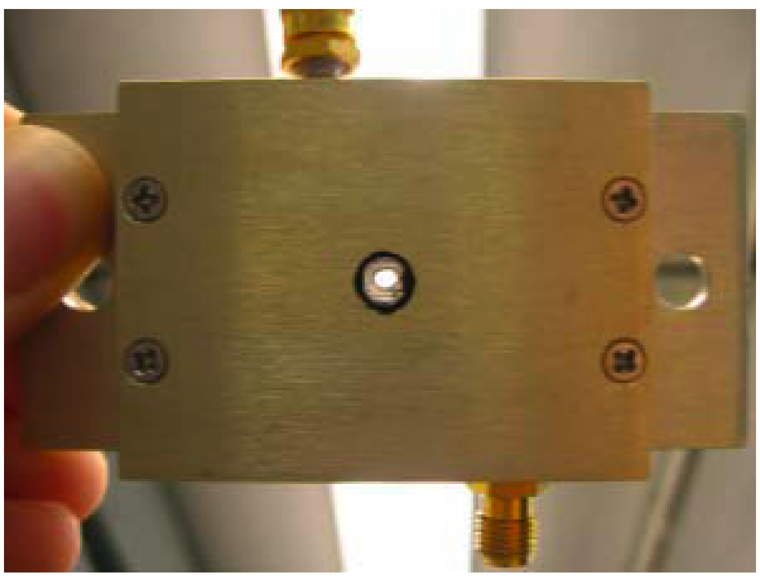




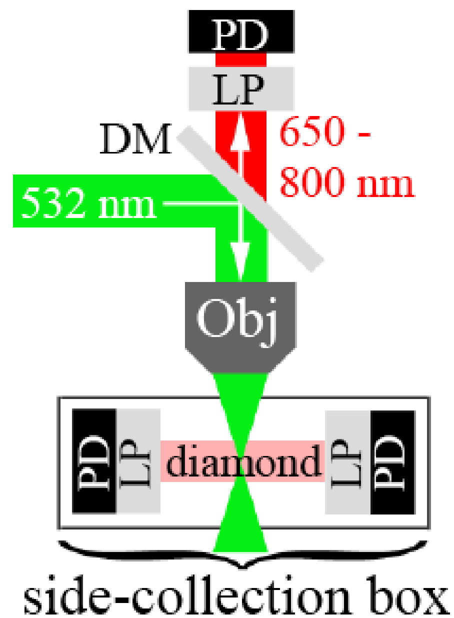
Recent results: Side-collection technique



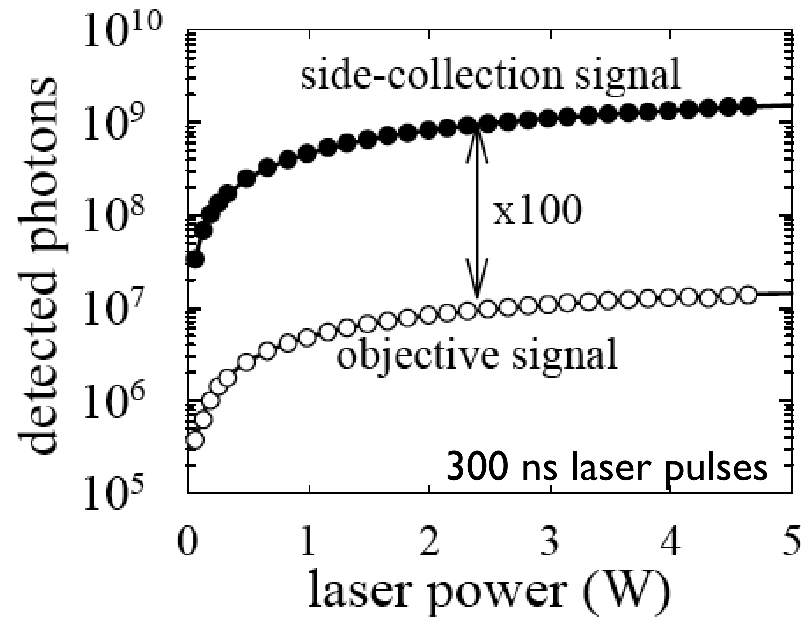




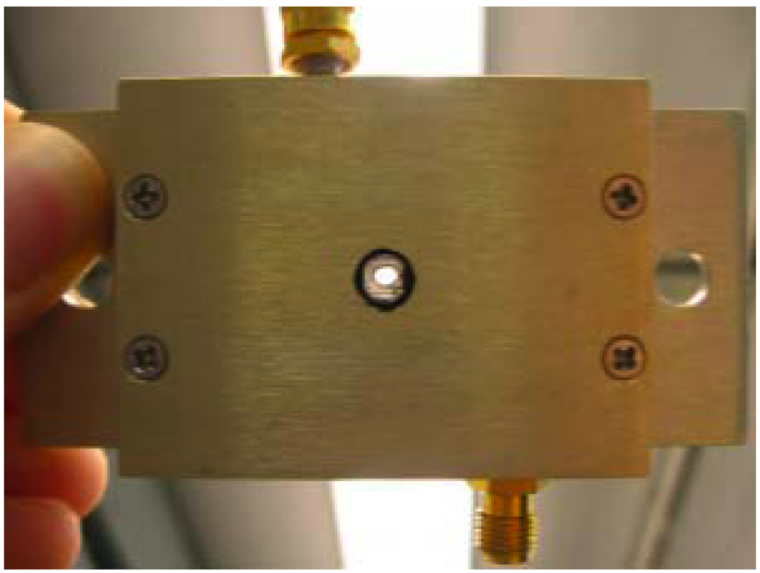
David Le Sage

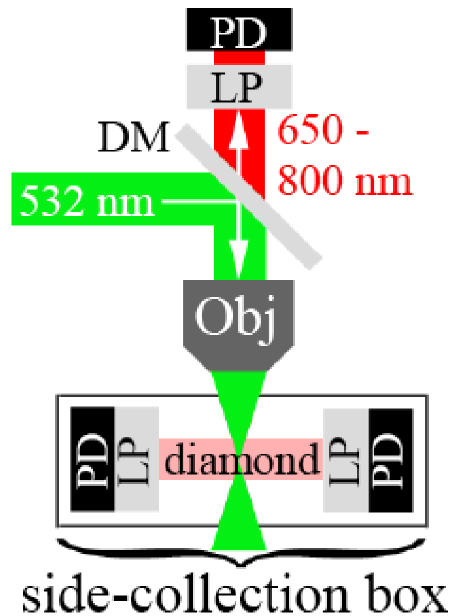


Recent results: Side-collection technique

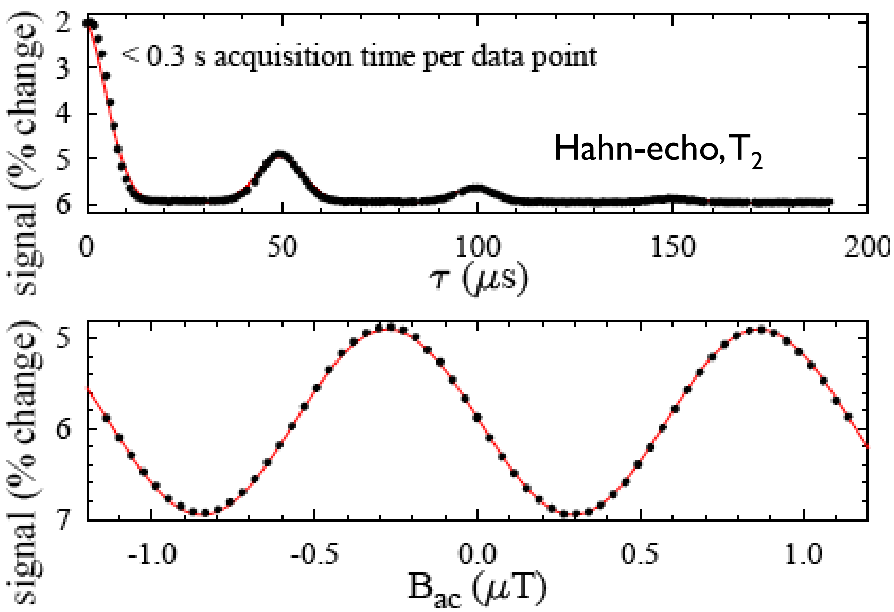


≈50% optical side-collection efficiency
>60% expected with optimization
=> single-shot NV readout?



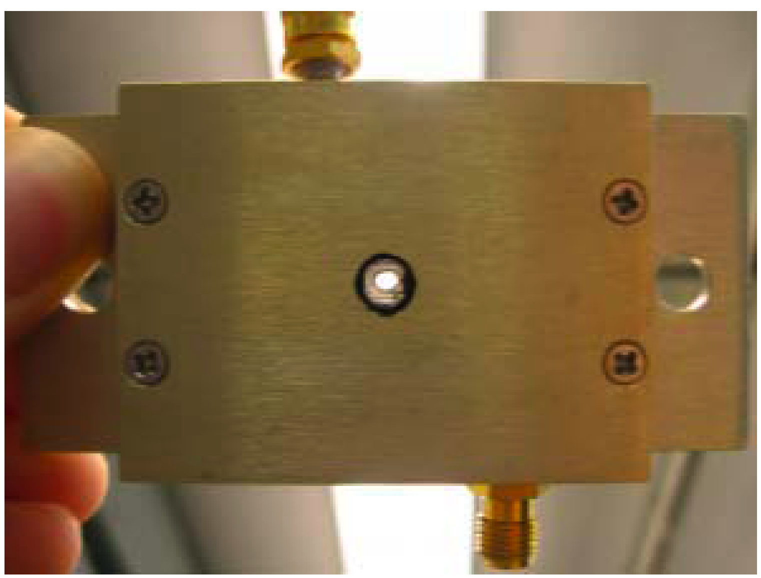


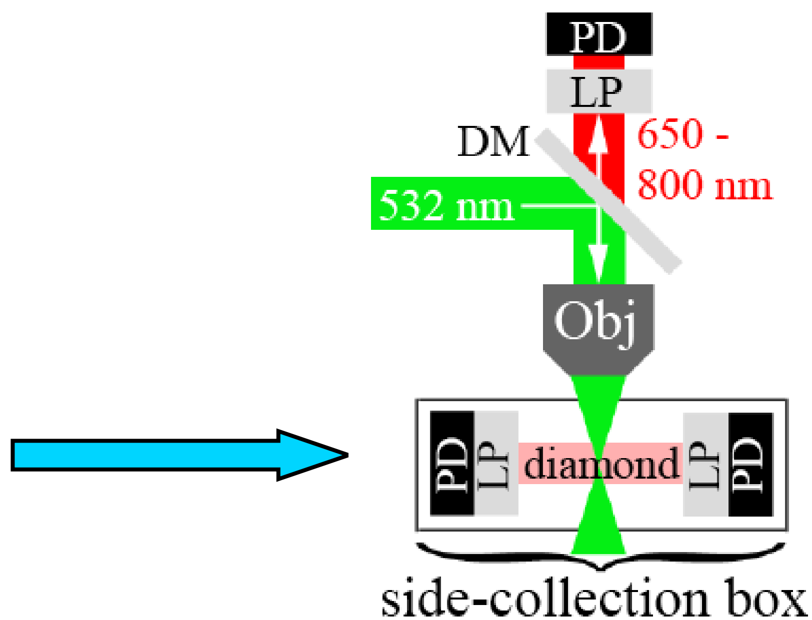
Recent results: Side-collection technique



≈50% optical side-collection efficiency
>60% expected with optimization
=> single-shot NV readout?

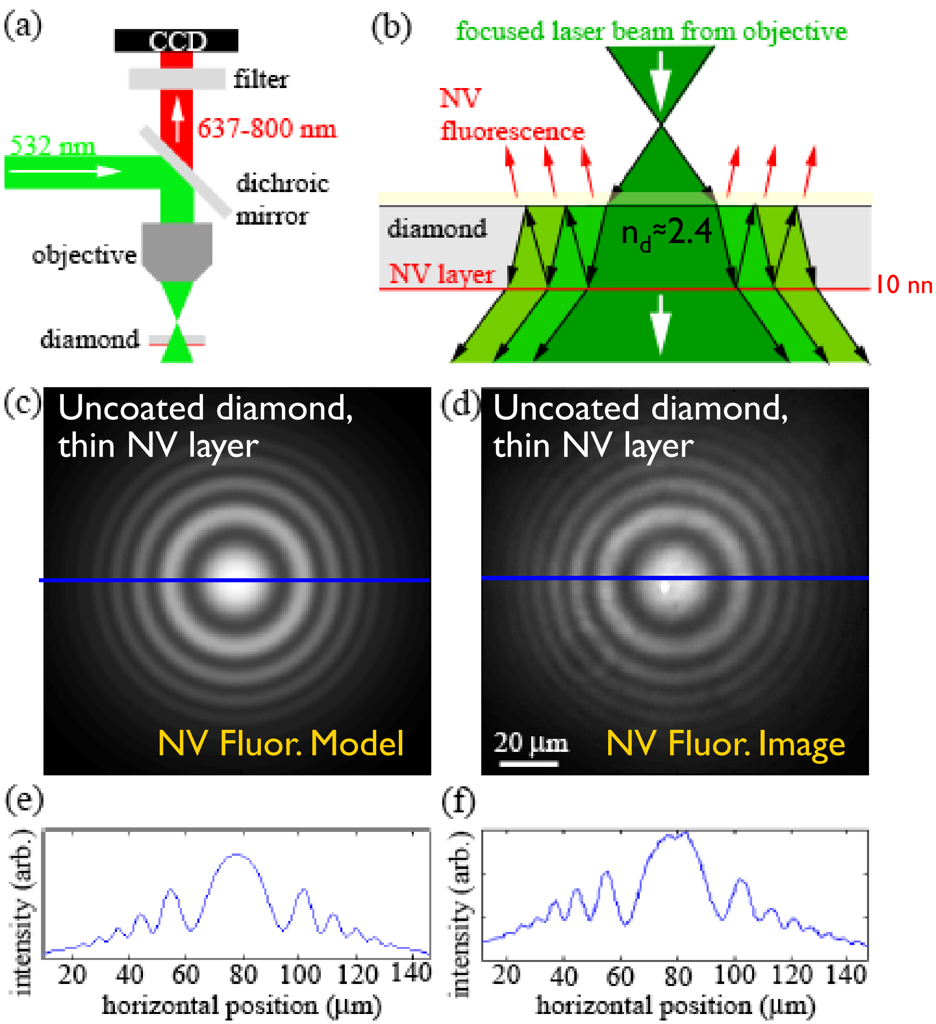
In progress: <100 pT $Hz^{-1/2}$ in ~1 μm^3, [NV] ~ 10^{16} cm^{-3}, T_2 ≈ 20 μs, FOM ≈ 2×10^{14} ms-cm^{-3}

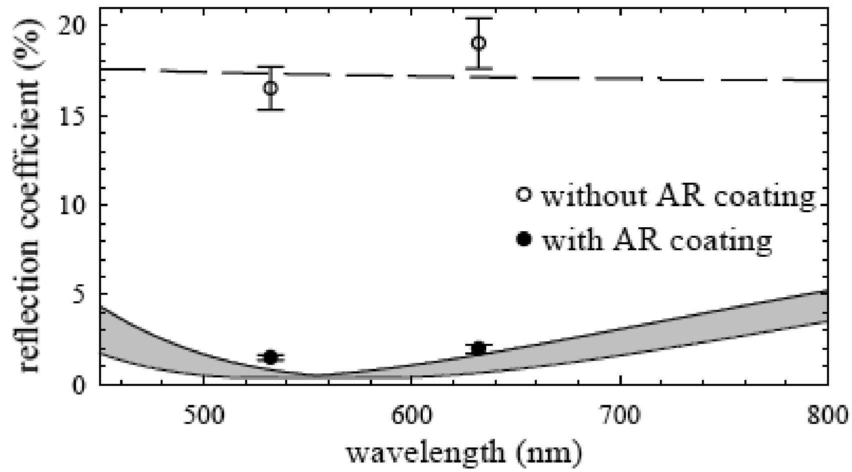


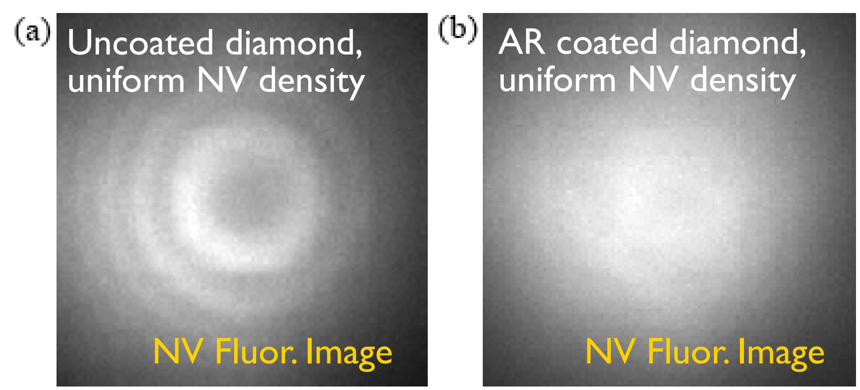


Recent results: AR-coating of diamond surface

Reduce etalon effect with λ/4 layer of silica (n=1.46)

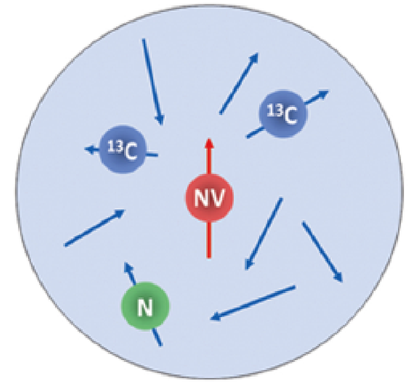






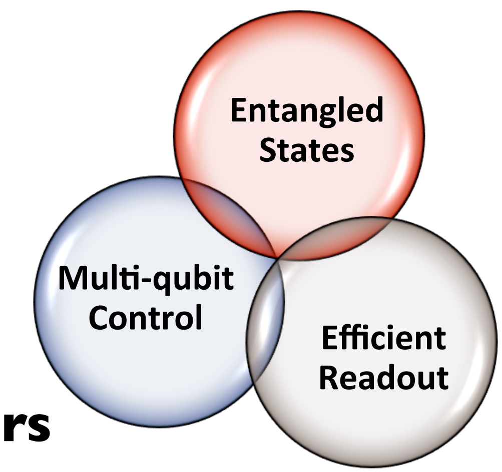
D. Le Sage et al. (2011)

Our role on QuISM team



- **NV-diamond as testbed for:**
  - Physics of many-body composite-spin systems
  - Optimal environmental control (dynamic decoupling)
  - Environment-enhanced metrology:
    e.g., ancilla sensing spins (N) & storage spins (^{13}C)
  - Creation & application of novel quantum states

- **Technical optimization of NV-diamond spin measurements:**
  - T_1, T_2, T_2^*
  - Optical collection efficiency & NV spin-state signal contrast
    => SNR, single-shot NV read-out
  - Diamond material properties & control techniques
  - Single NV vs. ensembles
  - Bulk diamond vs. thin NV layers vs. nanodiamonds
  - NV electronically excited, metastable & dark states
  - NV^- vs. NV^0



- **Physics interactions with other team members**

Posters

Application of Dynamical Decoupling to Enhance NV Ensemble Magnetometry

L.M. Pham[1], N. Bar-Gill[2], C. Belthangady[2], D. Le Sage[2], K. Arai[3], P. Cappellaro[4], R.L. Walsworth[5,2]

[1]School of Engineering and Applied Sciences, Harvard, Cambridge, MA 02138, [2]Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138
[3]Physics Department, MIT, Cambridge, MA 02133, [4]Nuclear Science and Engineering Department, MIT, Cambridge, MA 02139, [5]Physics Department, Harvard, Cambridge, MA 02138

Spectral Decomposition of Composite Solid-State Spin Environments for Improved Ensemble Metrology

Nir Bar-Gill[1,5], My Linh Pham[2], Chinmay Belthangady[1], David Le Sage[1], Paola Cappellaro[3], Jeronimo Maze[4], Mikhail Lukin[5], Amir Yacoby[5] and Ronald L. Walsworth[1,5]

[1] Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA. [2] School of Engineering and Applied Sciences, Harvard University, Cambridge, MA, USA. [3] Department of Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA. [4] Pontificia Universidad Catolica, Santiago, Chile. [5] Department of Physics, Harvard University, Cambridge, MA, USA.

Improved NV-Diamond Fluorescence Detection Technique

Harvard

D. Le Sage[1], L.M. Pham[2], D. Glenn[1], A. Trifonov[3], N. Bar-Gill[1], C. Belthangady[1], K.Arai[4], H. Zhang[1], R.L. Walsworth[1,3]

[1]Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138,
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[3]Department of Physics, Harvard University, Cambridge, MA 02138,
[4]Department of Physics, MIT, Cambridge, MA 02139,

Smithsonian

Room-temperature solid-state quantum memory using pairs of nuclear spins in diamond

Nir Bar-Gill[1,4], Stephen DeVience[2], David Le Sage[1], Chinmay Belthangady[1], Linh M. Pham[3] and Ronald L. Walsworth[1,4]

[1] Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA. [2] Department of Chemistry and Chemical Biology, Harvard University, Cambridge MA, USA. [3] School of Engineering and Applied Sciences, Harvard University, Cambridge, MA, USA. [4] Department of Physics, Harvard University, Cambridge, MA, USA.

MGH/HST Athinoula A. Martinos Center for Biomedical Imaging

Nuclear Spin Singlet States in NMR

Stephen DeVience[1], Ronald Walsworth[2,3], Matthew Rosen[3,4,5]

1. Harvard University Department of Chemistry and Chemical Biology, 2. Harvard-Smithsonian Center for Astrophysics,
3. Harvard University Department of Physics, 4. Martinos Center for Biomedical Imaging, 5. Harvard Medical School