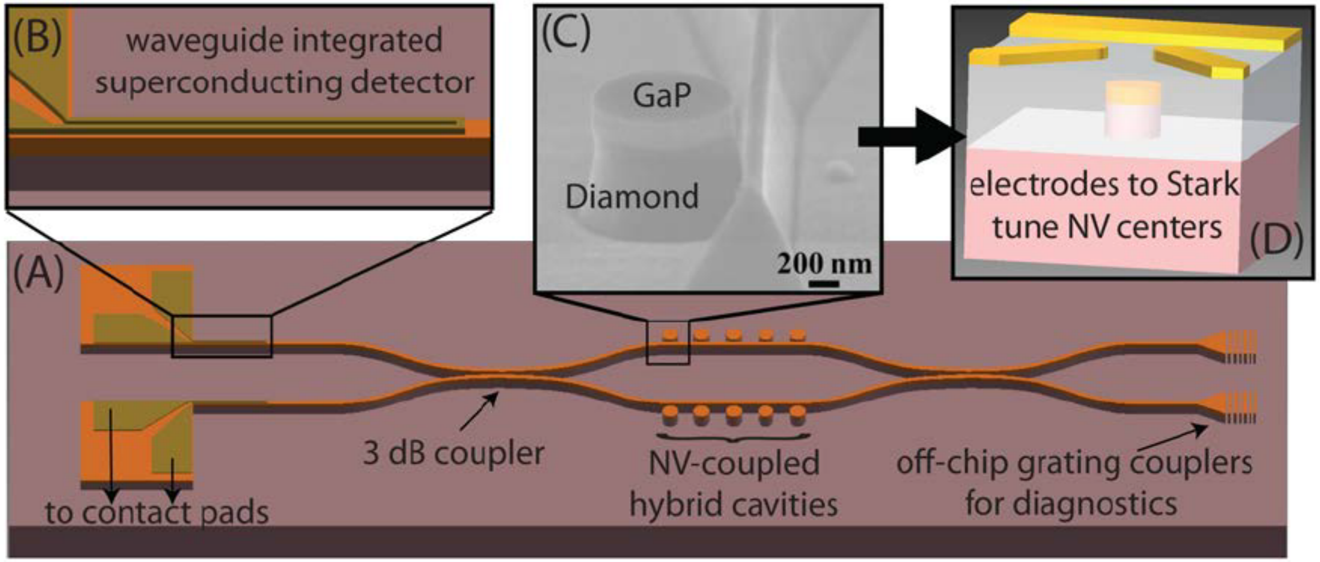
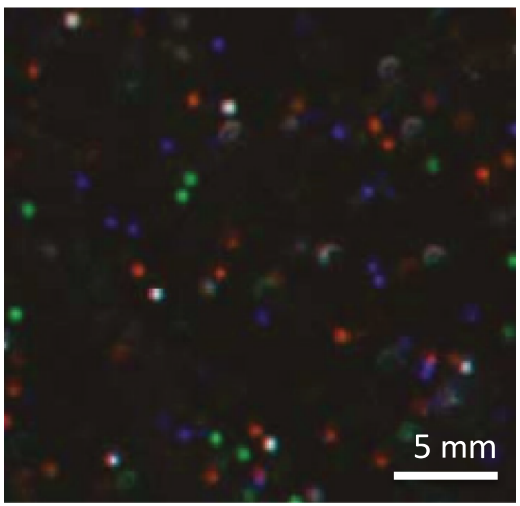


Quantum Information and Solid State Systems

Kai-Mei Fu, UW Physics and Electrical Engineering
INT Workshop: Quantum Computing for Nuclear Physics
November 14-15, 2017

Enabling developments for defect-based quantum information

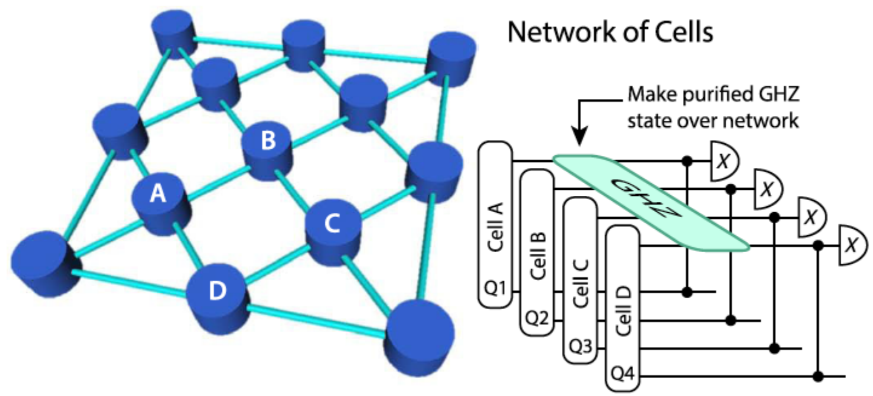
Single defect experiments



Optical image of single defects in commercial diamond substrate[1].

(Not just in diamond!)

Measurement-based quantum entanglement

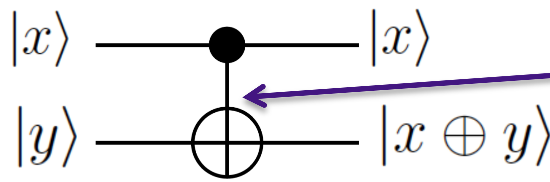


Distributed model of quantum information processing[2]

UNIVERSITY *of* WASHINGTON

[1]Edmonds *et al.* (Warwick, UW, HP) *PRB* 86, 035201 (2012)
[2]Nickerson, Fitzsimons, Benjamin *PRX* 4 041041 (2014)

Removing the need for local interaction

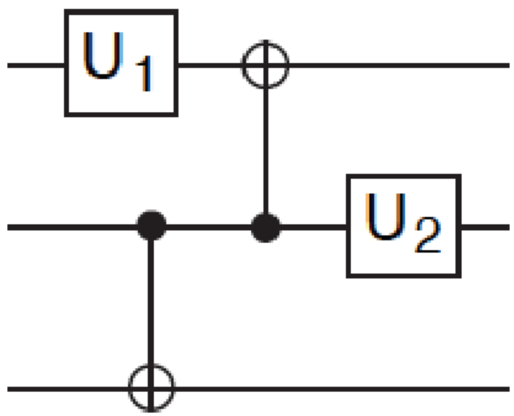


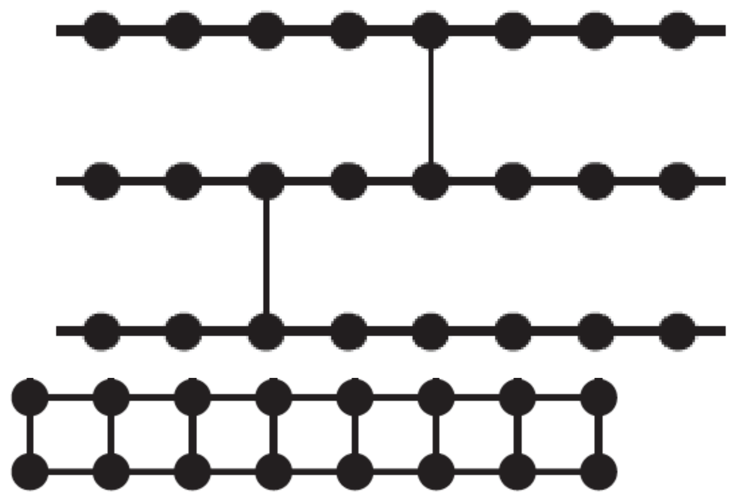
Looks like a local interaction that needs high level of control

qubit
tex

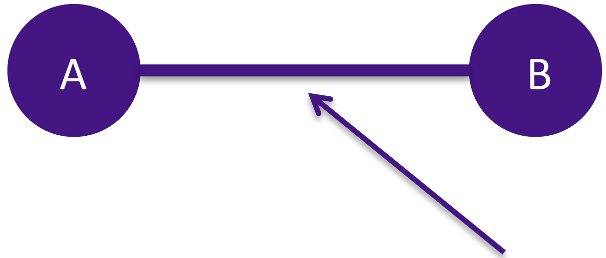
anglement
ge

A
“(
si





Raussendorf, Briegel, *PRL* 86, 5188 “A one-way quantum computer”

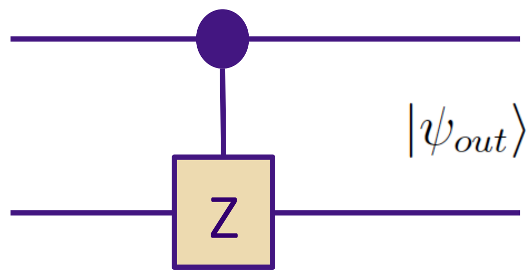


(Significant portion of my research)

This edge is created when a c-phase gate is applied to the following input states.

$$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

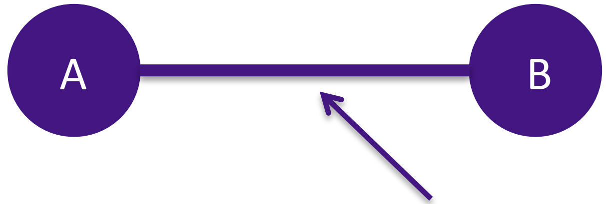
$$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$



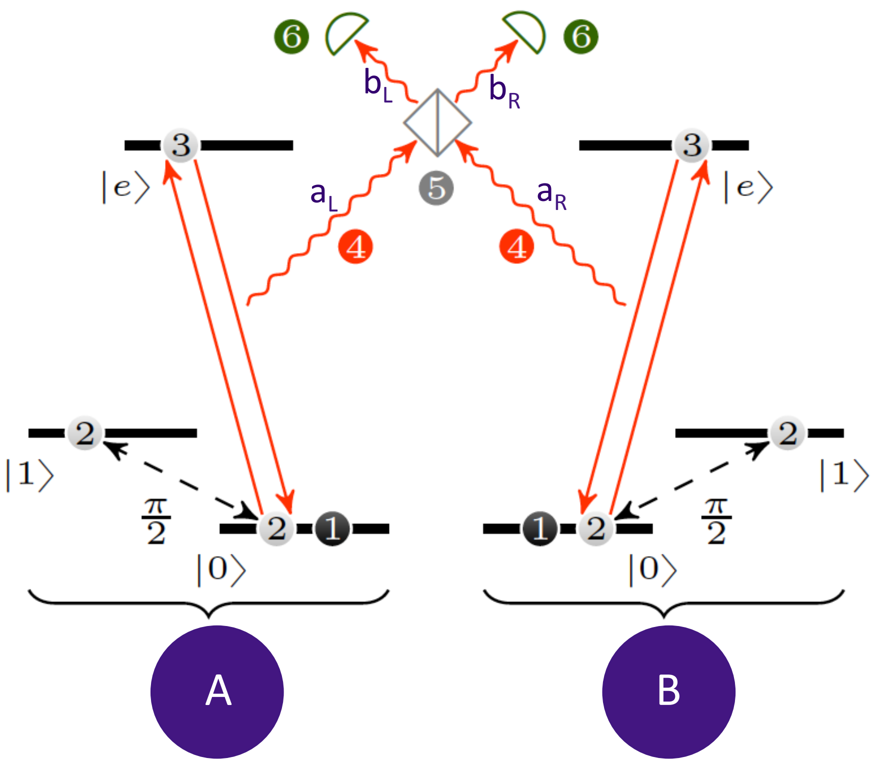
$$|\psi_{out}\rangle = \frac{1}{2}(|00\rangle + |01\rangle + |10\rangle - |11\rangle)$$

$$|\psi_{out}\rangle = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} \langle 00|\psi_{in}\rangle \\ \langle 01|\psi_{in}\rangle \\ \langle 10|\psi_{in}\rangle \\ \langle 11|\psi_{in}\rangle \end{bmatrix}$$

(Output state is local unitary equivalent to a Bell state.)



Can be created by measurement of emitted photons!



1 $[|0\rangle \otimes |0\rangle]\,|\text{vac}\rangle$

2 $[(|0\rangle + |1\rangle) \otimes (|0\rangle + |1\rangle)]\,|\text{vac}\rangle$

3 $[(|e\rangle + |1\rangle) \otimes (|e\rangle + |1\rangle)]\,|\text{vac}\rangle$

3‘ $[|e1\rangle + |1e\rangle]\,|\text{vac}\rangle$

4 $\left[|01\rangle a_{\mathrm{R}}^{\dagger} + |10\rangle a_{\mathrm{L}}^{\dagger}\right]|\text{vac}\rangle$

5 $\left[(|01\rangle + i|10\rangle) b_{\mathrm{L}}^{\dagger} + (i|01\rangle + |10\rangle) b_{\mathrm{R}}^{\dagger}\right]|\text{vac}\rangle$

6 $(|01\rangle + i|10\rangle)$

Barrett and Kok *PRA* 71, 060310

System requirements (subset)

- Two atoms must emit identical photons
- Photon must be detected
  - Described protocol scales linearly with detection efficiency
  - Protocols robust to loss error scale as square of efficiency
- At least 2 qubits per node with local operations
- Entanglement rate should be significantly faster than decoherence time.

Many different defect systems

- **Diamond: NV^-**, SiV^- ,SiV^0
  - Room temperature second-long spin coherence time
  - Phonon assisted optical transitions
- SiC: V_{si}-V_C, V_{si}
  - Mature host crystal for device fabrication
  - Phonon assisted optical transitions
- Si: P, Su
  - Silicon!!!
  - Nonradiative recombination
- Rare-earth doped crystals: Tm^{3+}, Pr^{3+}, Er^{3+} in KTP, YSO, YAG, etc.
  - 6-hour quantum memory
  - Weak optical transitions
- Quantum dots
  - Advanced device integration, large oscillator strength
  - Short decoherence time (single microseconds)
- **ZnO: Ga, In, Al**
  - high optical homogeneity
  - near-UV optical transitions

Many different defect systems

- **Diamond: NV$^-$**, SiV$^-$,SiV^0
  - Room temperature second-long spin coherence time
  - Phonon assisted optical transitions
- Si
  - –
  - –
- Si
  - –
  - –
- R
  - –
  - –
- Q
  - Advanced device integration, large oscillator strength
  - Short decoherence time (single microseconds)
- **ZnO: Ga, In, Al**
  - high optical homogeneity
  - near-UV optical transitions

Outstanding issues:

LARGE PARAMETER SPACE

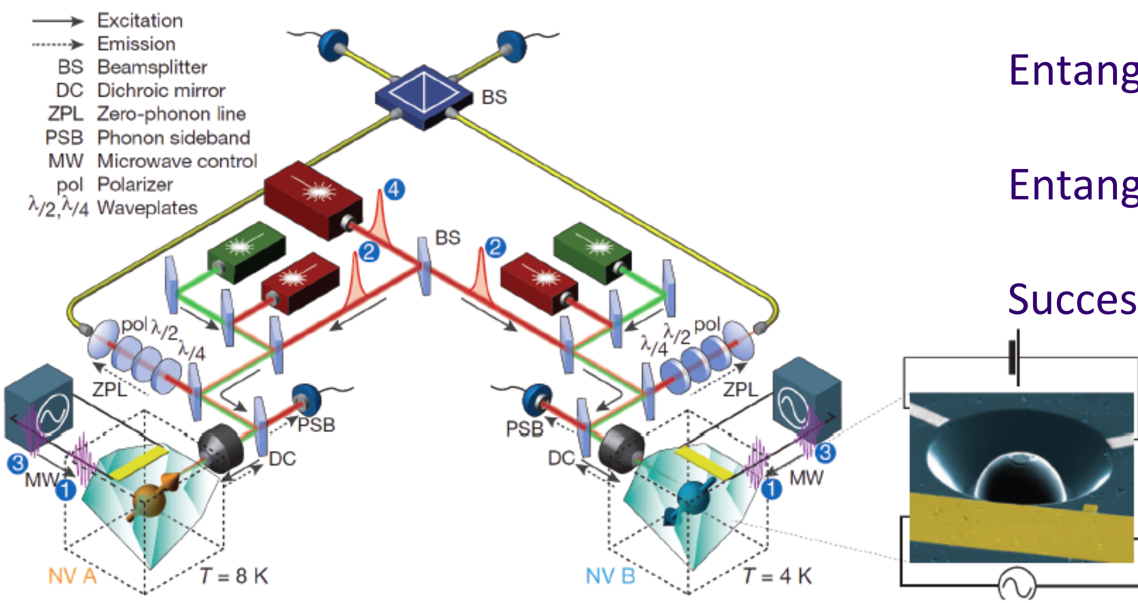
long characterization time

lack of predictive modeling

deterministic defect creation

degradation of quantum properties with device integration

Realization of measurement-based entanglement using NV centers in diamond



Entanglement Fidelity: 0.87

Coherence time: 1s

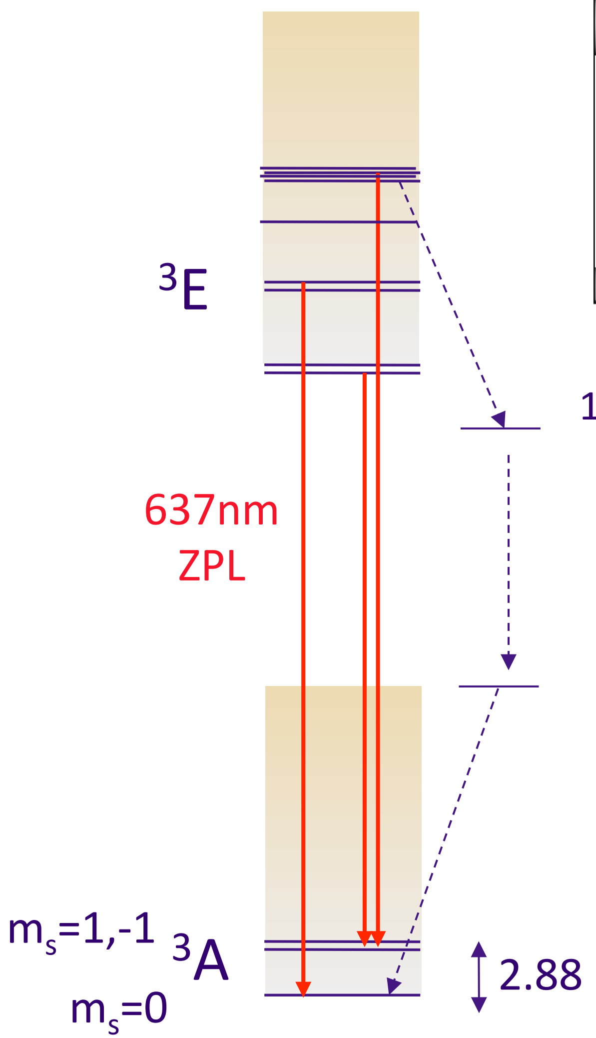
Entanglement attempt rate: 100 kHz

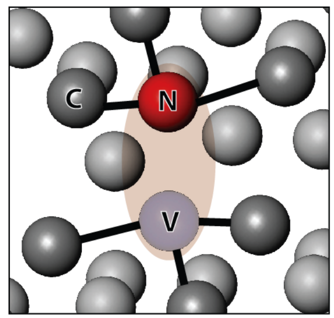
Entanglement rate: 4 mHz

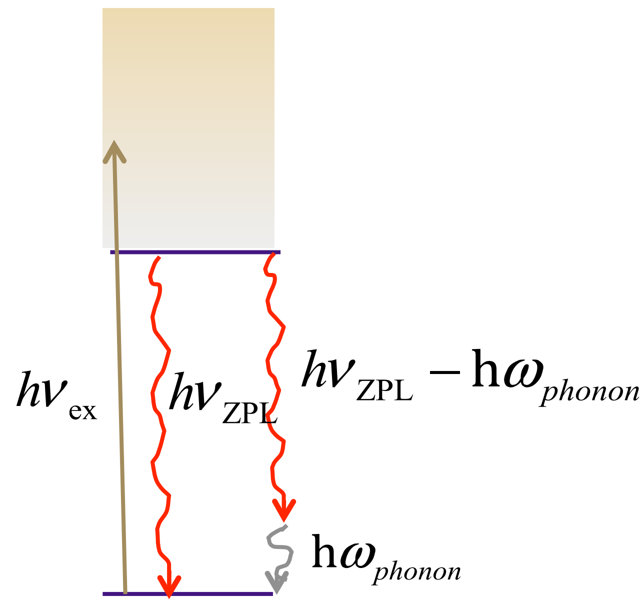
Success probability: < 1e-7

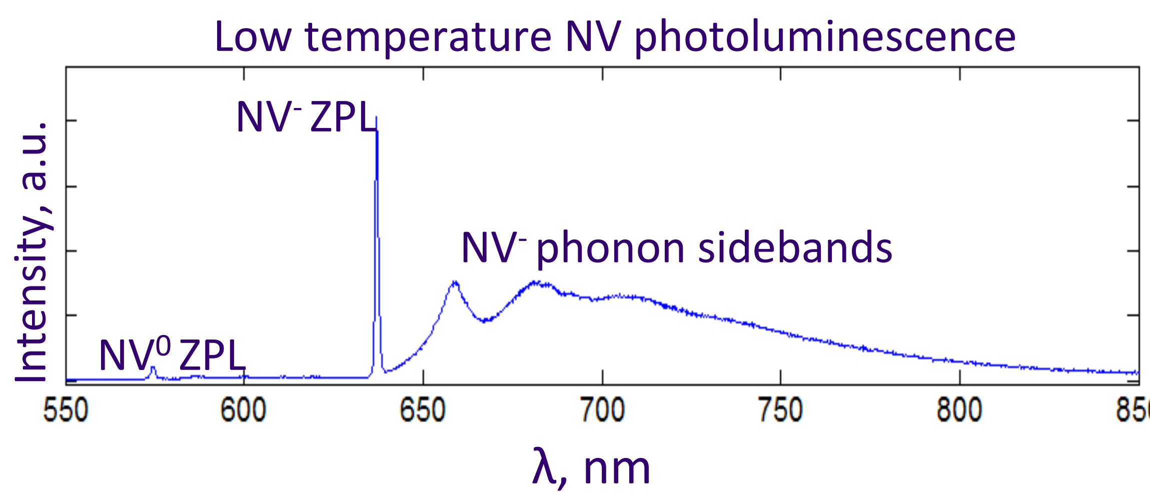
Pfaff et al. (Delft) *Science* 345, 532 (2014) (2014)

Reasons for poor entanglement efficiency:
1) Phonon assisted radiative recombination

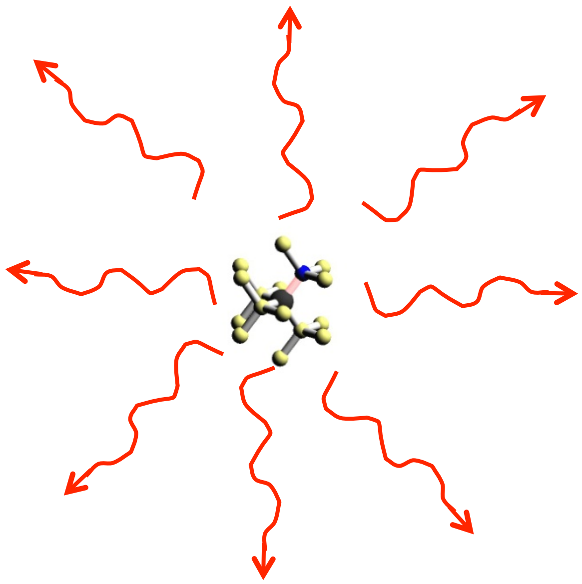


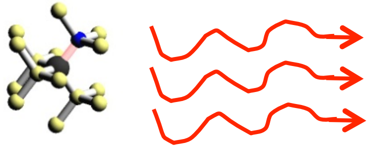


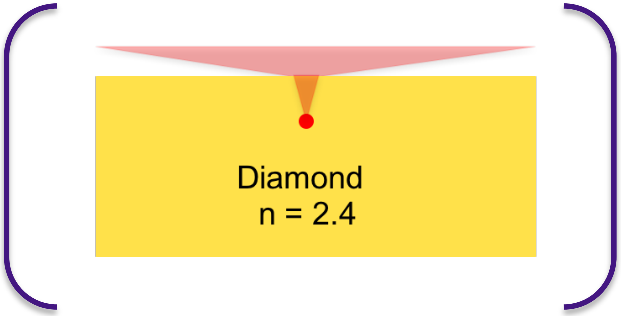




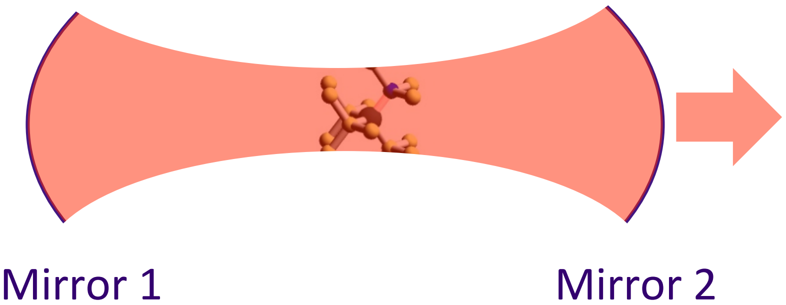
Reasons for poor entanglement efficiency:
2) Difficult to collect the emitted photon







Solution: use a cavity to enhance NV emission into a useful spectral and spatial mode



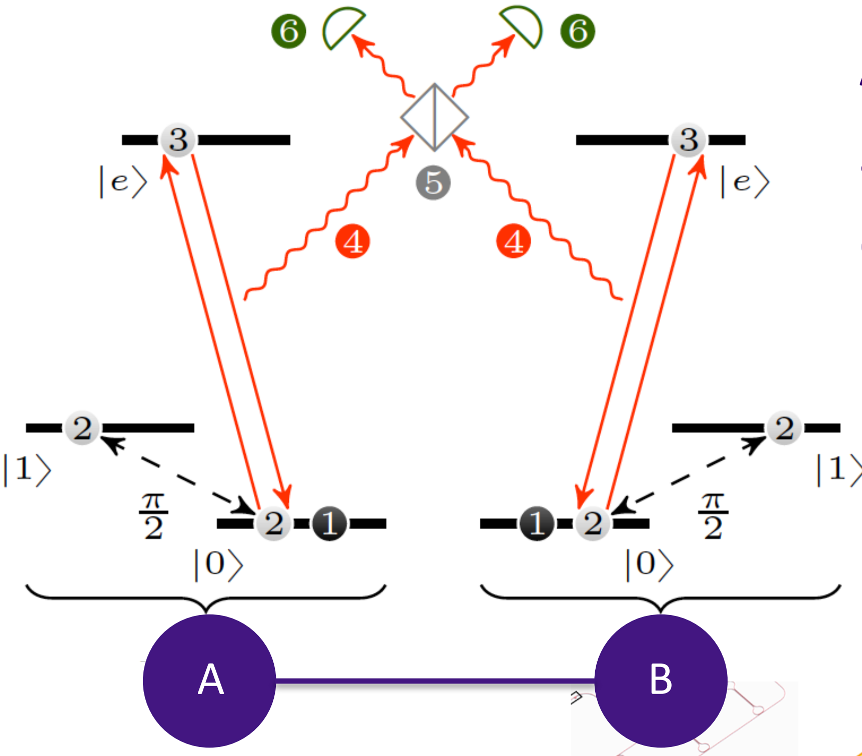
$$F_{\mathrm{cav}} = \frac{3}{4\pi^2}\left(\frac{\lambda}{n_{\mathrm{cav}}}\right)^3 \frac{n_{\mathrm{cav}}}{n_D}\frac{Q}{V_{\mathrm{mode}}}\frac{|E_{\mathrm{NV}}|^2}{|E_{\max}|^2}\frac{\vec{E}_{\mathrm{NV}}\cdot\vec{\mu}}{|\vec{E}_{\mathrm{NV}}||\vec{\mu}|}$$

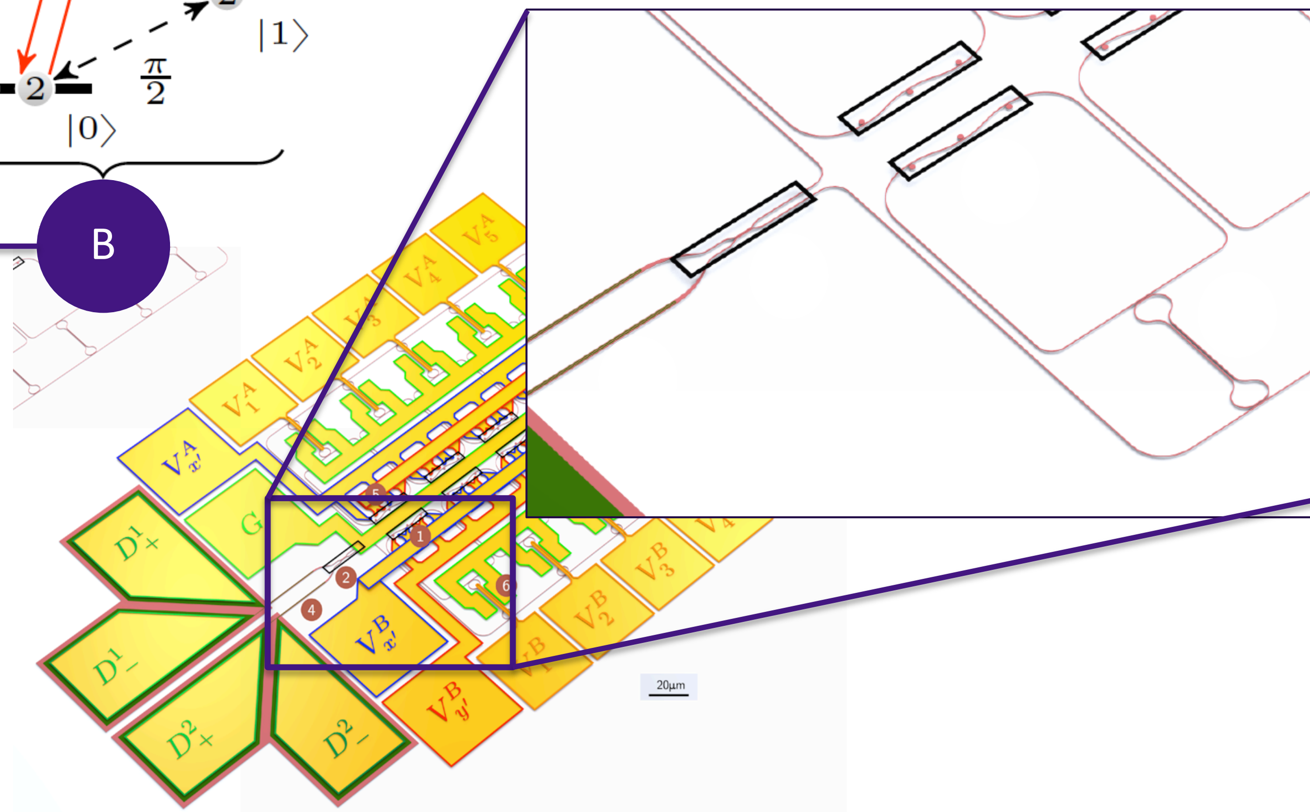
Santori, Faraon, Fu, Barclay (HP Labs)
Englund (MIT)
Lukin/Loncar/Hu (Harvard)
Wang (U. Oregon)
Childress (McGill)
Hanson (Delft)
...

- Cavity is on resonance with NV
- NV is at cavity maximum
- NV electric dipole is aligned to cavity mode.
- High quality factor
- Small mode volume

Purcell, 1946

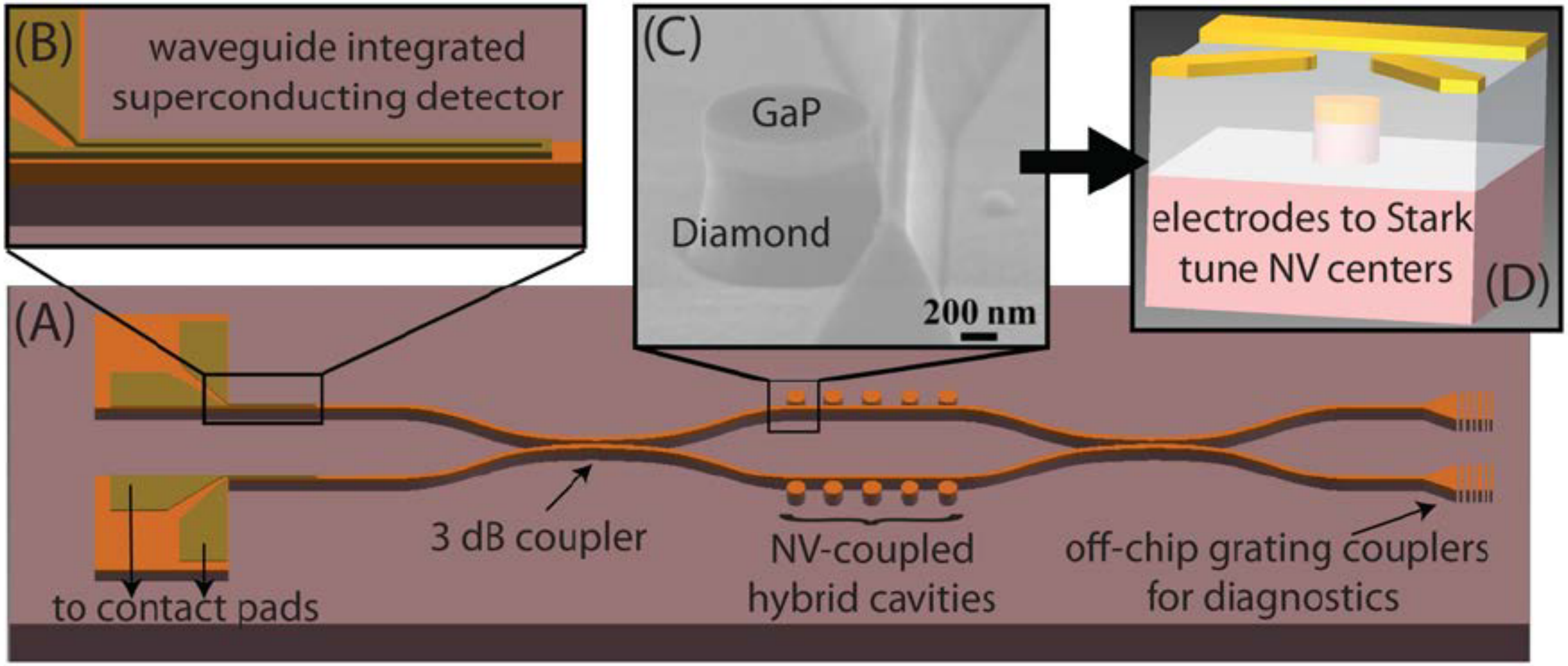
And do it all on a chip for scalability (with the NV center in diamond for now…)





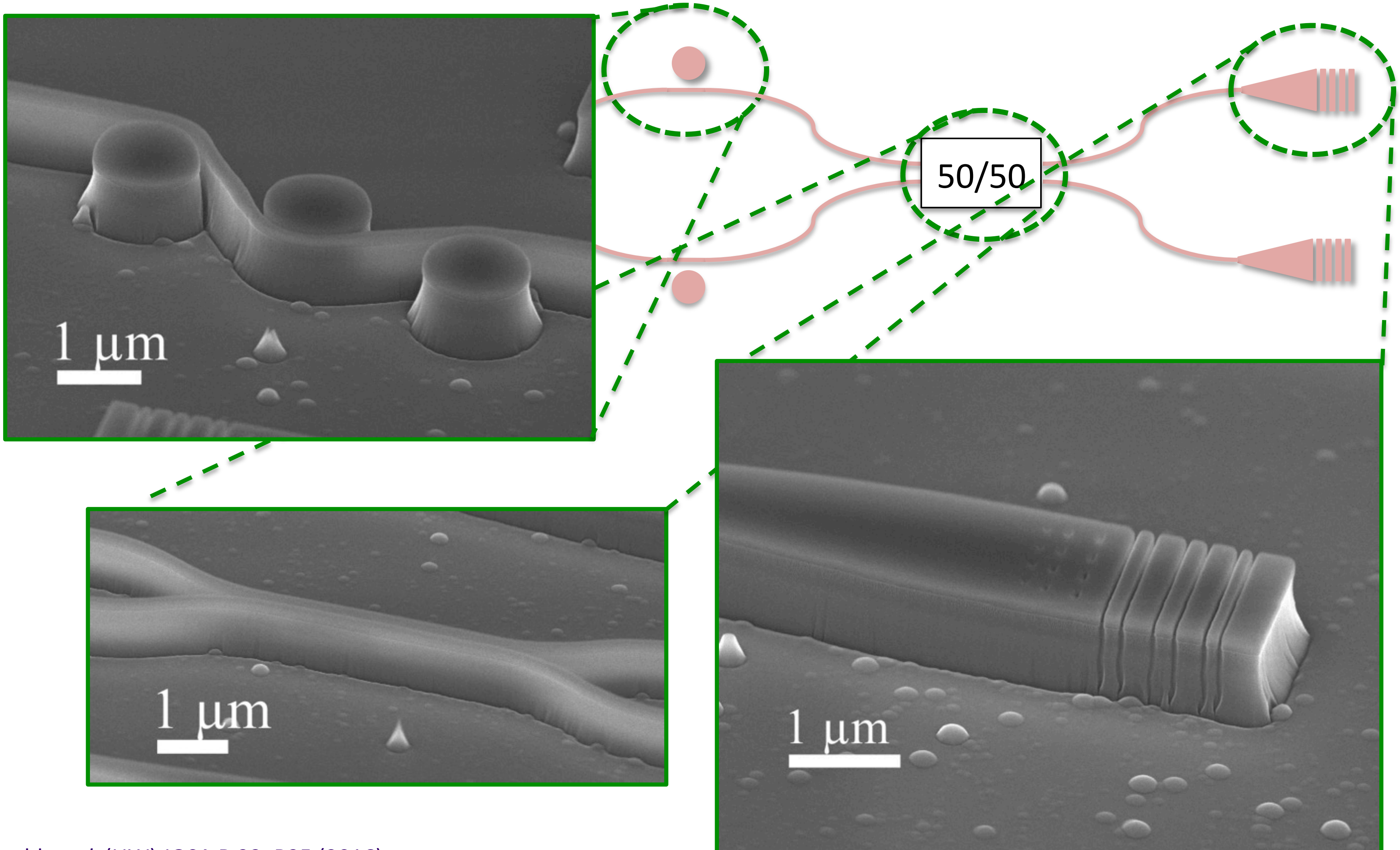
Graphics by I. Christen, Fu lab

Schematic for two-NV entanglement



1) Can we implement all passive components?
2) Can we efficiently extract photons from the NV center?
3) Can we stabilize the NV center optical transition?
4) Can we efficiently detect the photons?

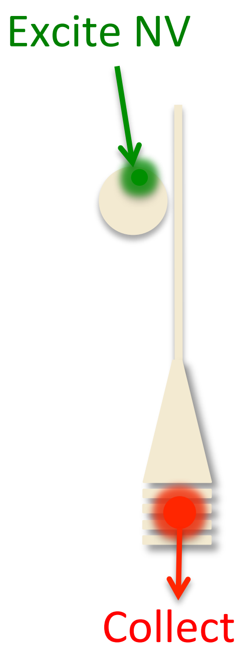
Passive Photonics

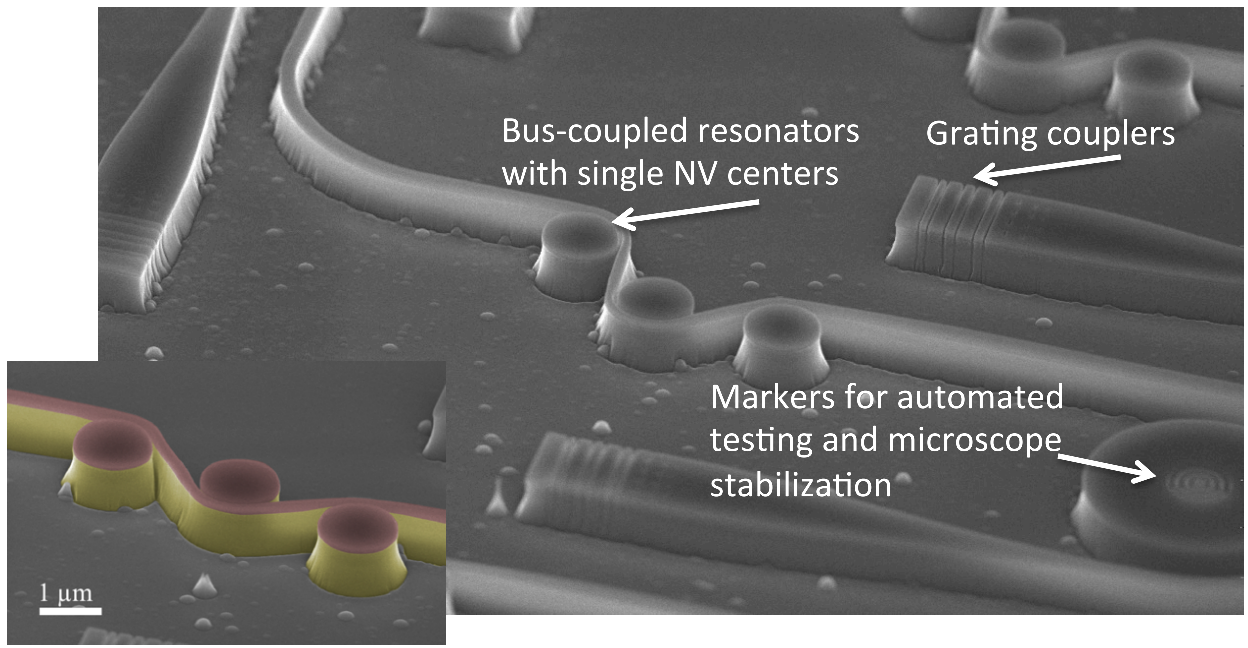


Gould *et al.* (UW) JOSA B 33, B35 (2016)

Take away message: performance and fabrication tolerances are reasonable for simple circuits.

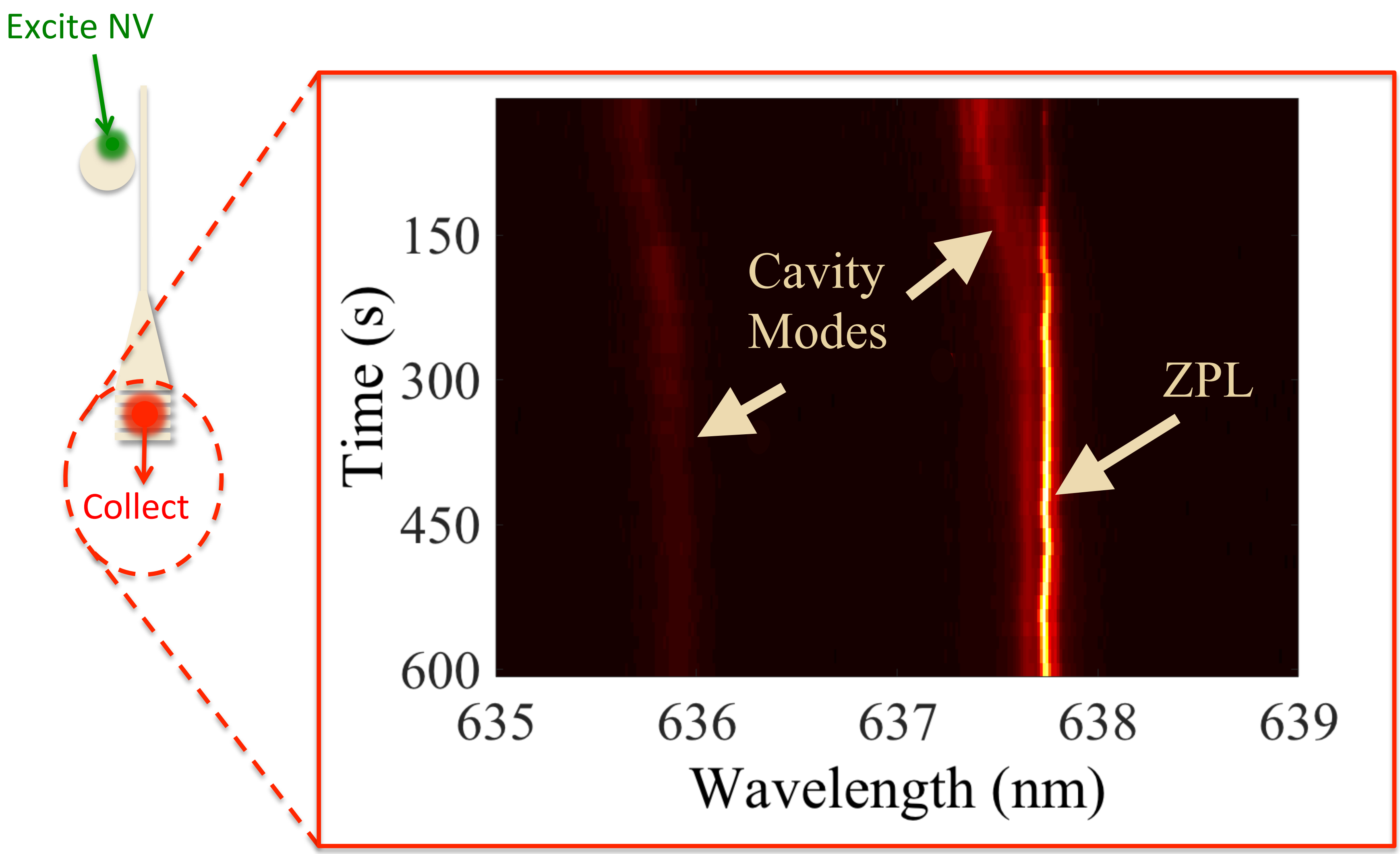
Resonant enhancement of the zero-phonon-line emission from a single NV center



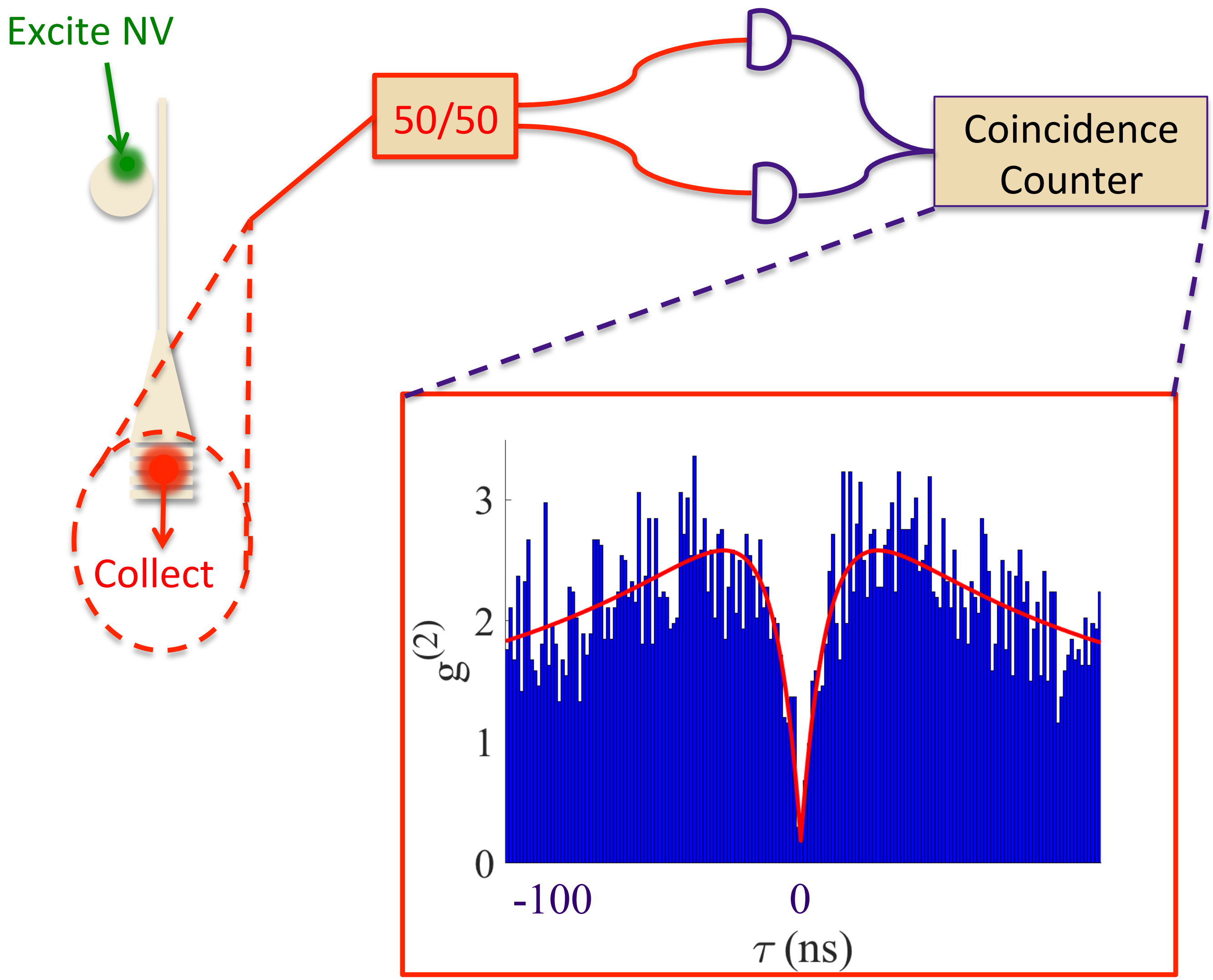


Gould, Schmidgall, Dadgostar, Hatami, Fu, "Efficient extraction of zero-phonon-line photons from single nitrogen-vacancy centers in an integrated GaP-on-diamond platform," Physical Review Applied (2016)

Zero Phonon Line Collection

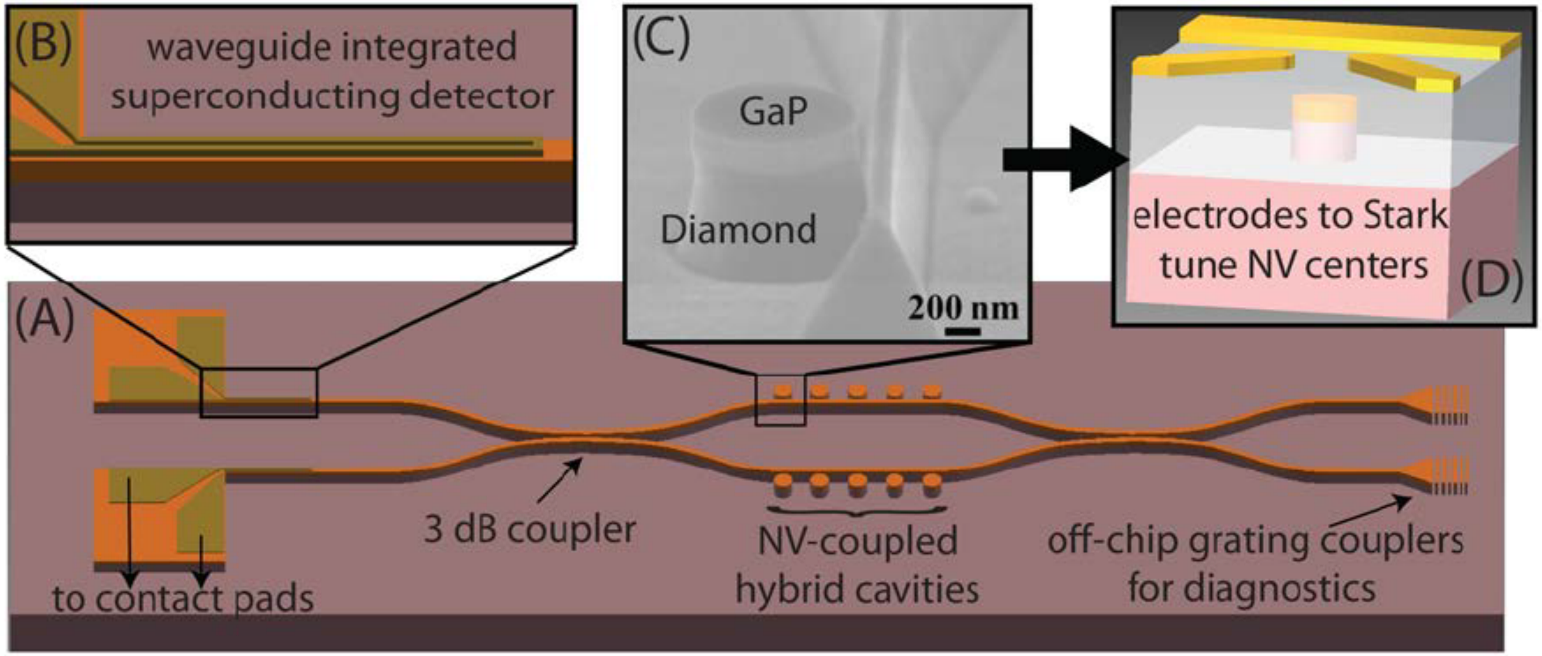


Single Photon Source



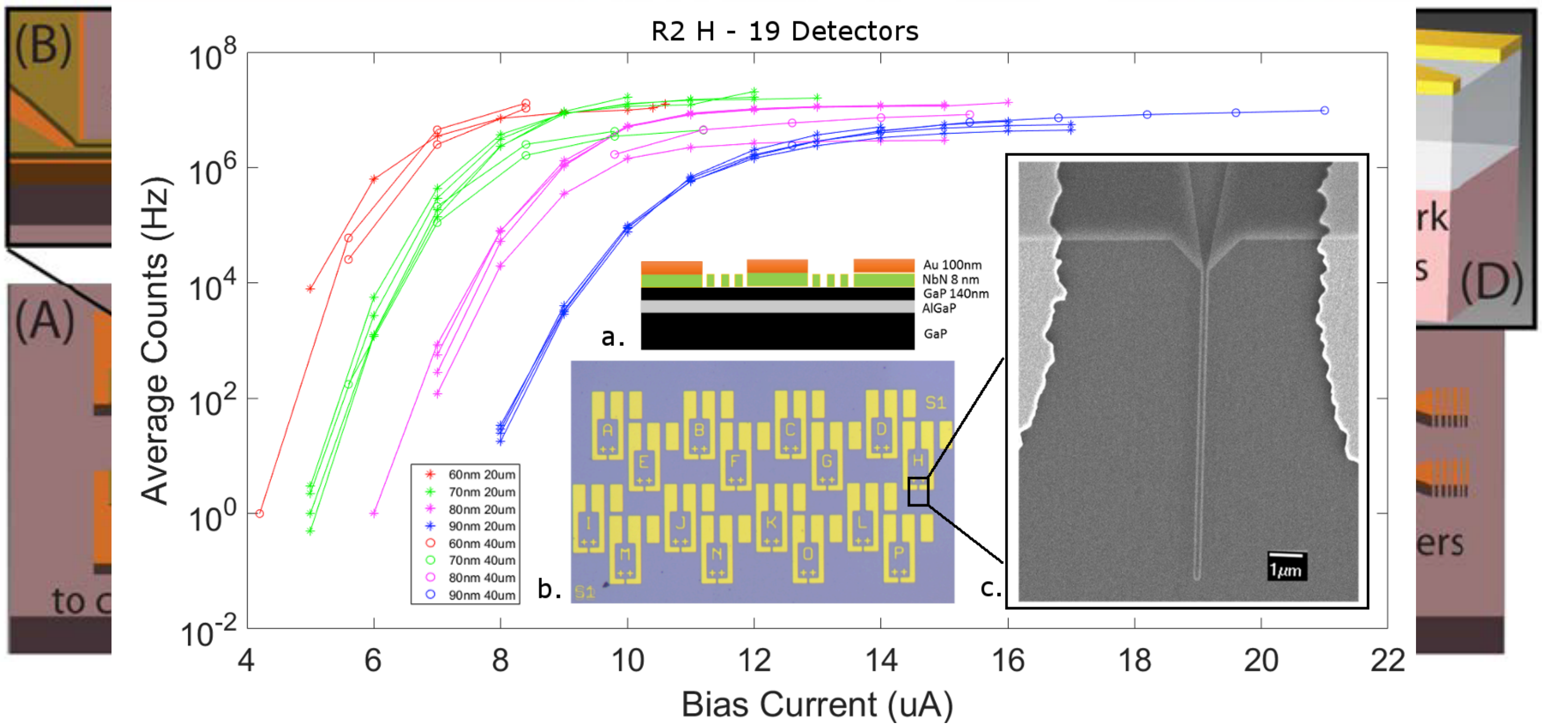
- Clear $g^{(2)}$ dip below 0.5

My groups current efforts in diamond



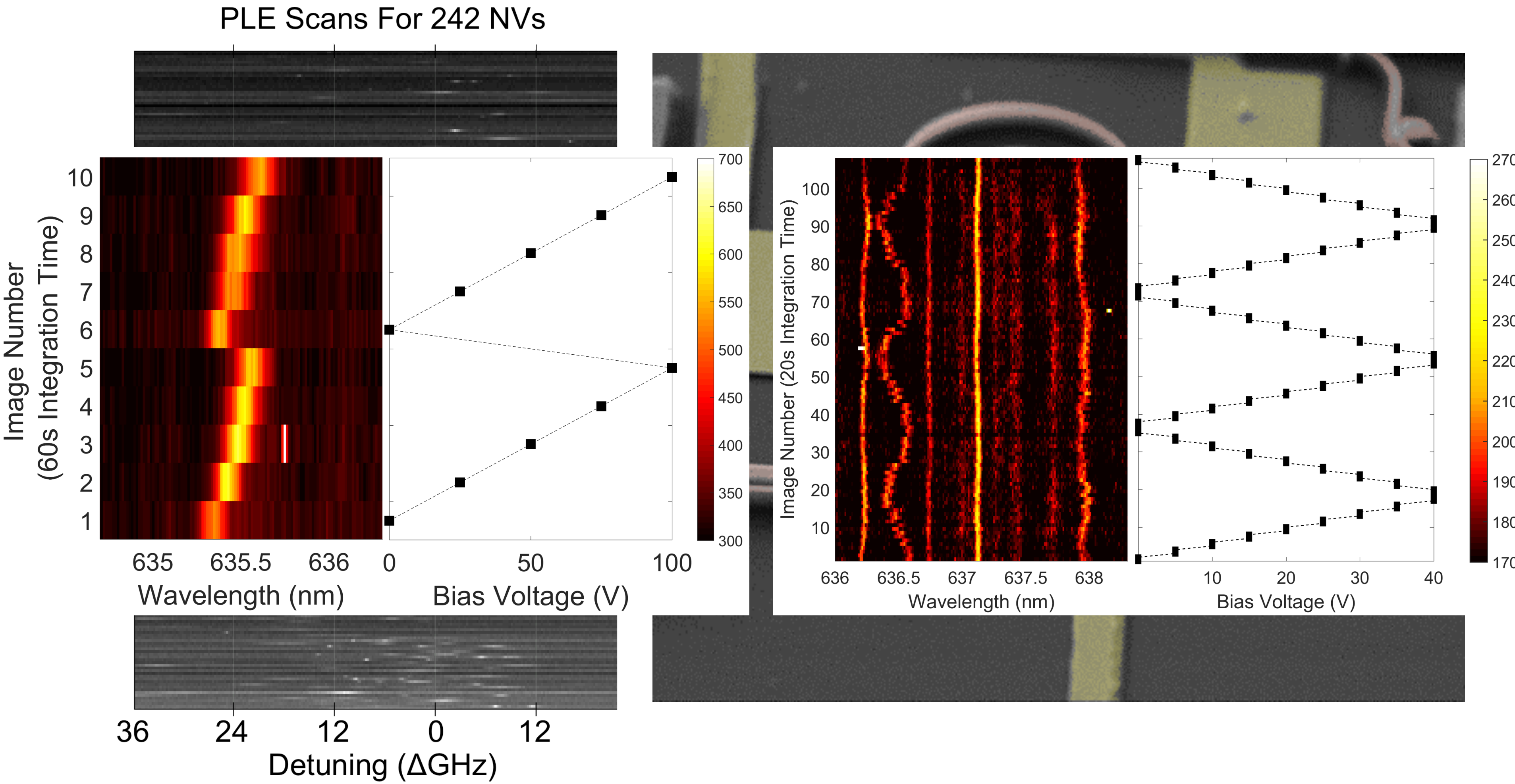
1) Moving detectors on-chip
2) Tuning and stabilizing the optical transition frequency of near-surface NV centers

Current efforts in diamond



1) **Moving detectors on-chip**
2) Stabilizing the optical transition frequency of near-surface NV centers

Current efforts in diamond

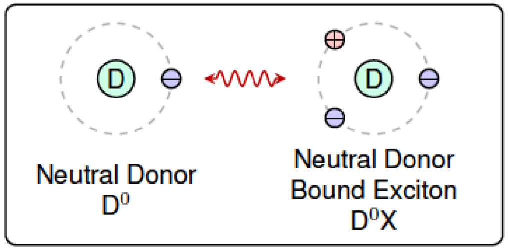


1) Moving detectors on-chip

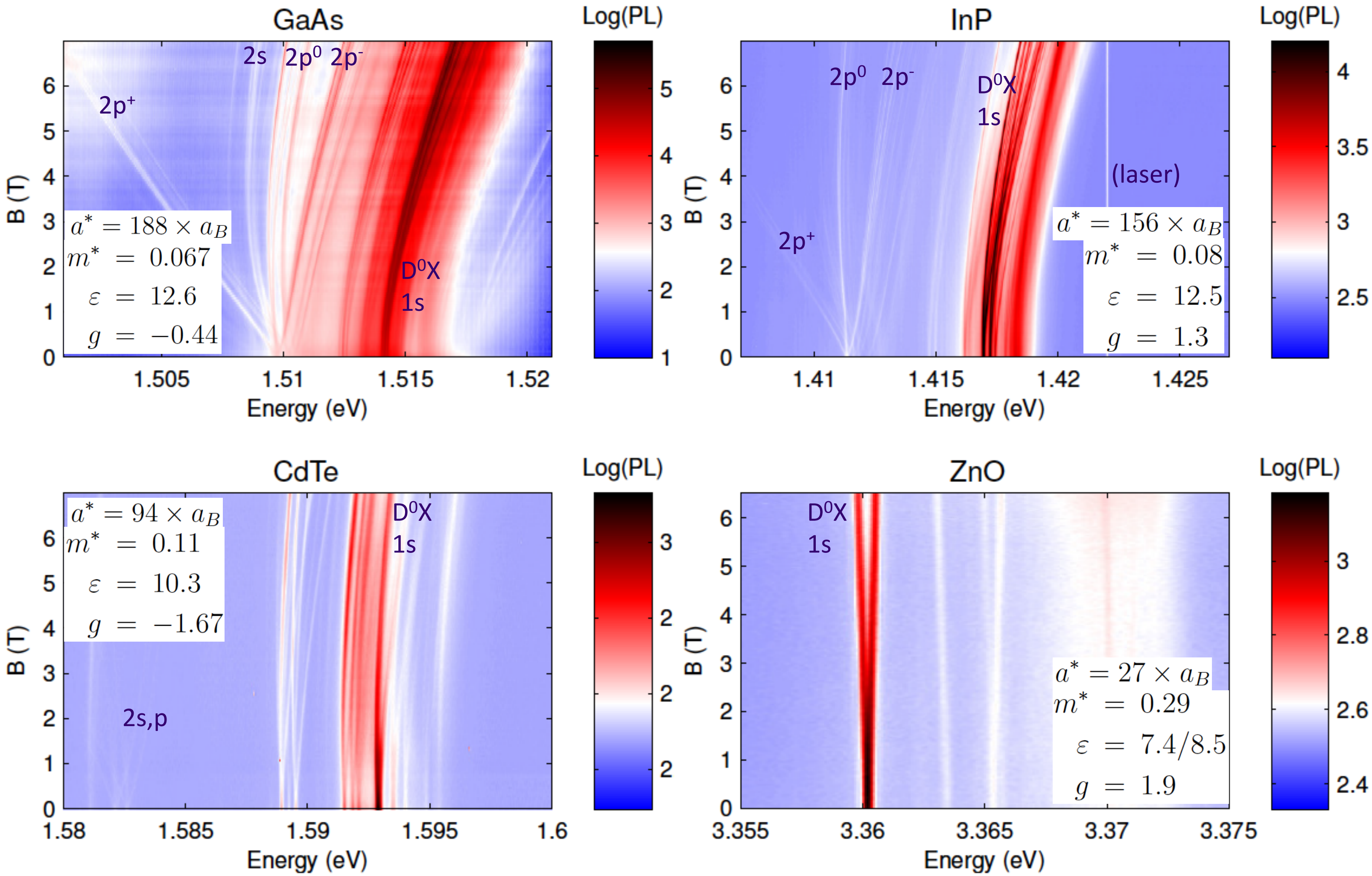
2) Tuning and stabilizing the optical transition frequency of near-surface NV centers

Example of quantum defect "discovery": donors in ZnO

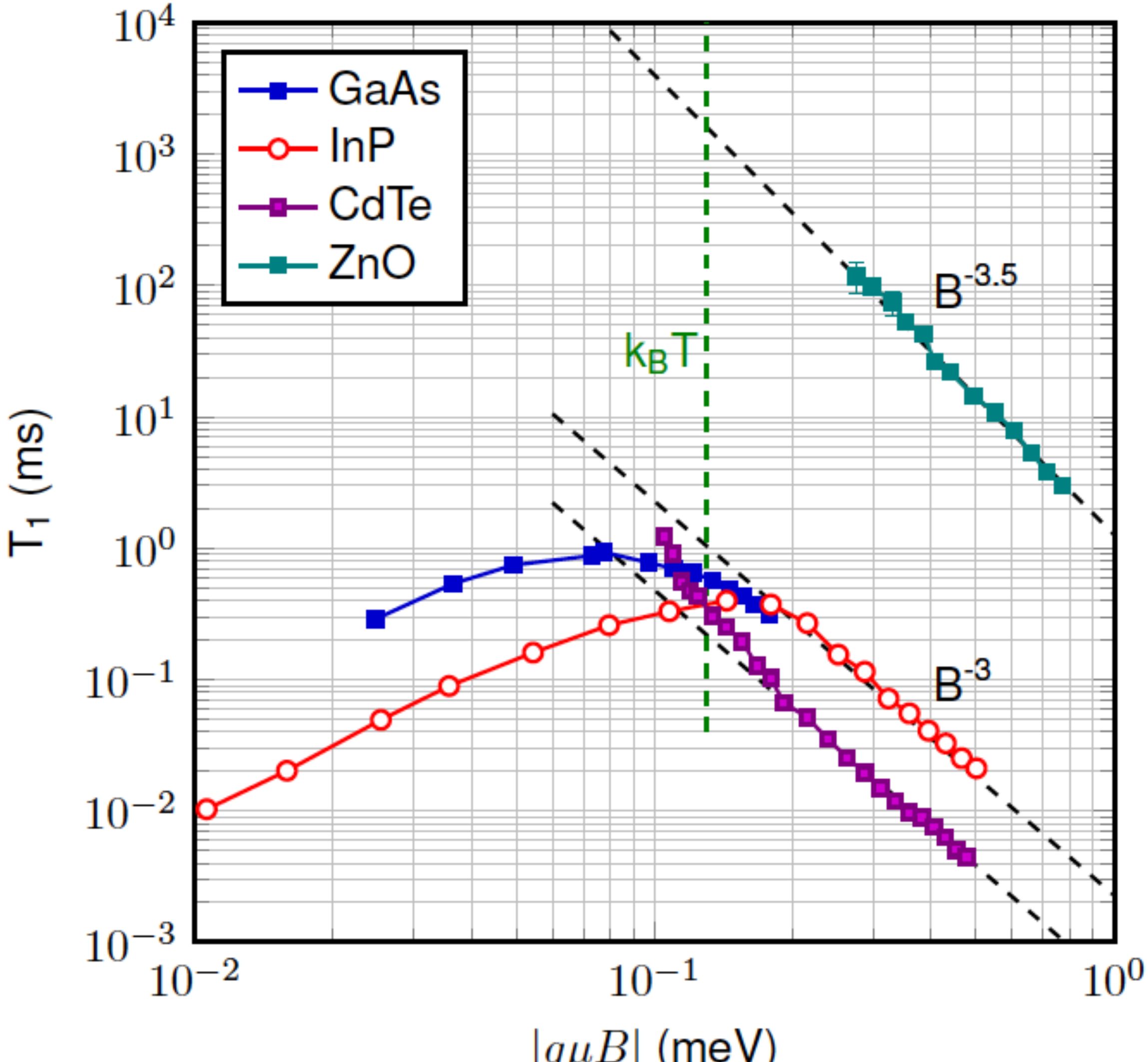
Donors in 4 direct-band gap semiconductors



$$E\psi = -\frac{\hbar^2}{2m}\nabla^2\psi - \frac{e^2}{4\pi\varepsilon}\frac{1}{r}\psi$$

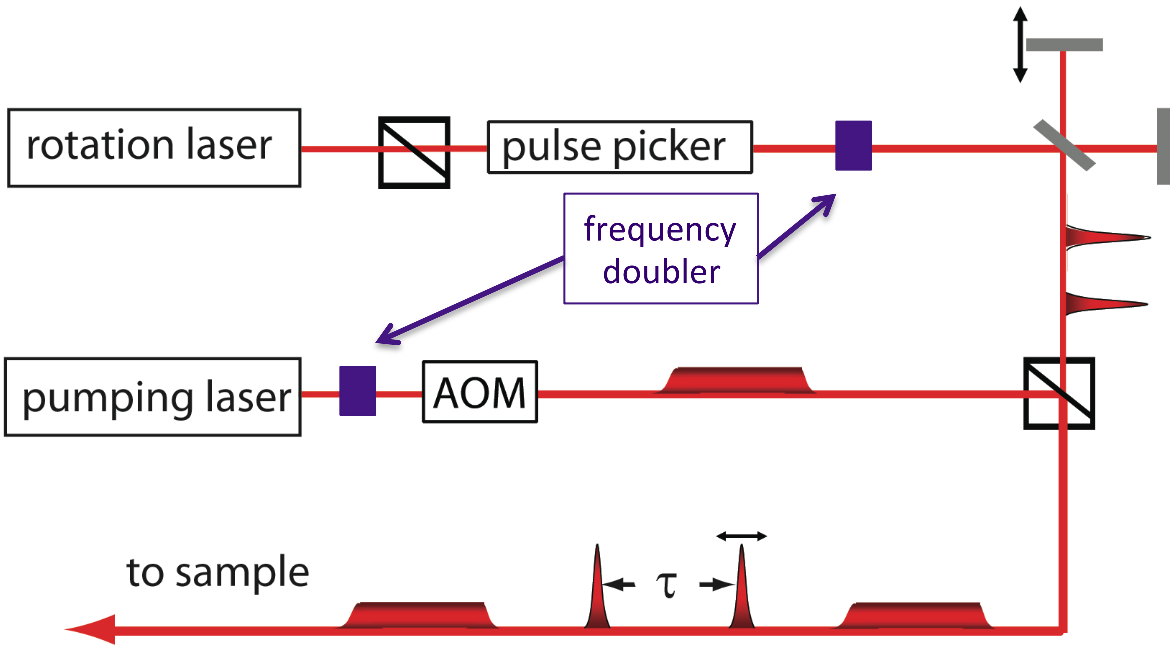


Gallium donor in ZnO: longitudinal spin relaxation time

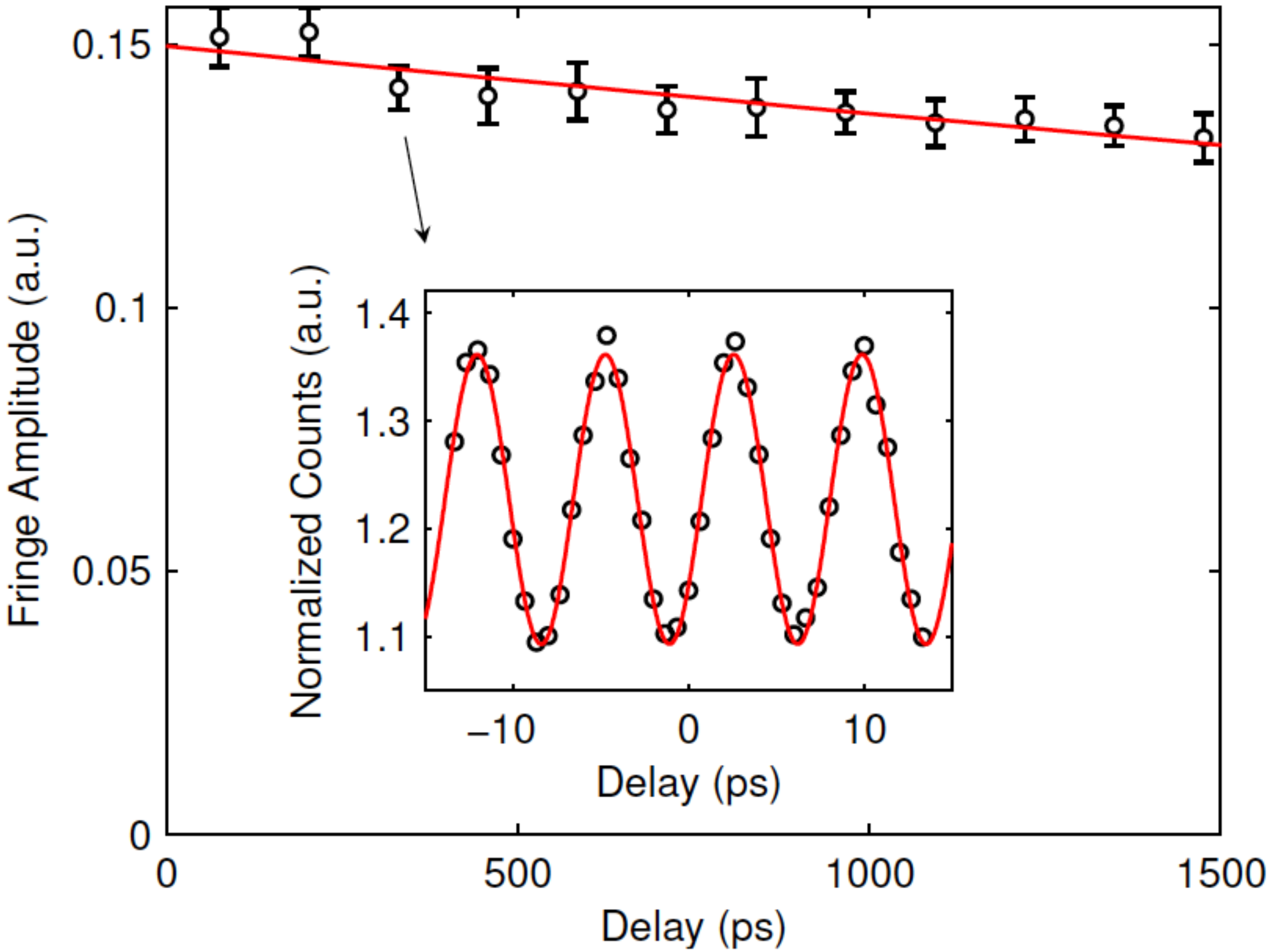


Theoretical work still in progress for wurtzite crystal structure.

Double pulse experiment



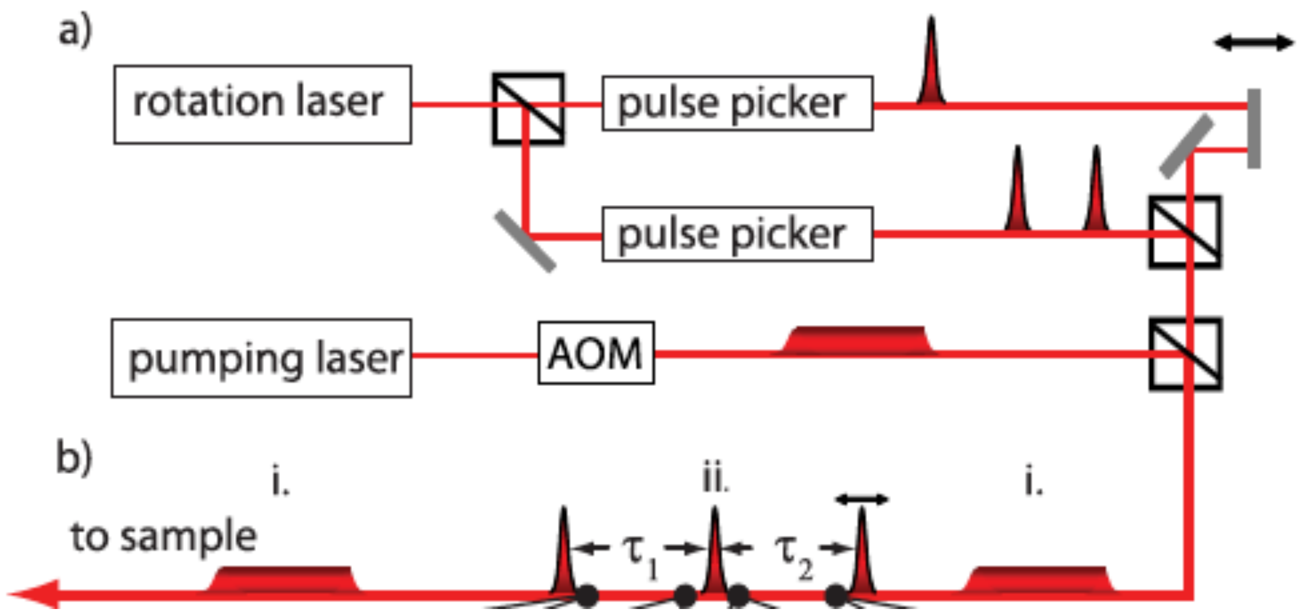
Inhomogeneous dephasing time



$T_2^* = 11 \pm 4$ ns

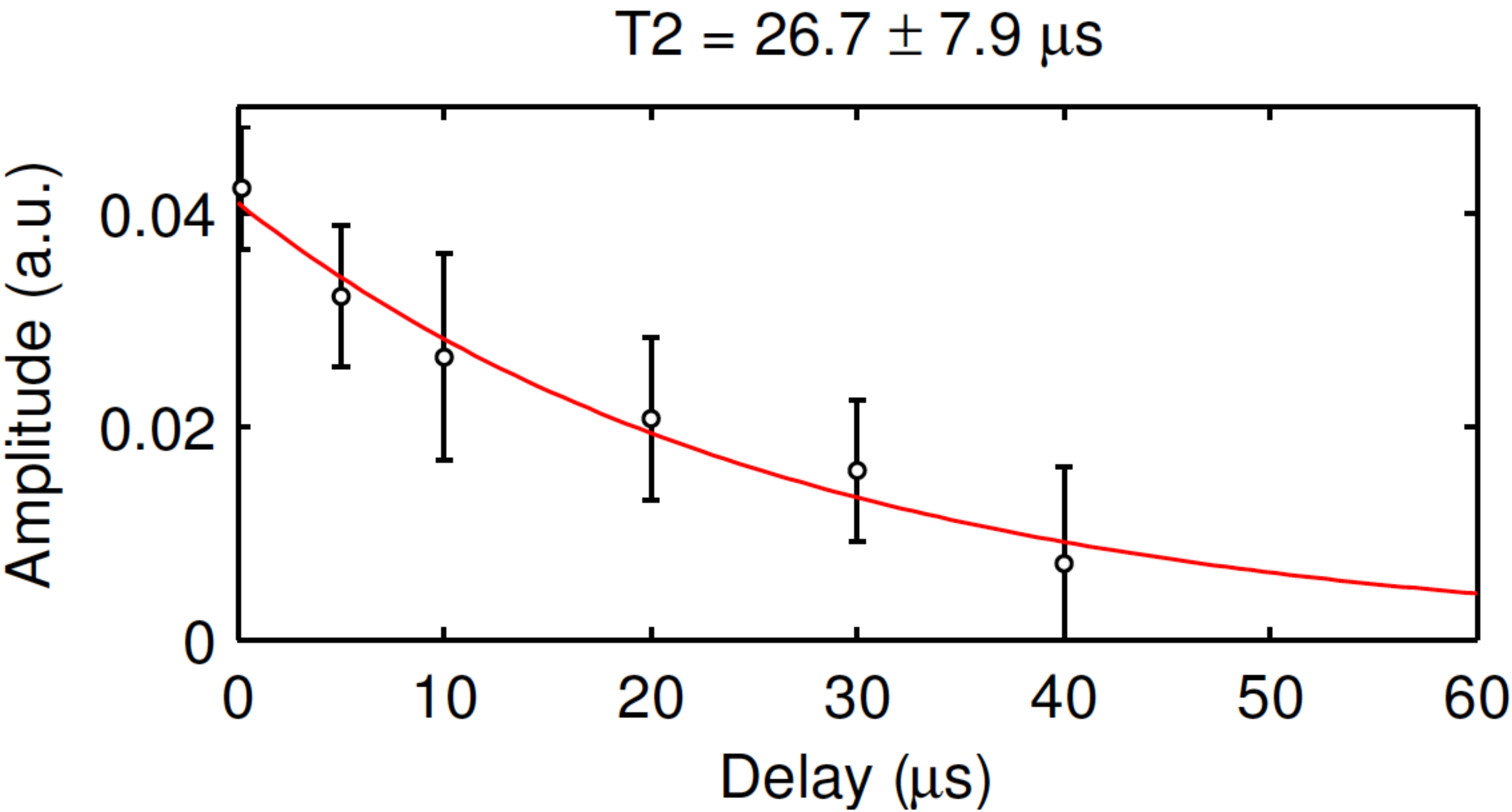
(Spin-echo measurement under construction.)

Triple pulse experiment (spin-echo)



T2 data

In a commercial, high-purity substrate- no “engineering”



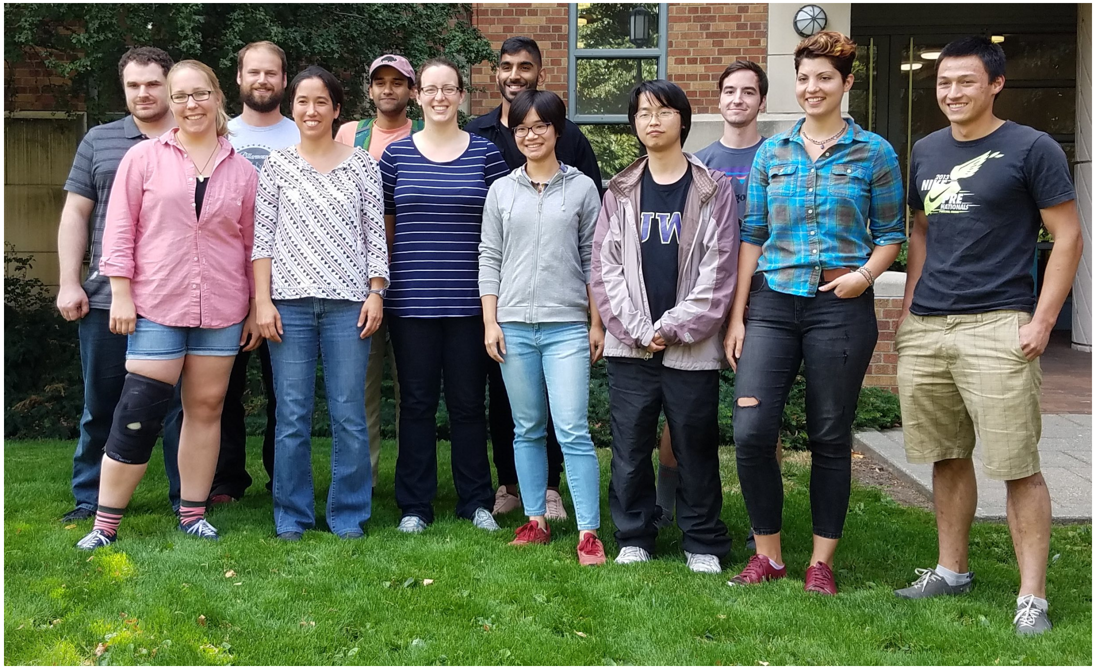
Summary and outlook

> Measurement-based model of quantum computing has several attractive features
  - Qubits do not need directly interact
  - Network is created by photons

> Utilizing defects for the nodes is promising but progress is slow

Fiscal Year (FY) 2018 Department of Defense
Multidisciplinary Research Program of the University Research Initiative

could also allow multifunctional sensing. However, the synthesis of isotope free quantum grade novel host materials, identification and incorporation of unique color centers, characterization of their quantum properties (coherence times, spectral stability etc.) and the understanding of their interactions with the external excitations (optical, electrical etc.) still remain significant challenges/unknowns.



Semiconductor Spins

*Todd Karin, PhD (physics)
Xiayu Linpeng, grad (physics)
Maria Viitaniemi, grad (physics)
*Cameron Johnson, undergrad (physics)

Growth Collaborators

Colin Stanley, GaAs, Glasgow
Satoru Seto, CdTe, Ishikawa
Simon Watkins, InP, Simon Fraser
Y. Kozuka, M.Kawasaki, ZnO, Tokyo

Theory collaborators

Mikhail Durnev, Ioffe
Mikhael Glazov, Ioffe
E. Ya Sherman, IKERBASQUE

Diamond Photonics

*Nicole Thomas, PhD (EE)
*Michael Gould, PhD (EE)
Emma Schmidgall, postdoc
Srivatsa Vardaraj, grad (EE)
*Ian Christen, undergrad (physics)

Growth Collaborators

Larry Lee, Yale
Fariba Hatami, Humboldt

Funding

NSF
DARPA
RESEARCH CORPORATION for SCIENCE ADVANCEMENT

UNIVERSITY of WASHINGTON

*graduated