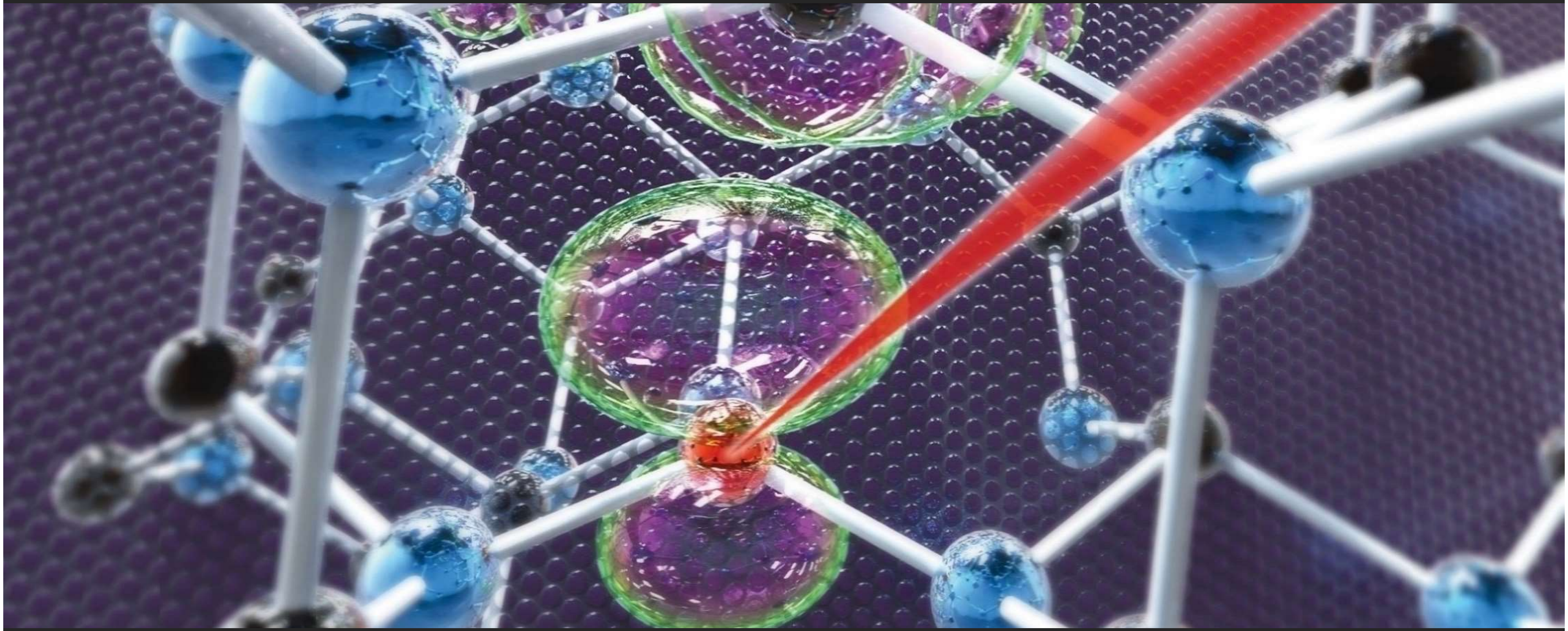
Driving the Quantum Dynamics of Single Diamond Spins with Light



Brian Zhou
University of Chicago
@ SPICE Workshop, Mainz (7-12-2018)

THE INSTITUTE FOR MOLECULAR ENGINEERING
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University of Konstanz

V. Shkolnikov

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NSF

DFG
German Research Foundation

Two Scales of Quantum

Harnessing quantum mechanics for next-generation technologies:

	Macroscopic Quantum Systems $(N \gg 1)$	***Single Quantum Systems*** $(N \sim O(1))$
Starting Point	Emergent many-body phenomena	Coherently-controlled single quantum systems
Examples	• Bose-Einstein condensates • Fractional quantum hall • "Quantum" materials …	Cold atoms Superconducting qubits Impurities/defects in solids …

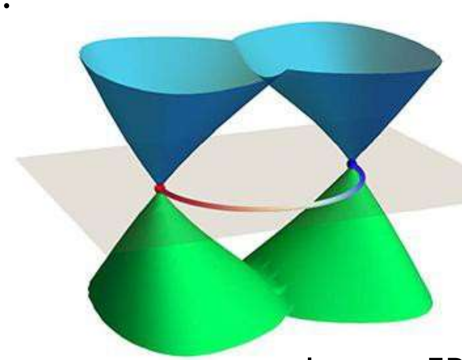


Image: EPFL

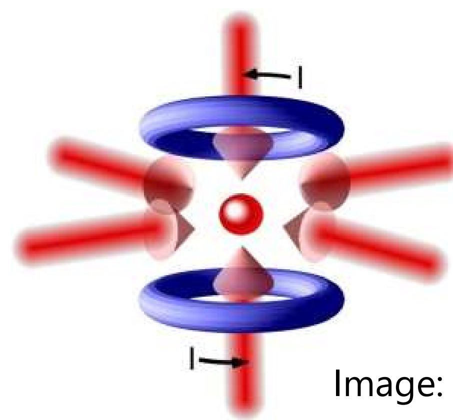


Image: Vescent

Two Scales of Quantum

Harnessing quantum mechanics for next-generation technologies:

	Macroscopic Quantum Systems $(N \gg 1)$	***Single Quantum Systems*** $(N \sim O(1))$
Challenges	Address/control individual quasiparticles; multiplex information; extend phases to ambient	Scale entanglement to non-trivial sizes; extend coherence in time

Cross-cutting resources	Hybrid quantum systems; novel materials for qubits; novel quantum sensors

This talk:
- ✓ Time-dependent driving
- ✓ Berry phase

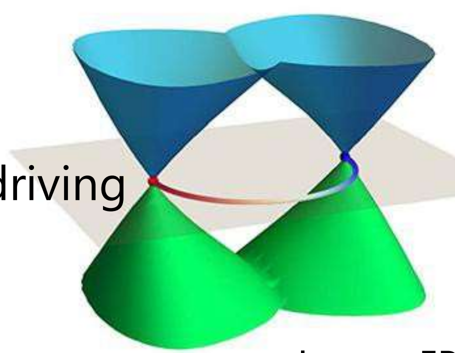


Image: EPFL

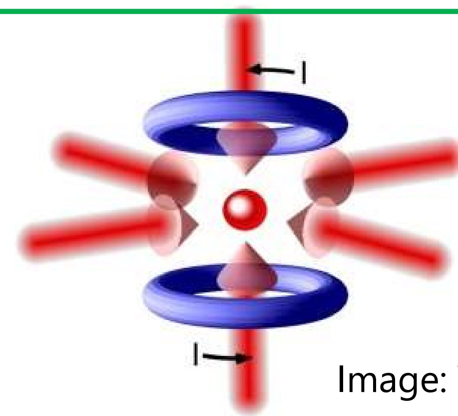


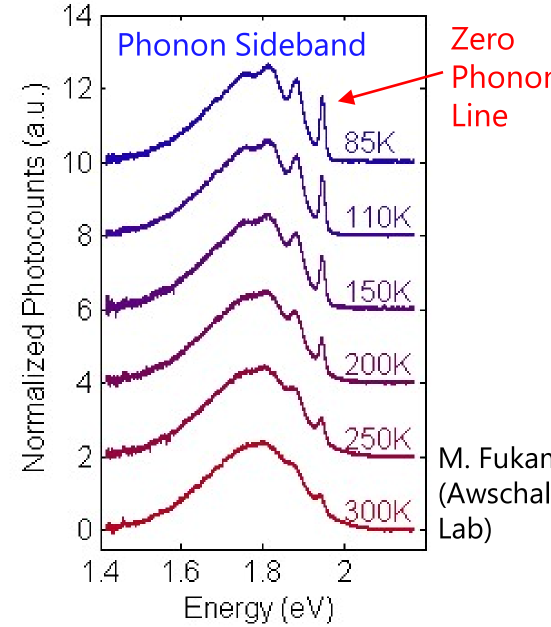
Image: Vescent

NV⁻ Center in Diamond

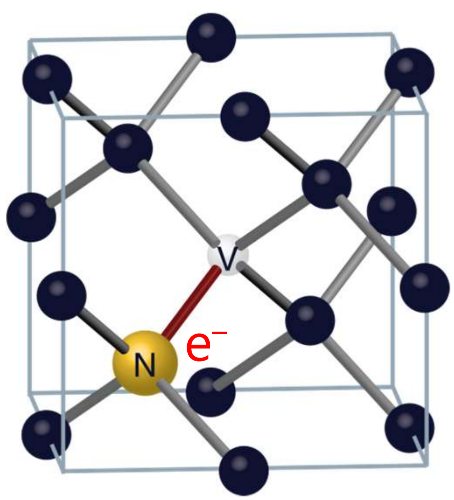
Negatively-charged nitrogen-vacancy center in diamond

- 6 electrons strongly localized at defect
- Spin triplet (S = 1) ground state
- Green excitation/red fluorescence

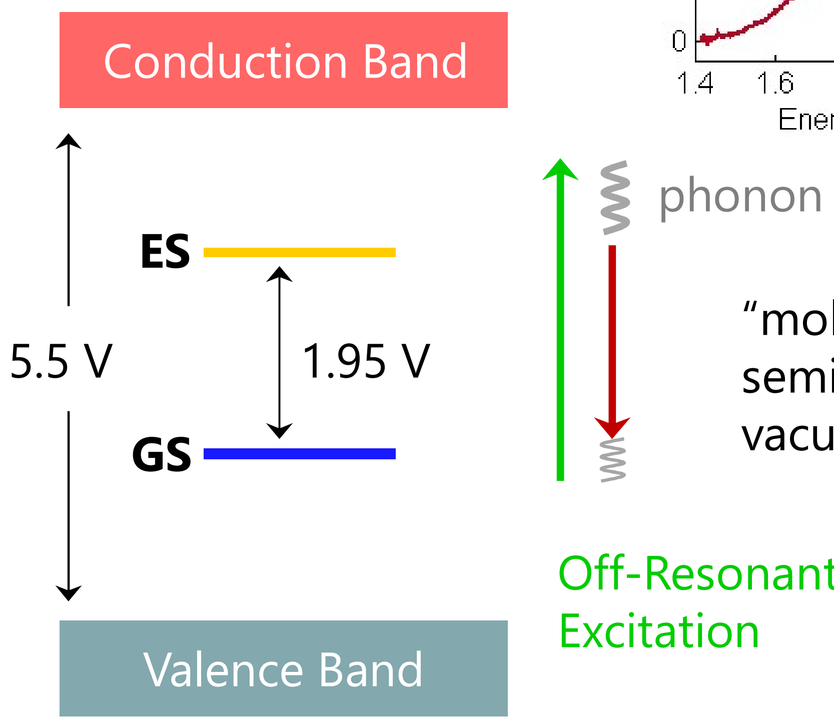
NV Emission Spectrum



M. Fukami (Awschalom Lab)



substitutional N next to C vacancy



"molecule inside semiconductor vacuum"

NV⁻ Center in Diamond

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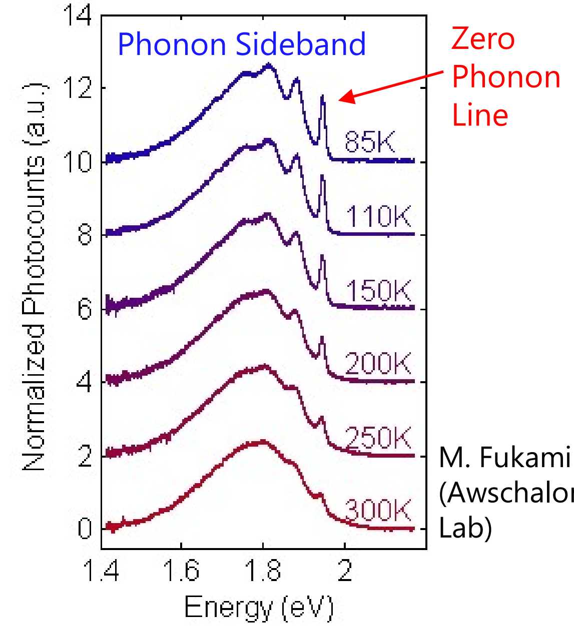
Optically-addressing single atomic defects by confocal microscopy:

NV Emission Spectrum



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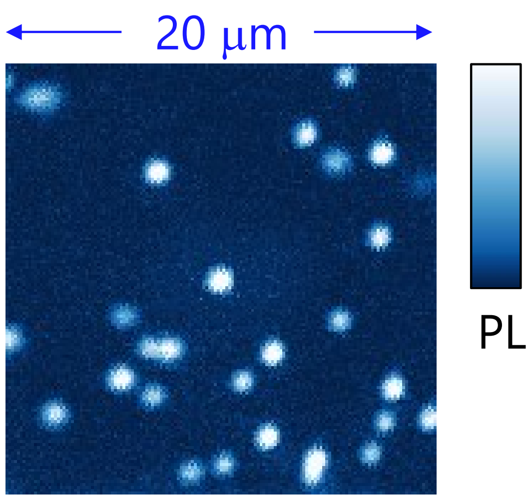
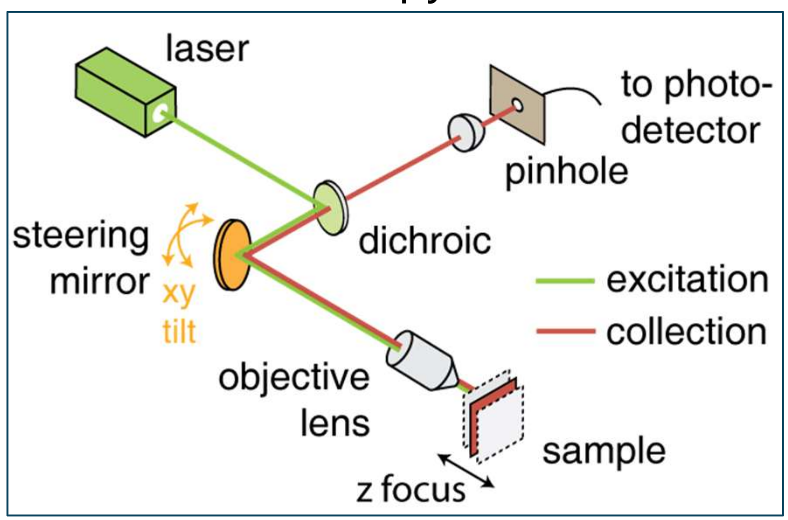


Extremely pure material! (~1 ppb N, ~.01 ppb NV)

Confocal Microscopy

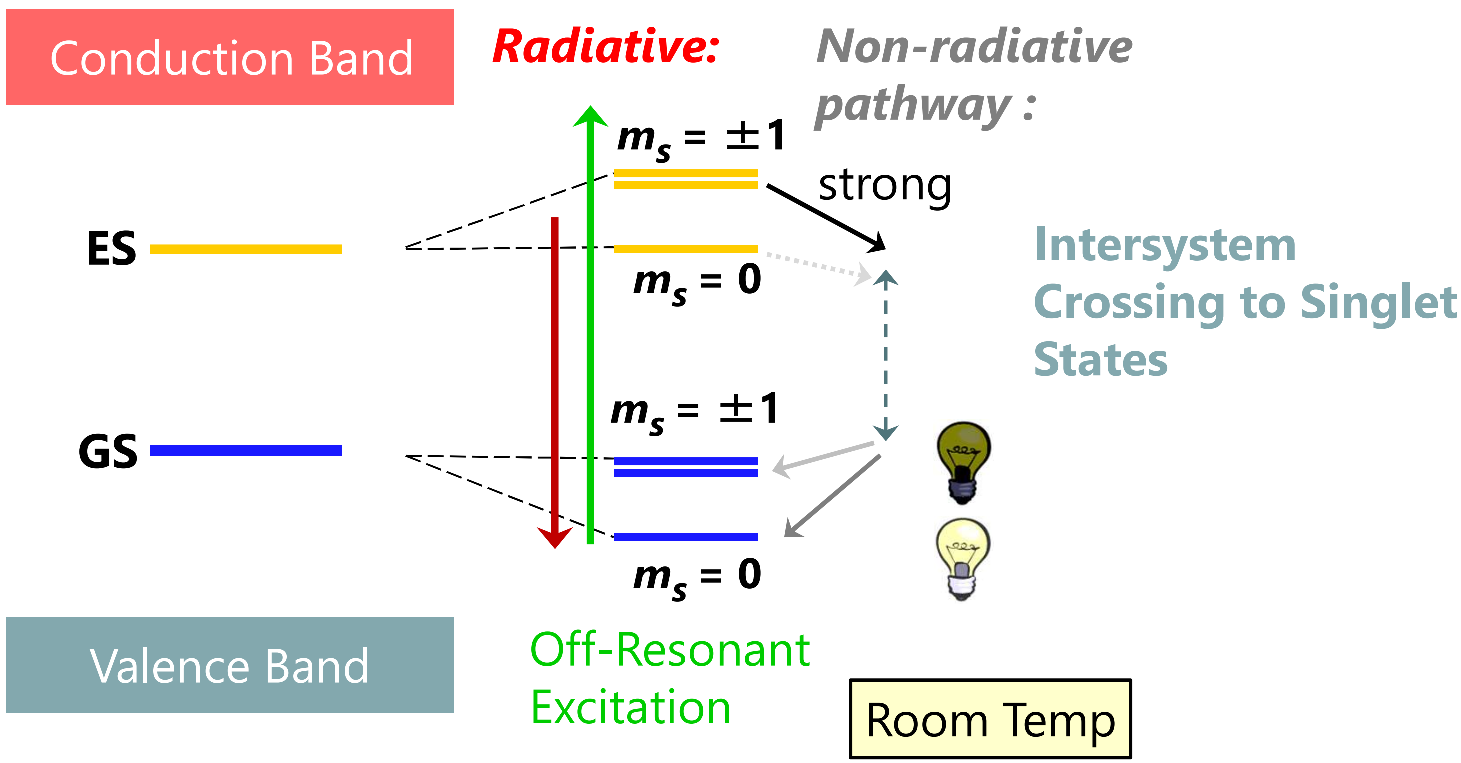


What makes NV centers special?

- Optical spin readout and initialization: spin-dependent photoluminescence
- Superlative spin coherence:

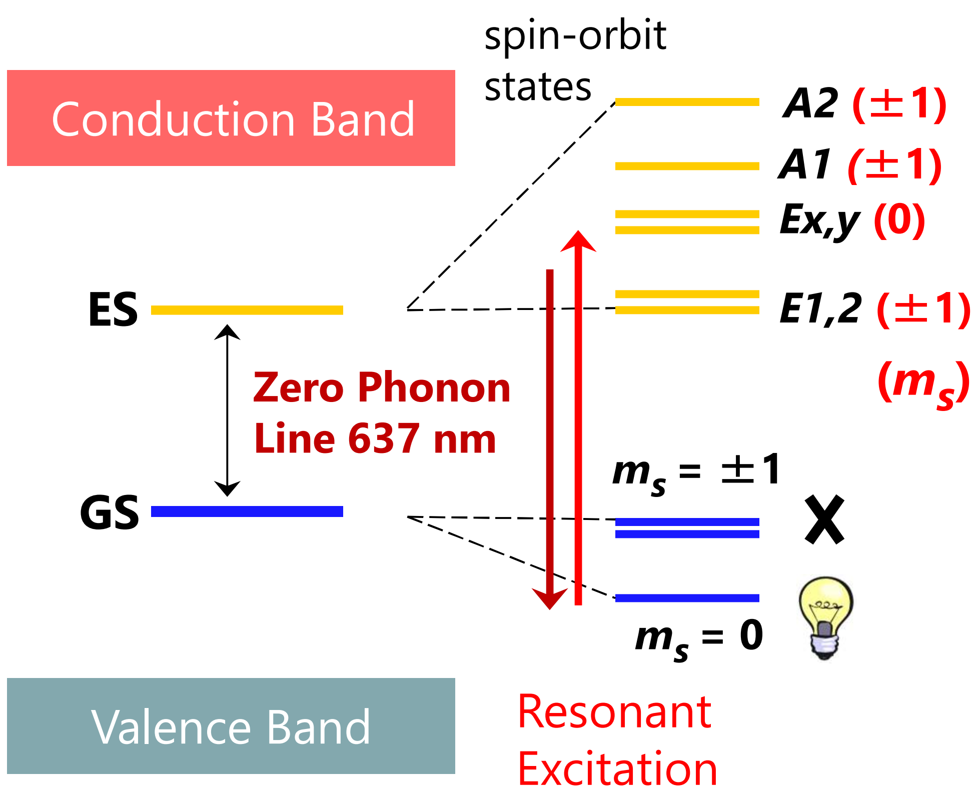
  ~1 ms T_2 (phase memory)

  > 100 μs T_2^* at **room temperature** for [12]C-purified samples!

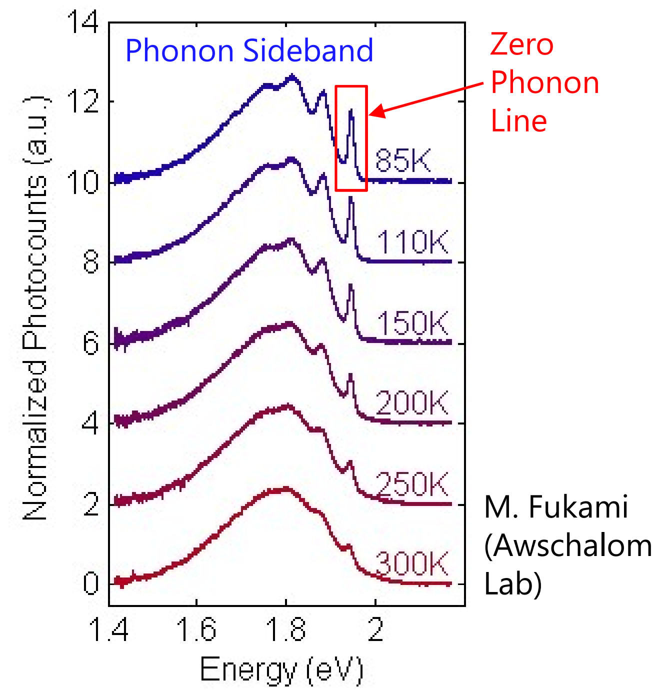


NV Center at Low Temperature

- Resolving spin-orbit fine structure of excited state below <20 K



NV Emission Spectrum

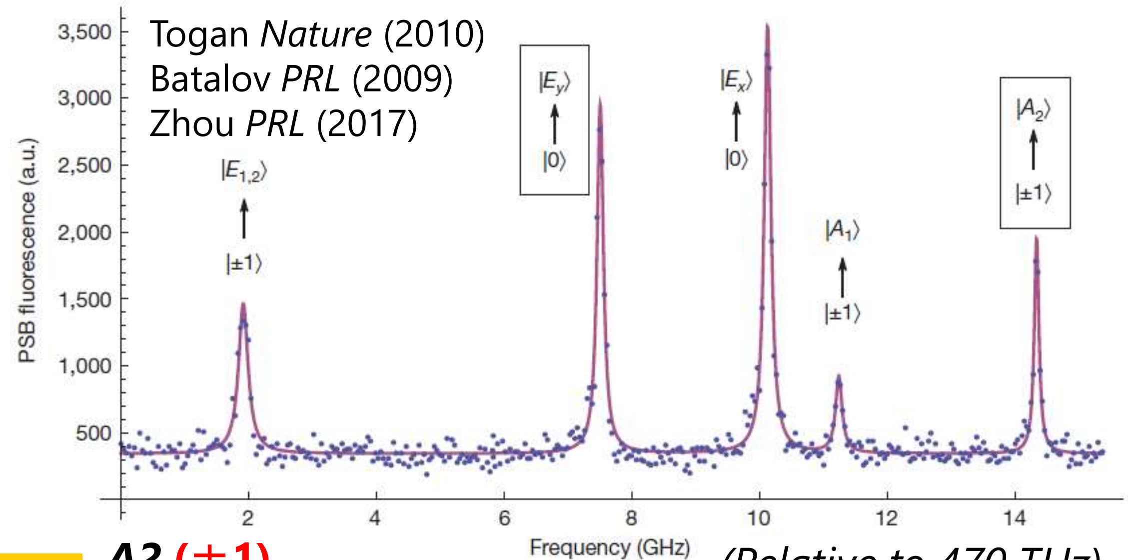


Zoom in on zero-phonon transitions…

Low Temperature (<20 K)

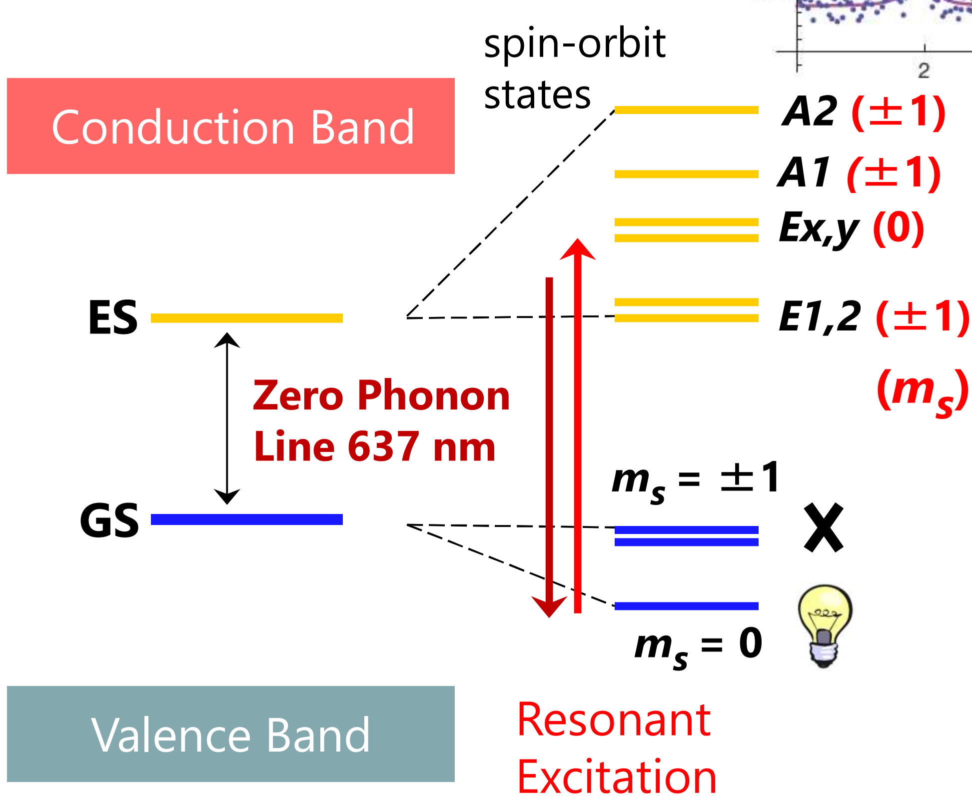
NV Center at Low Temperature

- Resolving spin-orbit fine structure of excited state below <20 K
- Quantum optics without laser trapping or high vacuum.

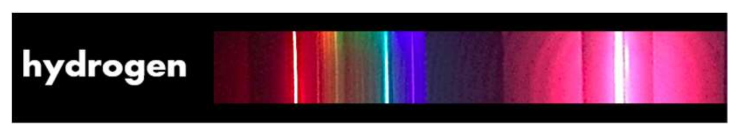


(Relative to 470 THz)

$*1 GHz = 4.1 \mu eV$



Solid-state analogue to atomic transition spectra

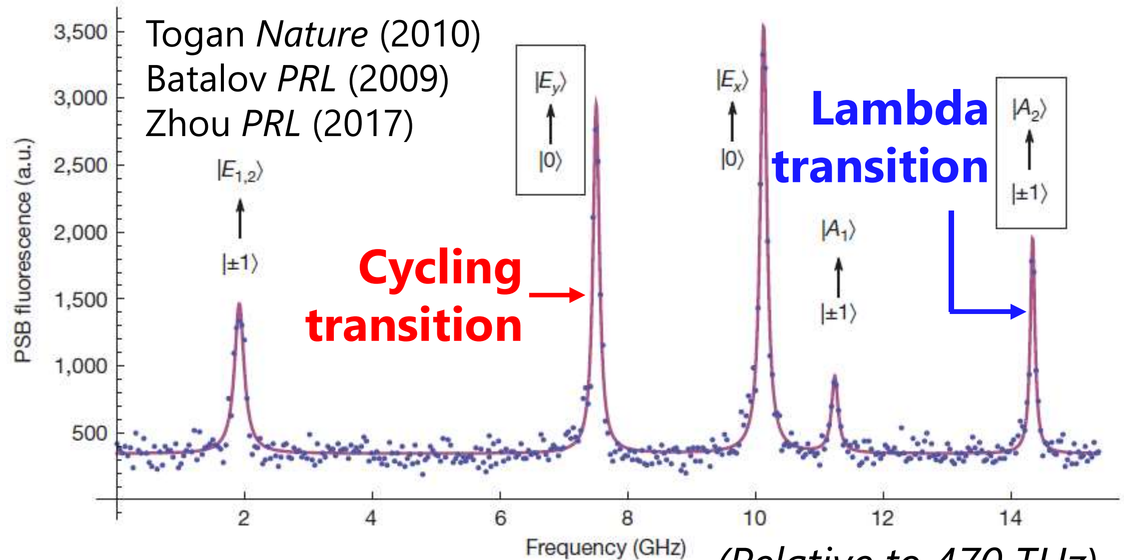


Low Temperature (<20 K)

NV Center at Low Temperature

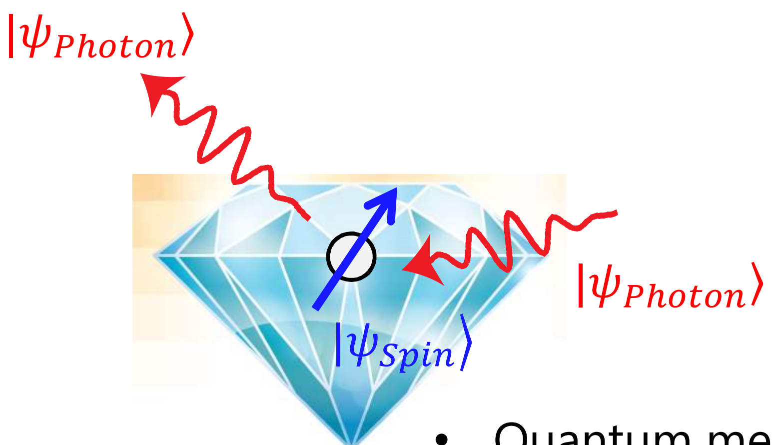
High-fidelity spin-selective transitions enables:

- Spin-photon entanglement
  - spin to photon polarization
  - spin to photon number
- Optical spin control

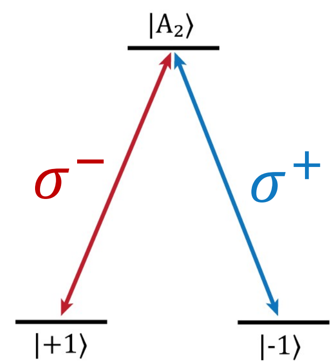


(Relative to 470 THz)

Quantum interface between spins and photons



- Quantum memory
- Remote entanglement



spin-photon entangled state

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|\sigma_-\rangle|+1\rangle + |\sigma_+\rangle|-1\rangle)$$

Low Temperature (<20 K)

NV Center at Low Temperature

High-fidelity spin-selective transitions enables:

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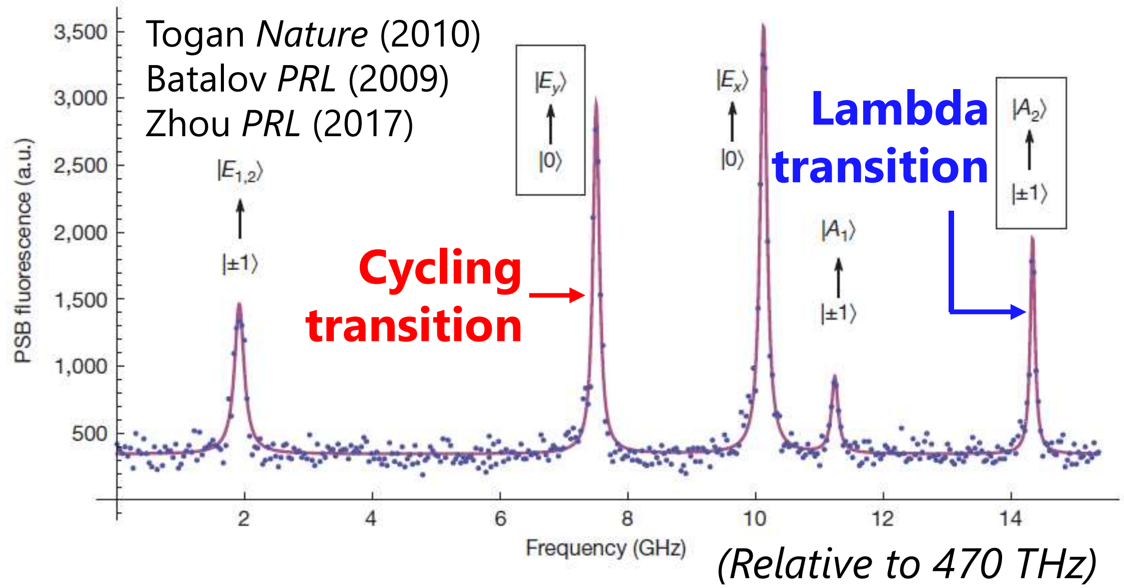
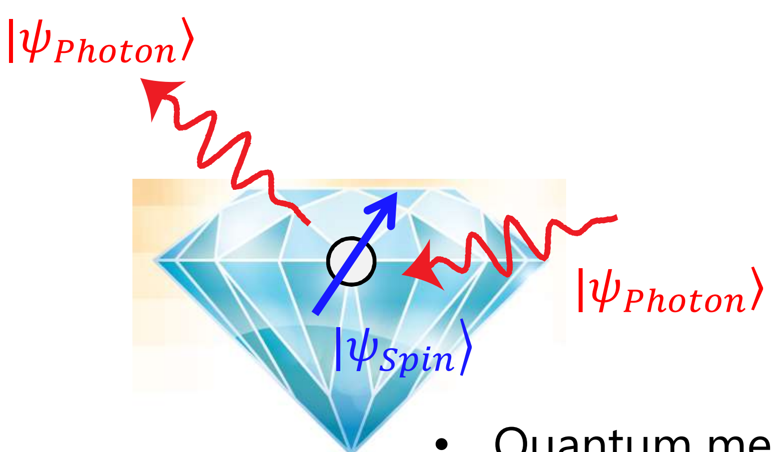
  - spin to photon number
- Optical spin control



Quantum interface between spins and photons



- Quantum memory
- Remote entanglement

See works by:
Hanson Group (Delft)
Wratchrup (Stuttgart)
Lukin (Harvard)...

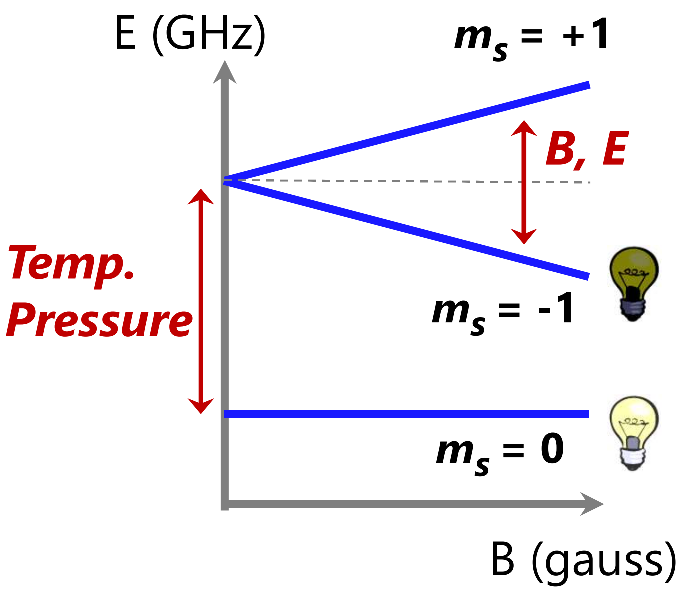
Low Temperature (<20 K)

+ Versatile Sensor!

Ground State Hamiltonian:

$$H_{GS} \approx D(T,P)\ S_Z^2 - d_{GS}\left(E_x\left(S_xS_y + S_yS_x\right) + E_y\left(S_x^2 - S_y^2\right)\right) + \gamma\,\vec{S}\cdot\vec{B}$$

Ground State Spin Energies



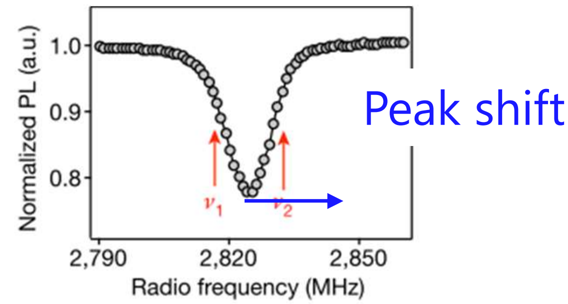
Parameter (P)	Response
$B_{\parallel}$	2.8 MHz/Gauss
$E_{\perp}$	17 Hz/(V/cm)
Temp.	-80 kHz/Kelvin
Pressure	15 MHz/GPa

"Quantum Sensing"

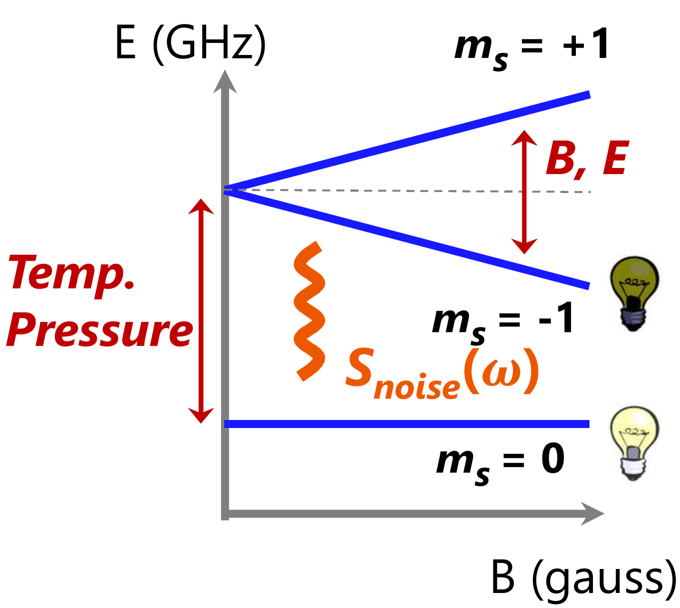
- **Nanoscale resolution**
- **Ease of use, wide-temperature range**

+ Versatile Sensor!

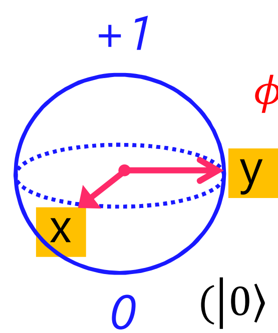
Measure energies directly (spectroscopy).



Ground State Spin



Or measure phase accumulation.



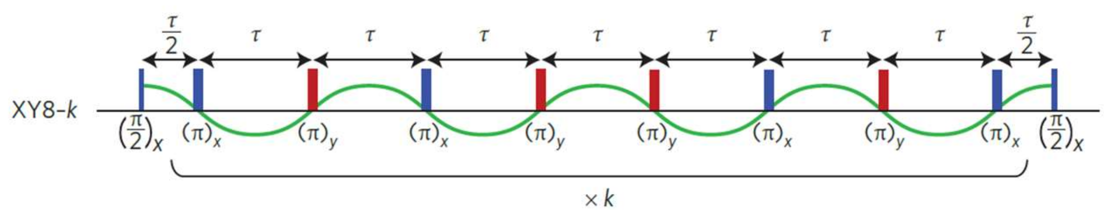
$$\phi \sim \frac{E(\vec{\mathbf{P}})}{\hbar} t$$

$$(|0\rangle + e^{i\phi}|+1\rangle)/\sqrt{2}$$

Long coherence times key!

$$\sigma \sim \frac{1}{\sqrt{T_{meas} \cdot T_{coh}}}$$

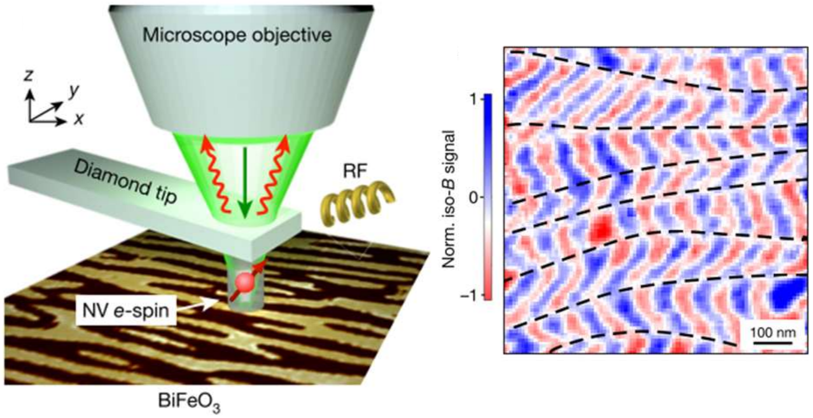
Ramsey Sequence (DC Fields)



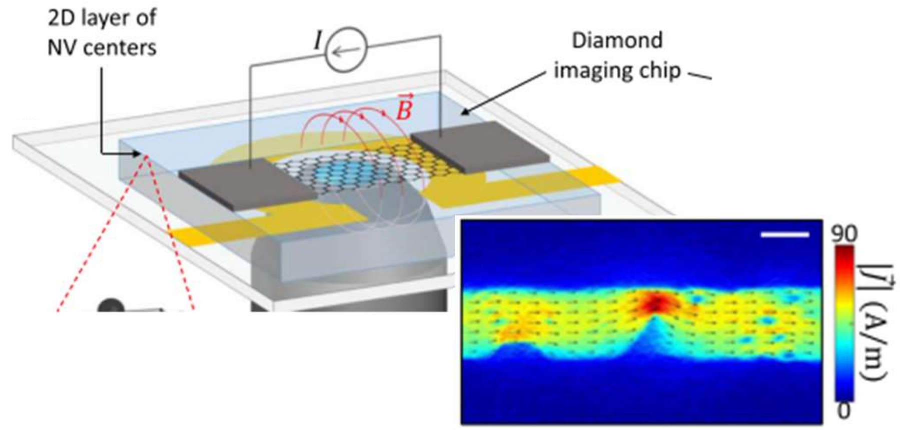
Dynamical Decoupling Sequence (AC Fields)

+ Versatile Sensor!

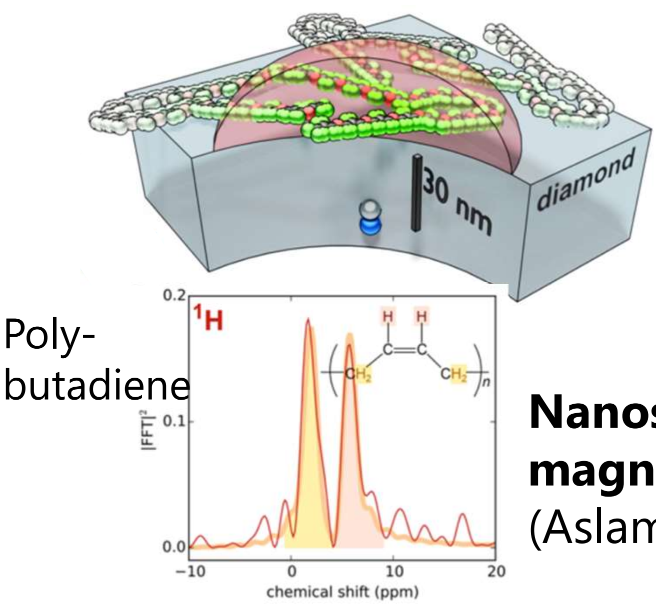
Wide-ranging applications in physics, chemistry, biology, medicine



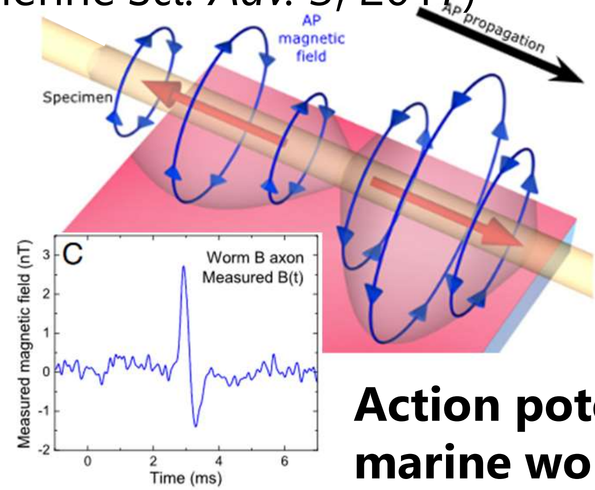
Non-collinear magnetic order in $BiFeO_3$
(Gross *Nature* 549, 2017)



Electron/spin transport in 2D materials
(Tetienne *Sci. Adv. 3*, 2017)



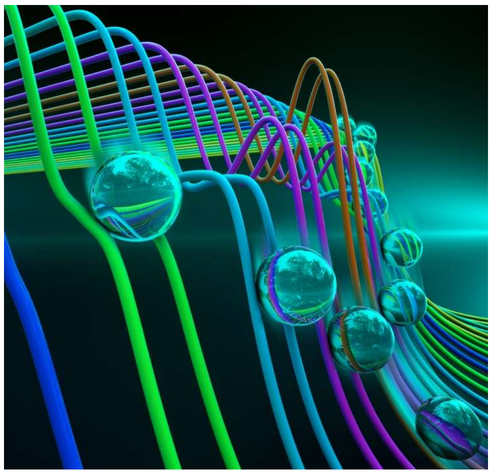
Nanoscale nuclear magnetic resonance
(Aslam *Science* 357, 2017)



Action potential of marine worm
(Barry *PNAS* 113, 2016)

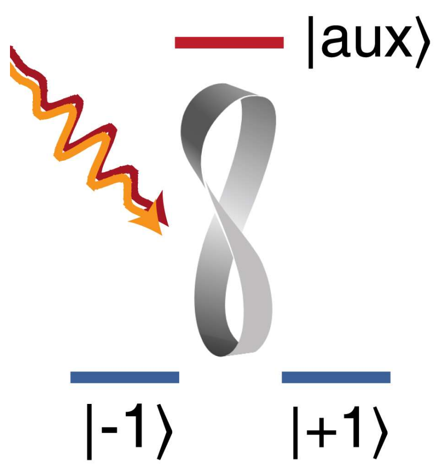
Controlling Quantum Dynamics (Optically)

Accelerating Adiabatic Quantum Control



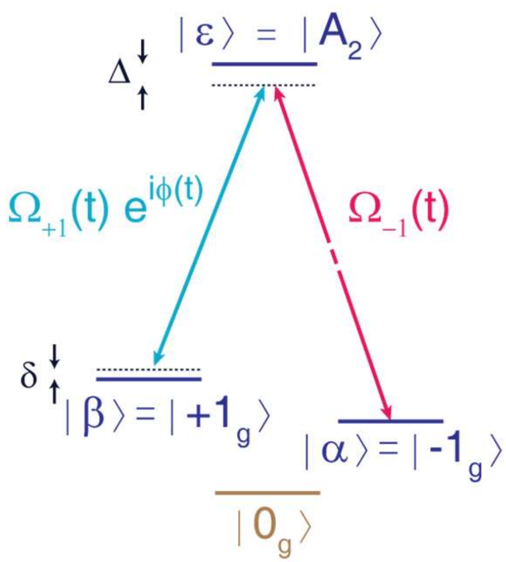
- Engineering quantum shortcuts to adiabaticity
- Fast optical pulse shaping for state transfer via STIRAP

Manipulating Spins by Geometry

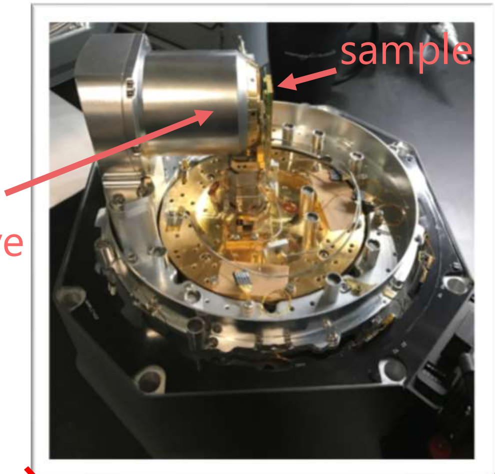


- Robustness of Berry phases to noise
- Arbitrary single qubit quantum gates by non-abelian holonomies

Our Lab – Low Temp Confocal Microscope

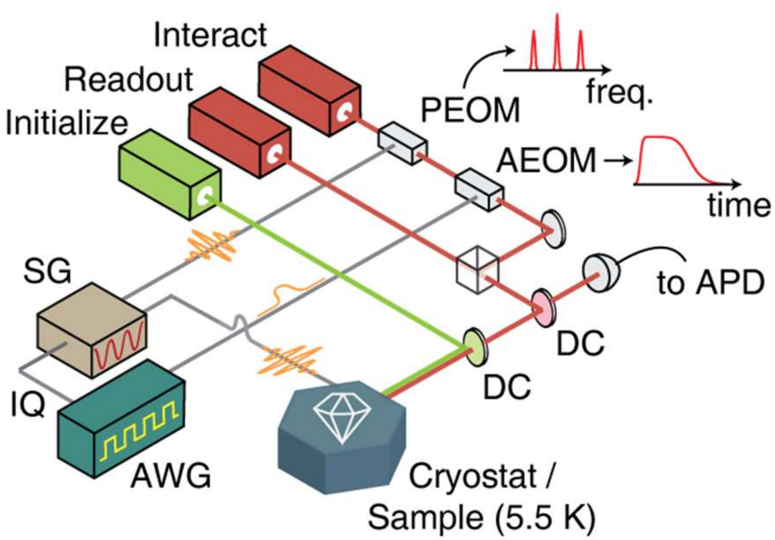


Closed-Cycle Cryostat (5 K)



in-cryo objective

Optimized for phase/amplitude controlled two-color excitation of Λ systems

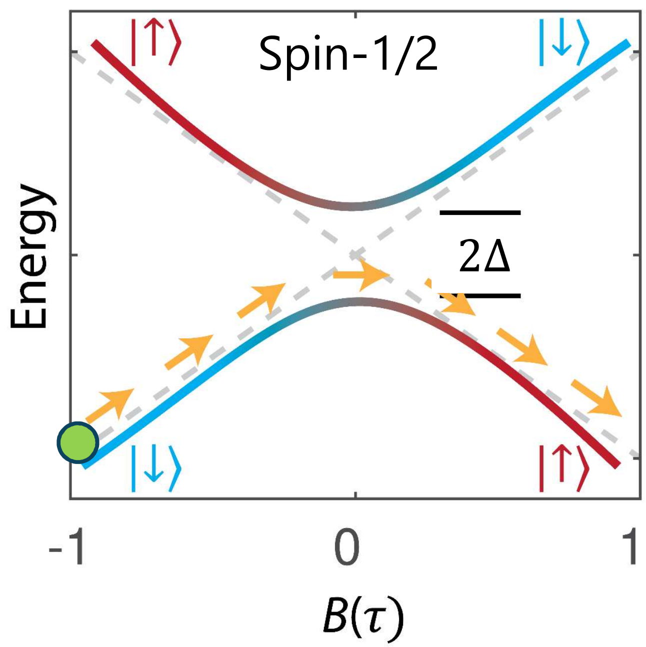


Quantum Adiabaticity as a Powerful Tool

Robust state manipulation

- **cooling atomic systems**
- **nuclear magnetic resonance (ensembles)**
- **adiabatic quantum simulation**

Landau-Zener Transition



(e.g. sweeping a magnetic field)

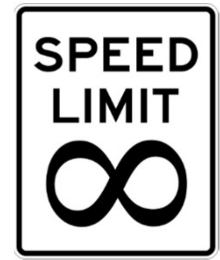
System remains in instantaneous eigenstate if its rate of change is *adiabatic.*

Adiabatic Criterion: $\frac{dB(\tau)}{d\tau} \ll \Delta^2$

$$H_{LZ} = \begin{bmatrix} B_z(t) & \Delta \\ \Delta & -B_z(t) \end{bmatrix}$$

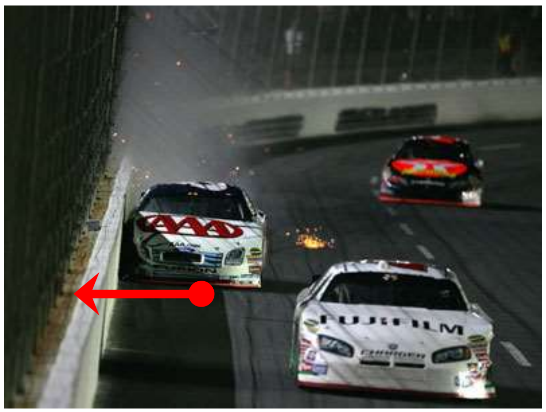
Important consequences for more complex systems:
Quantum simulations
Quantum thermodynamics

Shortcuts to Adiabaticity – The Need for Speed



A classical analogy for non-adiabatic transitions:

Non-Adiabatic



Counterdiabatic (bank!)

Engineering the quantum track:

$$H_0(t) \rightarrow H_0(t) + \underbrace{H_{CD}(t)}$$

Extra control to counteract non-adiabatic transitions

Review: Torrontegui *Advances in AMO Physics* 62 (2013). Originally: Berry, Demirplak/Rice.

Counterdiabatic (CD)/Transitionless Driving

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FAST FORWARD

Hamiltonian in moving frame of adiabatic eigenstates $|\varphi_k(t)\rangle$:

$$\hat{U}(t) = \sum_k |\varphi_k\rangle\langle\varphi_k(t)|$$

Evolution is useful to us

$$\hat{H}_{\text{ad}}(t) = \hat{H}_0(t) + \hat{W}(t)$$

$$= \sum_k E_k(t)|\varphi_k\rangle\langle\varphi_k| + i\frac{d\hat{U}(t)}{dt}\hat{U}^\dagger(t)$$

diagonal — off-diagonal $\widehat{W}(t)$

"Fictitious force", drives transitions!

The counterdiabatic term exactly cancels $\widehat{W}(t)$:

$$H_0(t) \to H_0(t) - \underbrace{\widehat{U}^\dagger(t)\widehat{W}(t)\widehat{U}(t)}_{H_{CD}(t)}$$

Is $H_{CD}(t)$ experimentally practical?

(How to calculate $H_{CD}(t)$ without exact diagonalization?)

Jarzynski *PRA* 2013. Deffner *PRX* 2014. Vandermause *PRA* 2016. Ribeiro *PRX* 2017.

e.g. for Landau-Zener Hamiltonian:

$$H_{LZ} = \begin{bmatrix} B_z(t) & \Delta \\ \Delta & -B_z(t) \end{bmatrix}$$

$$H_{CD}(t) = -\frac{dB_z(t)}{dt}\frac{\Delta}{B_z(t)^2 + \Delta^2}\hat{\sigma}_y$$

Add $B_y(t)$!

Review: Torrontegui *Advances in AMO Physics* 62 (2013). Originally: Berry, Demirplak/Rice.

Superadiabatic Transitionless Driving (SATD)

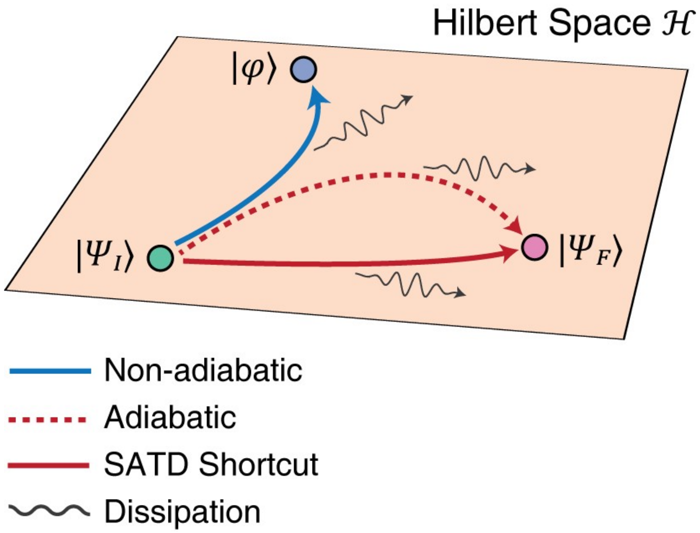
Aash Clerk's Group

For state transfer, only initial t_i and final t_f times are important!

Follow dressed adiabatic eigenstates:

$$\hat{V}(t)|\varphi_k(t)\rangle$$

$$\boldsymbol{H_0(t) \rightarrow H_0(t) + H_{SATD}(t)}$$



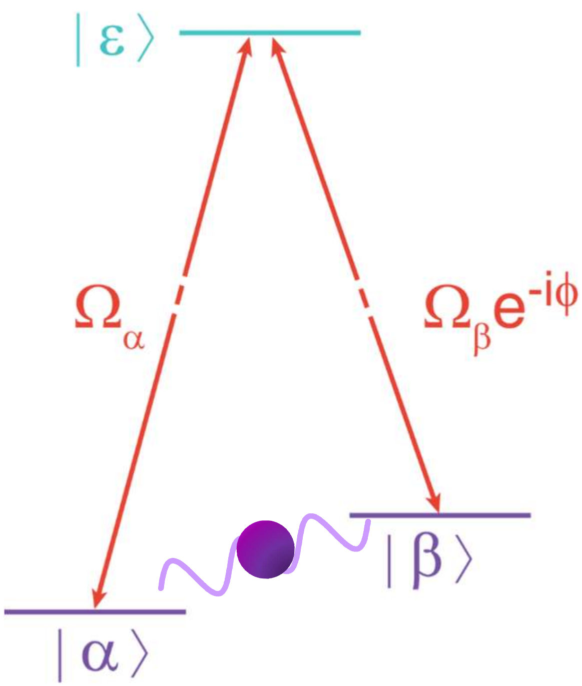
Multiple choices for $\hat{V}(t)$ gives multiple forms for $\boldsymbol{H_{SATD}(t)}$!

A. Baksic, H. Ribeiro, A. Clerk, *PRL* 116 (2016).

Application: STIRAP

Stimulated Raman Adiabatic Passage (STIRAP):

State transfer by dark state $|D\rangle$ of a lambda (Λ) system



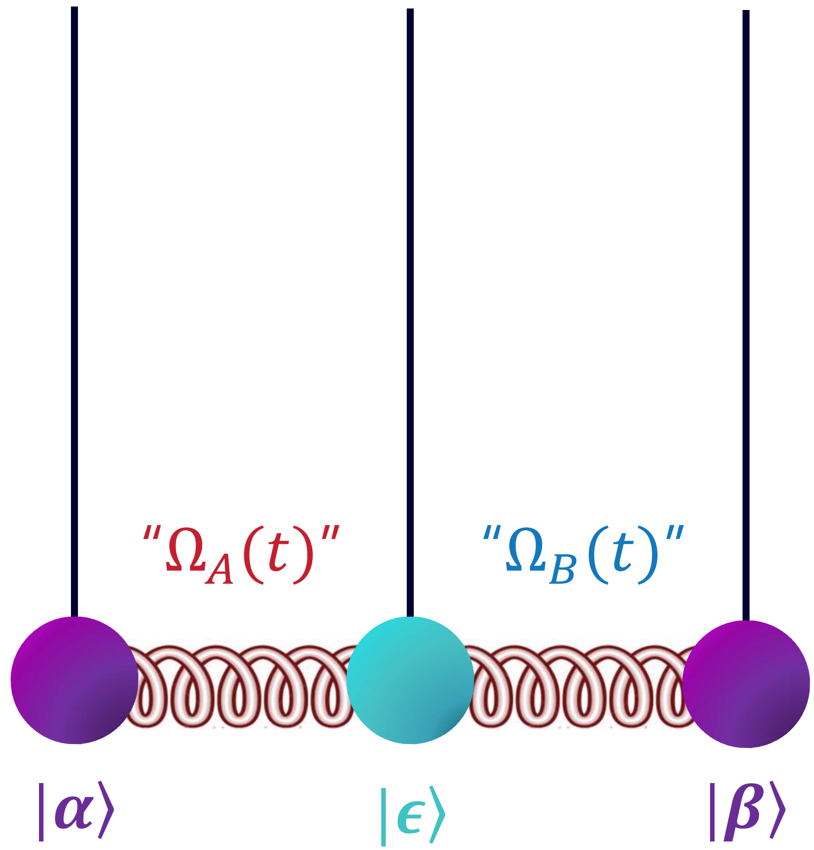
$$|D\rangle = \cos(\theta/2)|\alpha\rangle - e^{i\,\phi}\sin(\theta/2)|\beta\rangle$$

$$\theta = 2\tan^{-1}(\Omega_\alpha/\Omega_\beta)$$

$$\phi = \arg(\Omega_\alpha/\Omega_\beta)$$

Superposition that does not absorb light!

Dark State → anti-symmetric normal mode



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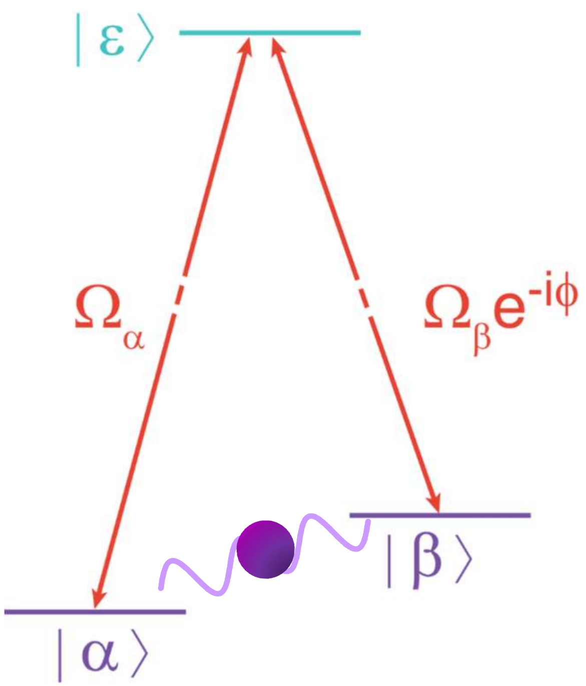
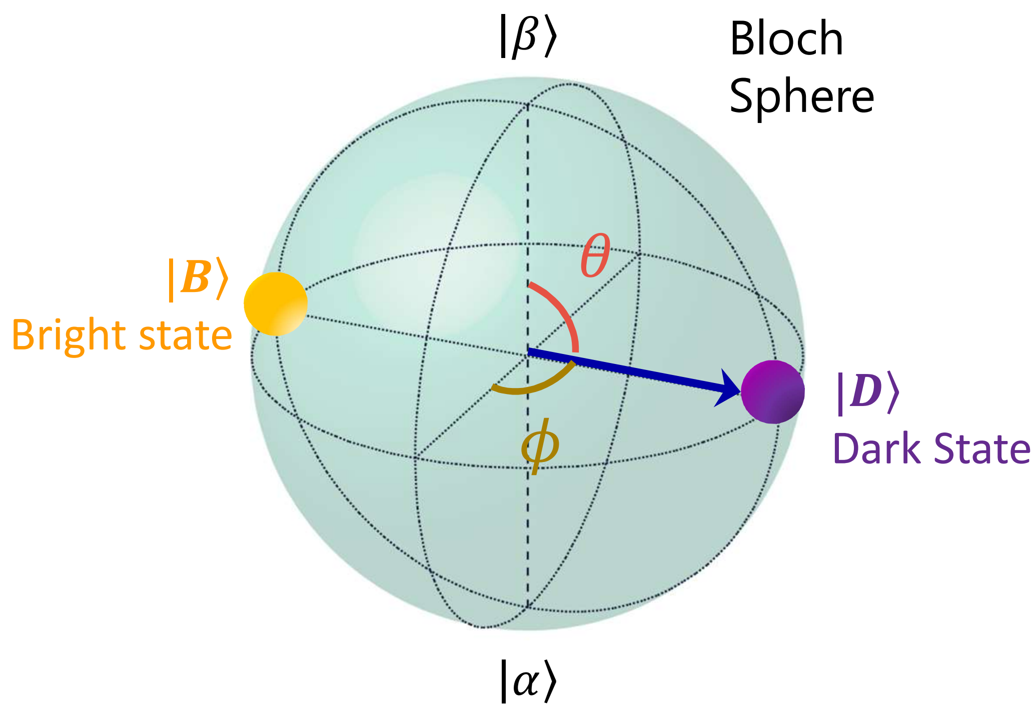




$$|D\rangle = \cos(\theta/2)|\alpha\rangle - e^{i\phi}\sin(\theta/2)|\beta\rangle$$

$$\theta = 2\tan^{-1}(\Omega_\alpha/\Omega_\beta)$$

$$\phi = \arg(\Omega_\alpha/\Omega_\beta)$$

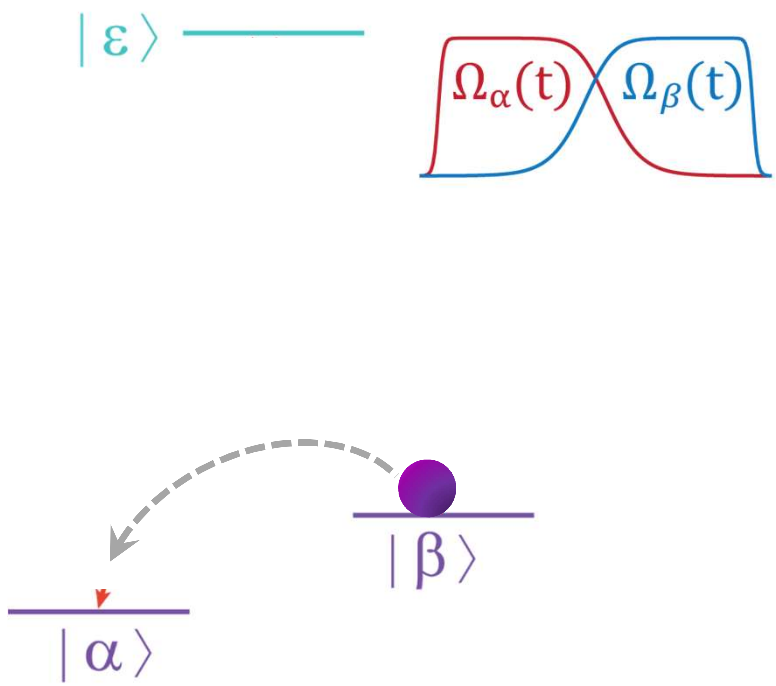
Superposition that does not absorb light!

STIRAP:

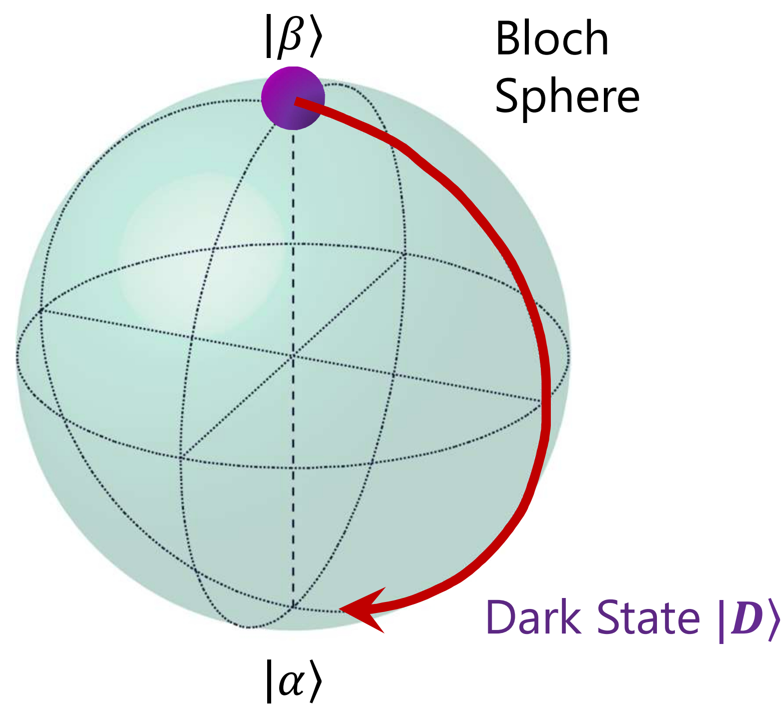
Bergmann *Rev. Mod. Phys.* 70 (1998).
Yale*, Heremans*, Zhou* *Nature Photon.* 10 (2016).
Golter *Phys Rev Lett* 112 (2014).

Application: STIRAP

Evolve **dark state** as a function of time by evolving the phase and amplitude of 2 optical fields:



No excitations if fields are changed adiabatically!



$$|\boldsymbol{D}\rangle = \cos(\theta/2)|\alpha\rangle - e^{i\,\phi}\sin(\theta/2)|\beta\rangle$$

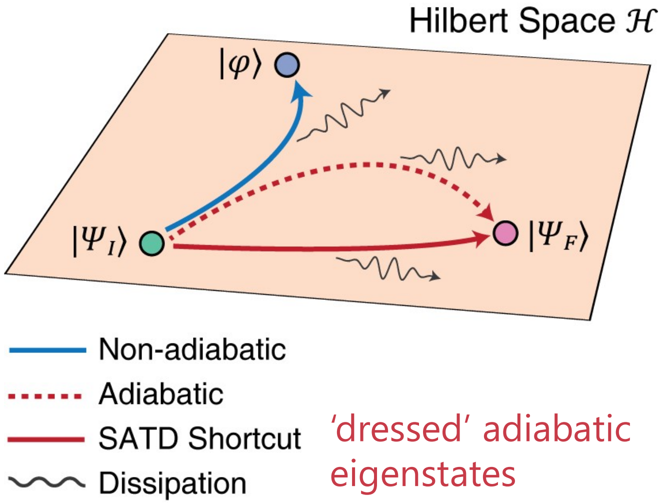
$$\theta = 2\tan^{-1}(\Omega_\alpha/\Omega_\beta)$$

$$\phi = \arg(\Omega_\alpha/\Omega_\beta)$$

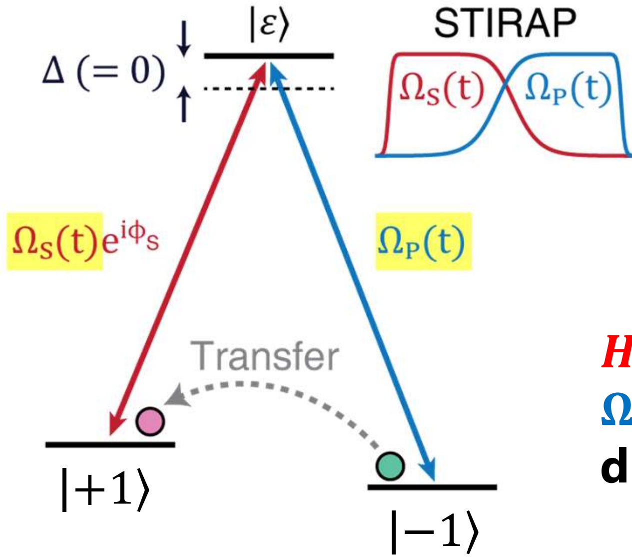
STIRAP:

Bergmann *Rev. Mod. Phys.* 70 (1998).
Yale*, Heremans*, Zhou* *Nature Photon.* 10 (2016).
Golter *Phys Rev Lett* 112 (2014).

A ‘*Shortcut to Adiabaticity*’ for STIRAP



‘dressed’ adiabatic eigenstates

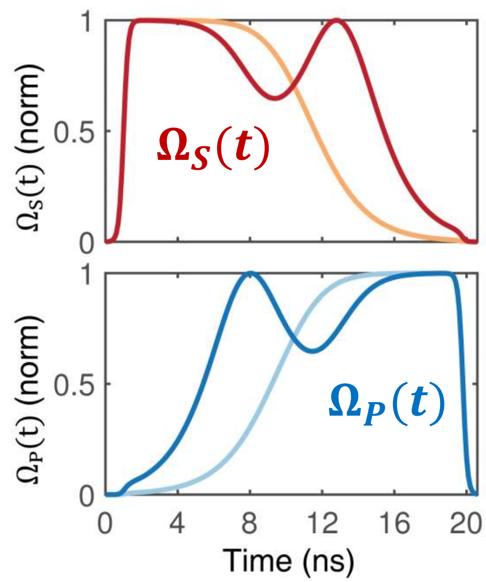


$H_0(t) \rightarrow H_0(t) + H_{SATD}(t)$

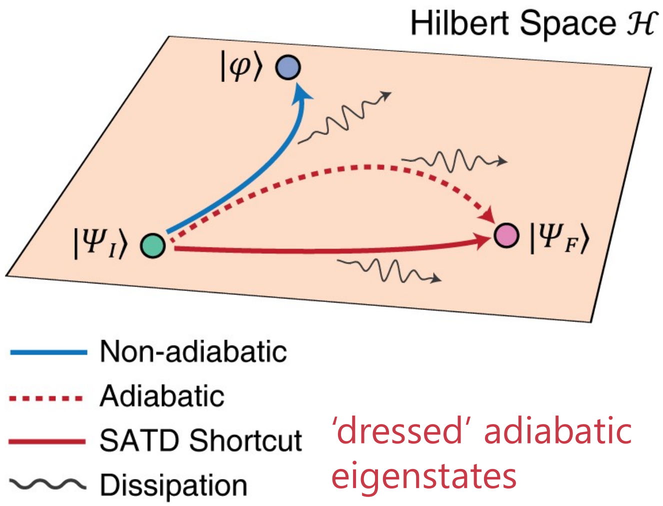
Optimal adiabatic shape
$\Omega_S^2(t)+\Omega_P^2(t) = C$
Vasilev *PRA* 80 (2009)

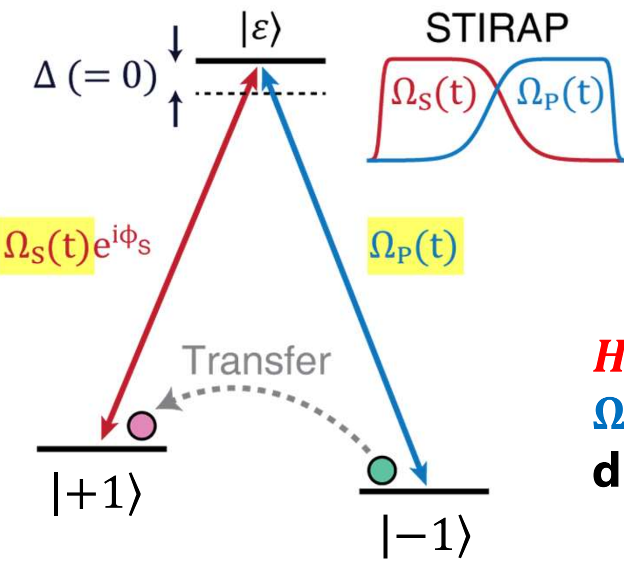
$H_{SATD}(t)$ modifies Ω_S and Ω_P, but **involves $|\varepsilon\rangle$ in dressed state dynamics.**

Task: shape two optical pulses.
Race against excited state decoherence (T_1 ~ 12 ns)!



A *'Shortcut to Adiabaticity'* for STIRAP





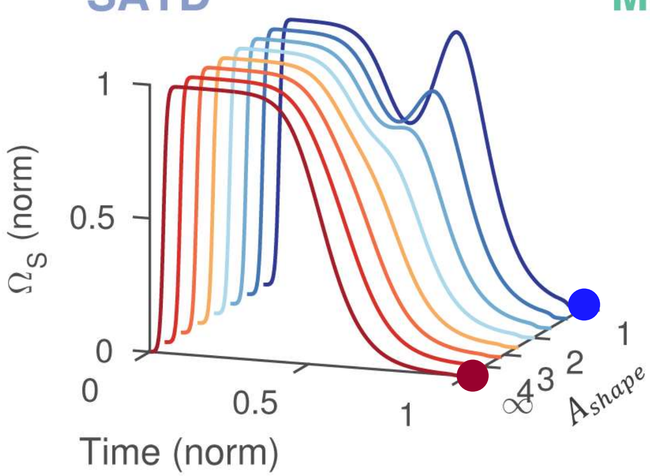
$H_0(t) \rightarrow H_0(t) + H_{SATD}(t)$

Optimal adiabatic shape
$\Omega_S^2(t)+\Omega_P^2(t) = C$
Vasilev *PRA* 80 (2009)

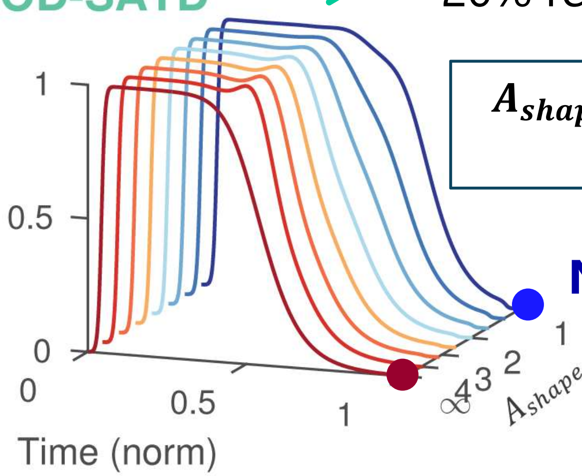
$H_{SATD}(t)$ modifies Ω_S and Ω_P, but **involves $|\varepsilon\rangle$ in dressed state dynamics.**

Two choices ($\widehat{V}(t)'s$) for 'dressed' dark state:

SATD



MOD-SATD → ~20% reduced $|\varepsilon\rangle$ occupation



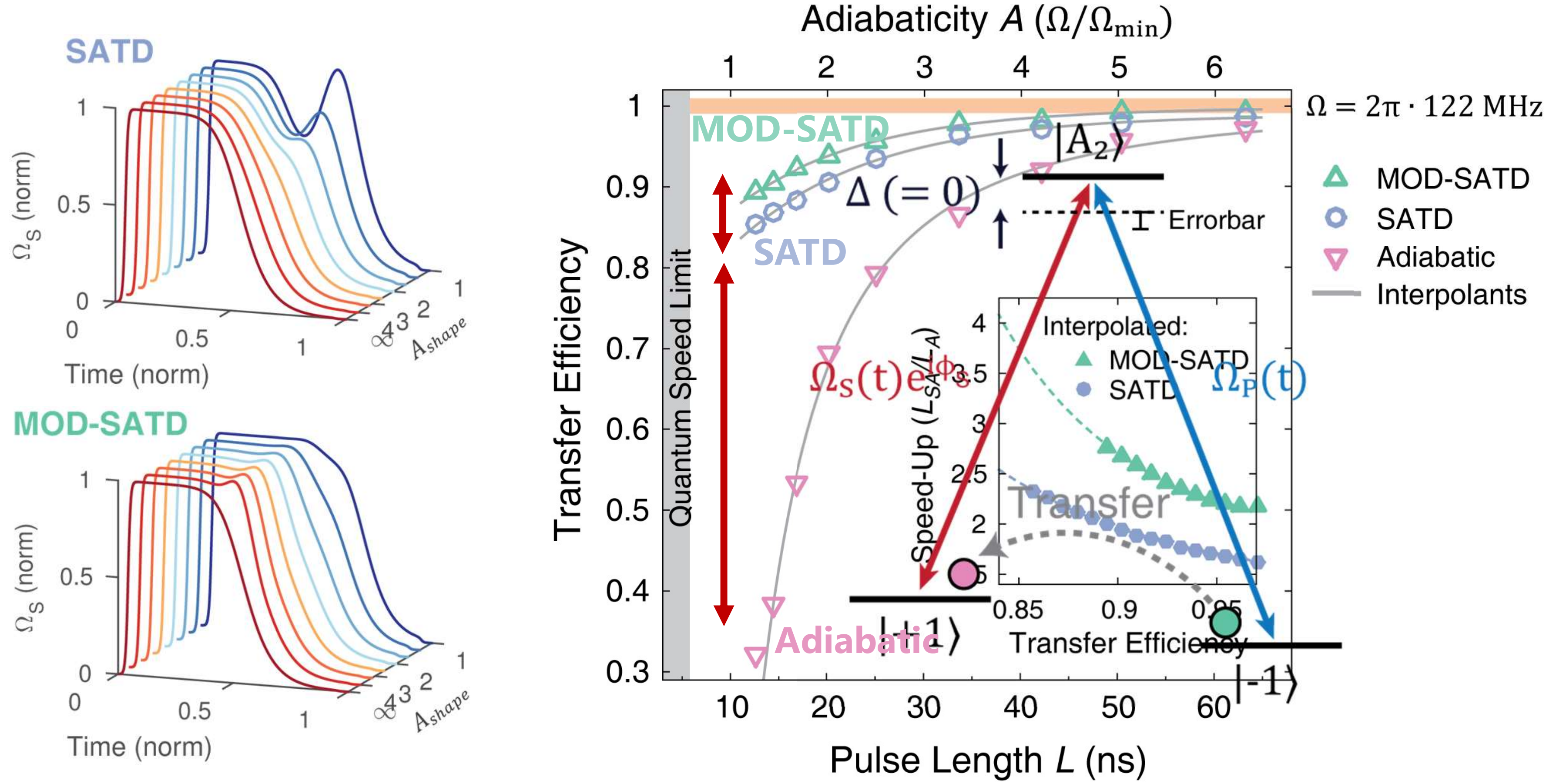
$A_{shape} = \Omega_{shape}/\Omega_{min}$
$\approx$ **Energy Gap $*$ Duration**

Non-adiabatic (*Ashape* = 1)

Adiabatic (*Ashape* = ∞)

Accelerated State Transfer with STIRAP

Transfer efficiency vs speeding up protocol:
MOD-SATD is 3x faster than the adiabatic protocol to reach 90% transfer.



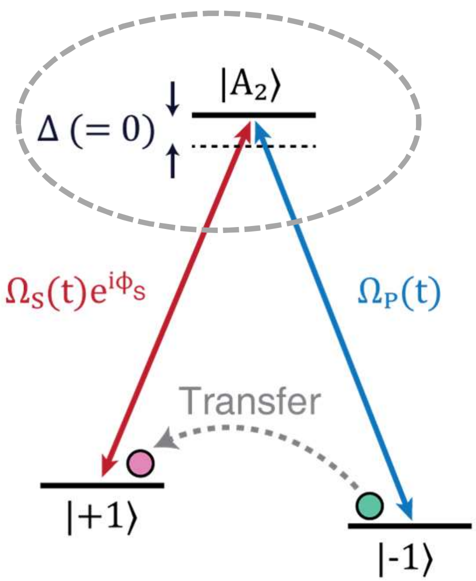
$A_{shape} \approx$ **Energy Gap** $(\Omega) *$ **Duration (L)**

Constant optical power   Vary protocol duration

Accelerated State Transfer with STIRAP

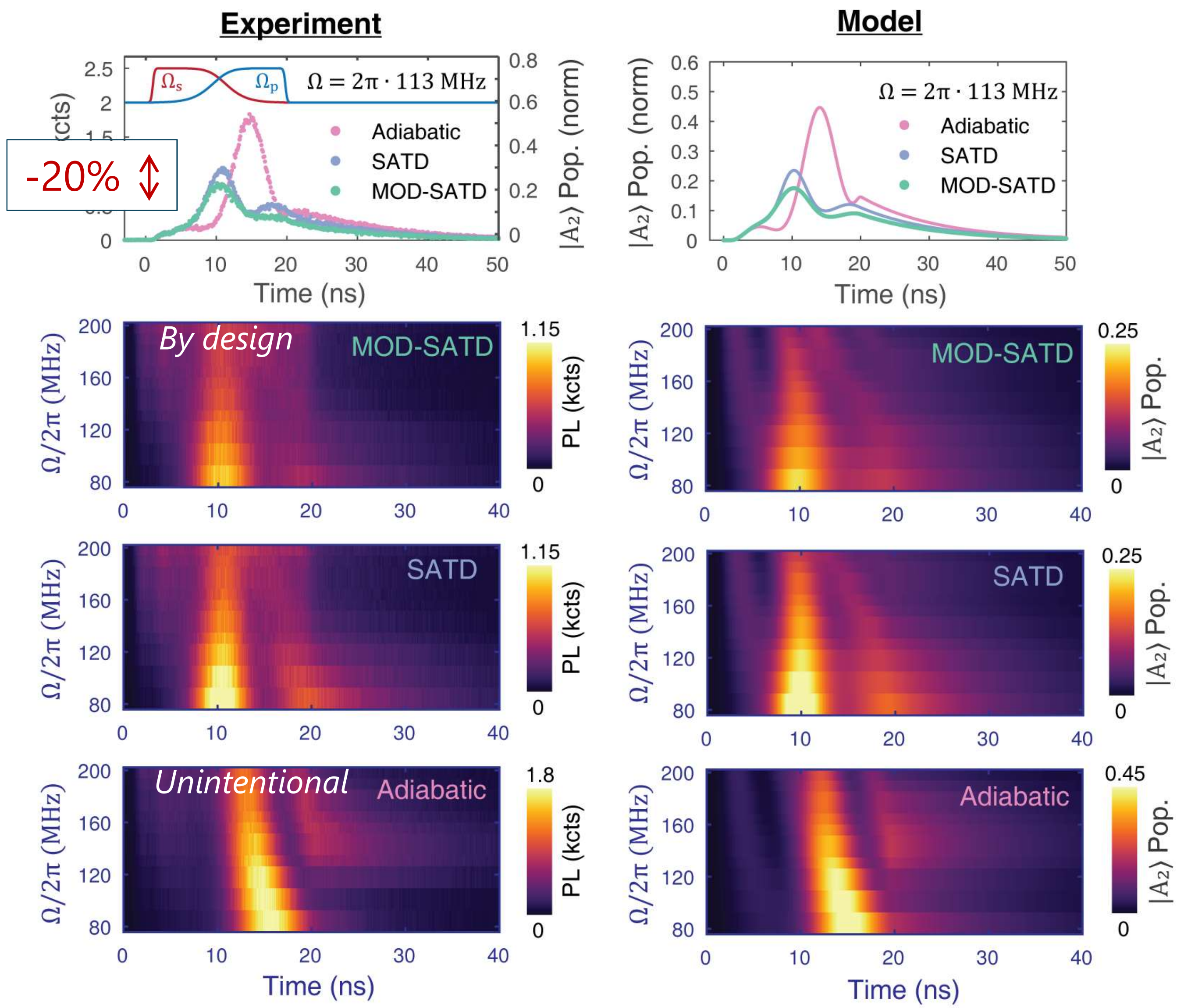
Time-Resolved Excited State Population:

Source of infidelity:



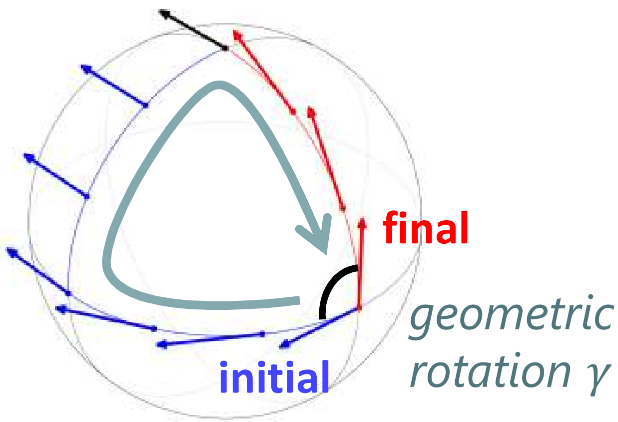
MOD-SATD > SATD
≫ Adiabatic

Dynamics working
as designed!



Geometric Phases in Physics

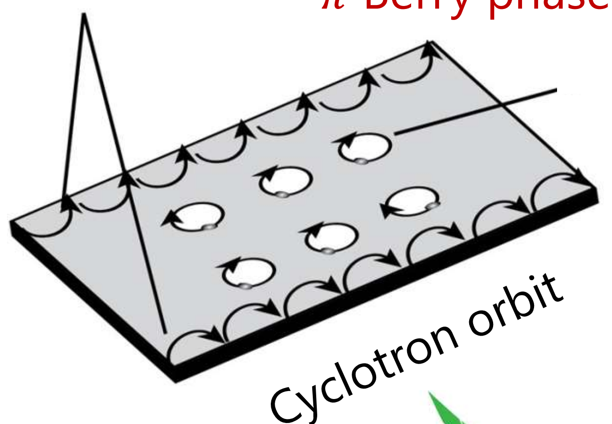
Classical Parallel Transport



Intrinsic to cyclic evolution, reflecting the underlying geometry of the space.

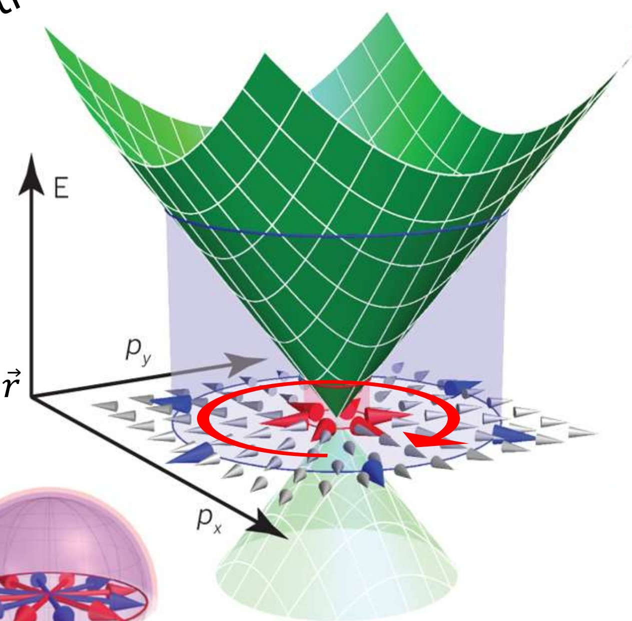
Quantum Electronic Wavefunctions

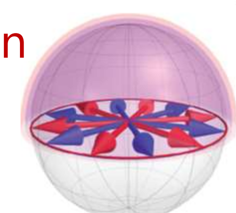
π Berry phase for graphene



$$\psi_{\vec{k}}(\vec{r}) \sim \begin{pmatrix} A(\vec{k}) \\ B(\vec{k}) \end{pmatrix} \cdot e^{i\vec{k}\cdot\vec{r}}$$

pseudospin



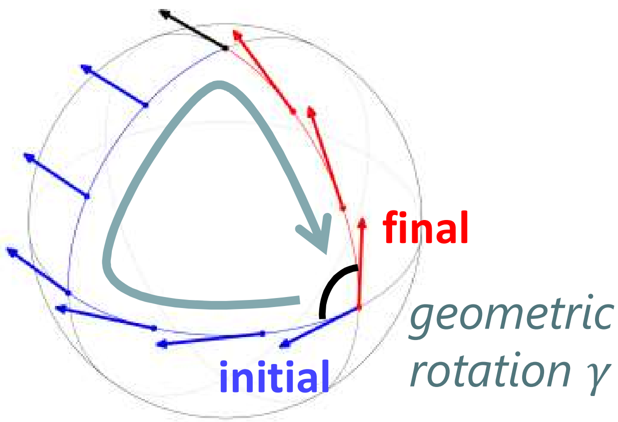


momentum space

2-component Bloch wavefunction
– sublattice degree of freedom

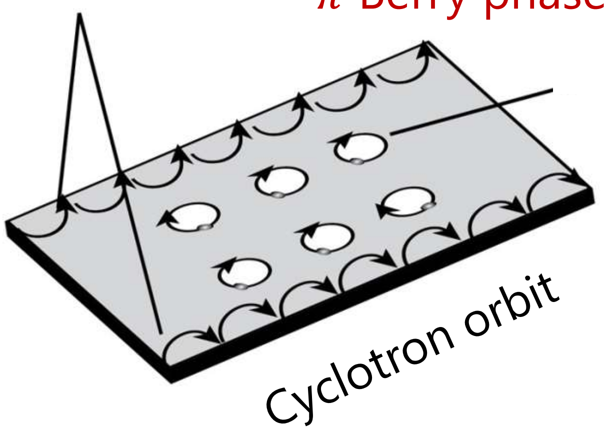
Geometric Phases in Physics

Classical Parallel Transport



Quantum Electronic Wavefunctions

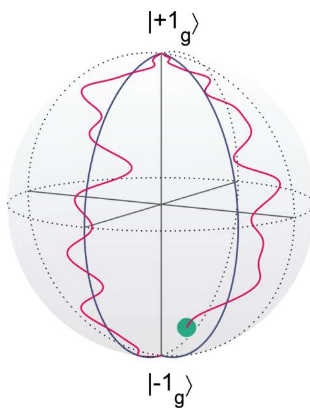
π Berry phase for graphene



Intrinsic to cyclic evolution, reflecting the underlying geometry of the space.

Control cyclic evolutions of a single quantum system (real spin)!

Use geometric phases as robust logic operations.



Leek *Science* 318, 1889 (2007). Berger *PRA* 87, 060303 (2013). Zu *Nature* 514, 72 (2014).

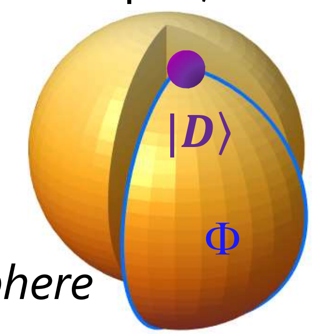
Optically Controlled Berry Phase

Berry Phase

- ***from adiabatic cycle for a two-level system***

C. G. Yale*, F. J. Heremans*, B. B. Zhou*,
D. D. Awschalom et al, *Nat. Photonics* 10, 184 (2016).

Bloch sphere



$|\psi\rangle \to e^{i\gamma}|\psi\rangle$

Phase gate

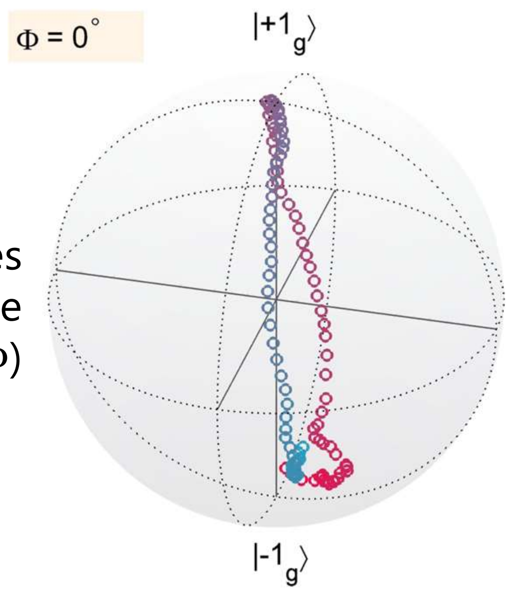
$\gamma = \frac{Solid\ Angle}{2}$

Dark State: $|-1_g\rangle \to |+1_g\rangle \to |-1_g\rangle$

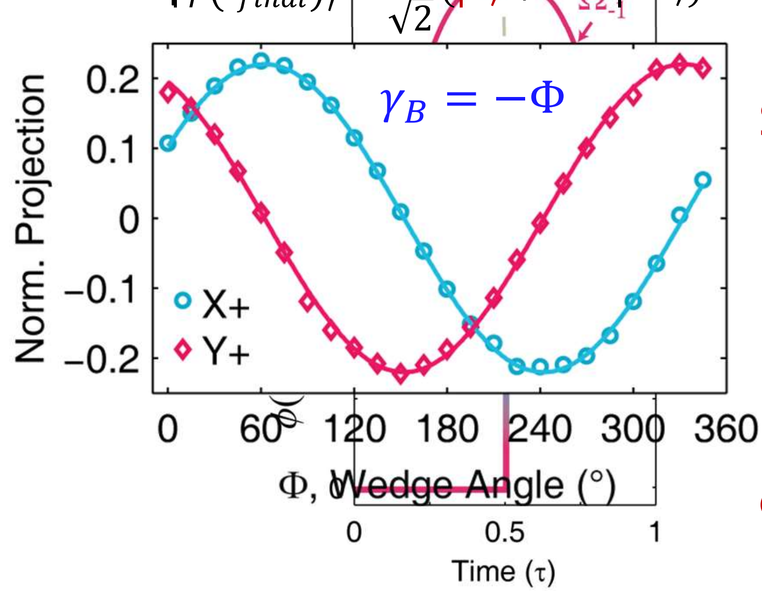
Amplitude:

$|\psi_{final}\rangle = \frac{1}{\sqrt{2}}(|0\rangle + e^{i\gamma_B}|-1\rangle)$

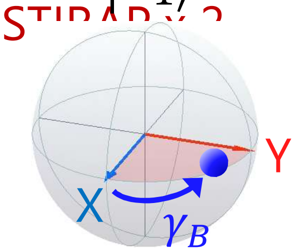
Tangerine slices (vary wedge angle Φ)



Ω = 31 MHz
Δ = 65 MHz



STIRAP x 2



Increment phase opposite pole

$|0\rangle$ **(phase reference)**

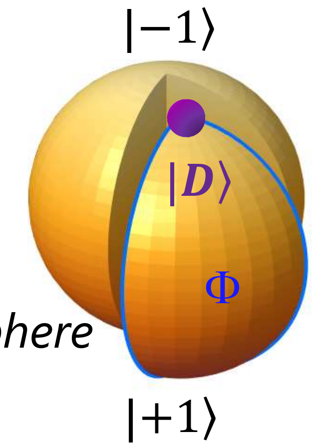
Optically Controlled Berry Phase

Berry Phase

- ***from adiabatic cycle for a two-level system***

C. G. Yale*, F. J. Heremans*, B. B. Zhou*,
D. D. Awschalom et al, *Nat. Photonics* 10, 184 (2016).

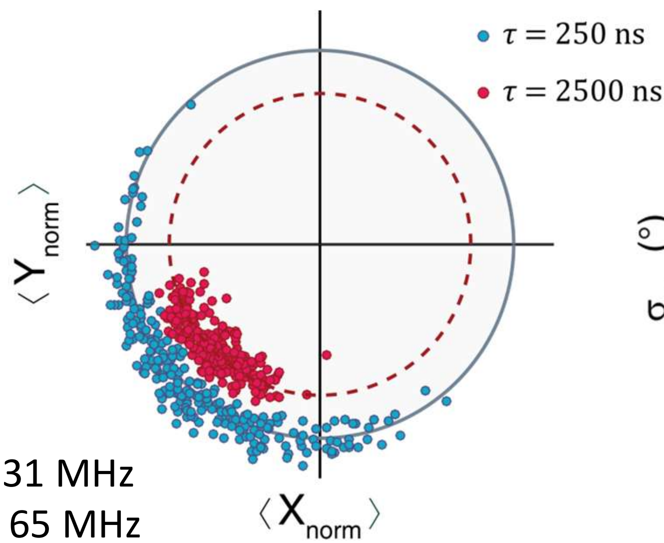
Bloch sphere



$|\psi\rangle \rightarrow e^{i\gamma}|\psi\rangle$

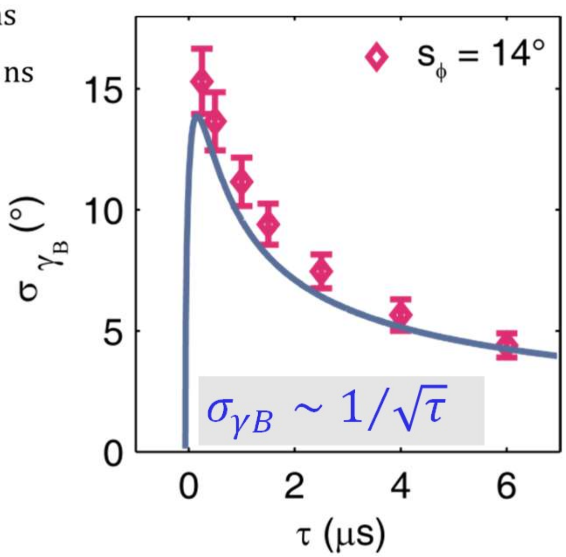
Phase gate

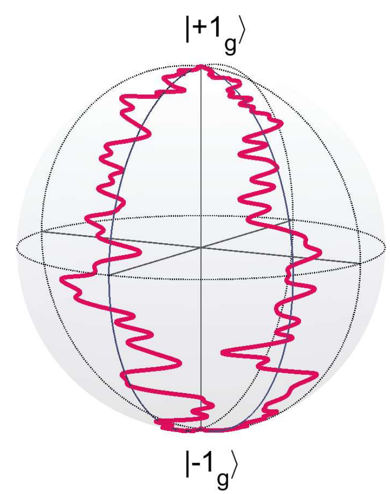
$\gamma = \frac{Solid\ Angle}{2}$



Ω = 31 MHz
Δ = 65 MHz

Noise Bandwidth 3 MHz



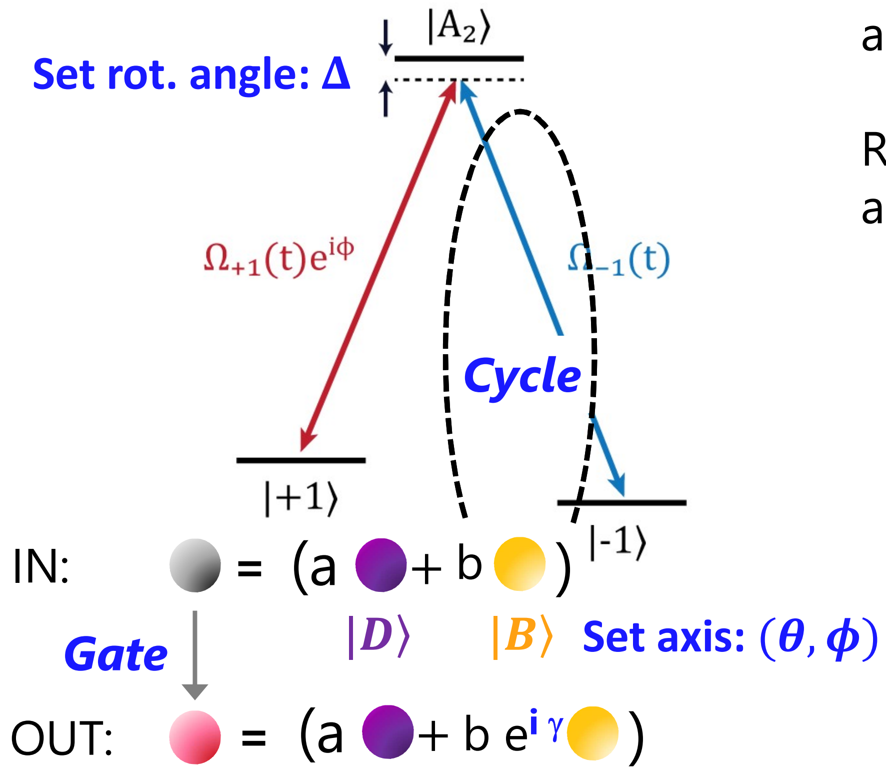


Inject artificial phase noise $\delta\phi$ into laser.

Berry phase robust to noise in long cycle time limit!

Non-Adiabatic Holonomic Quantum Gates

Geometric rotation around arbitrary axis?



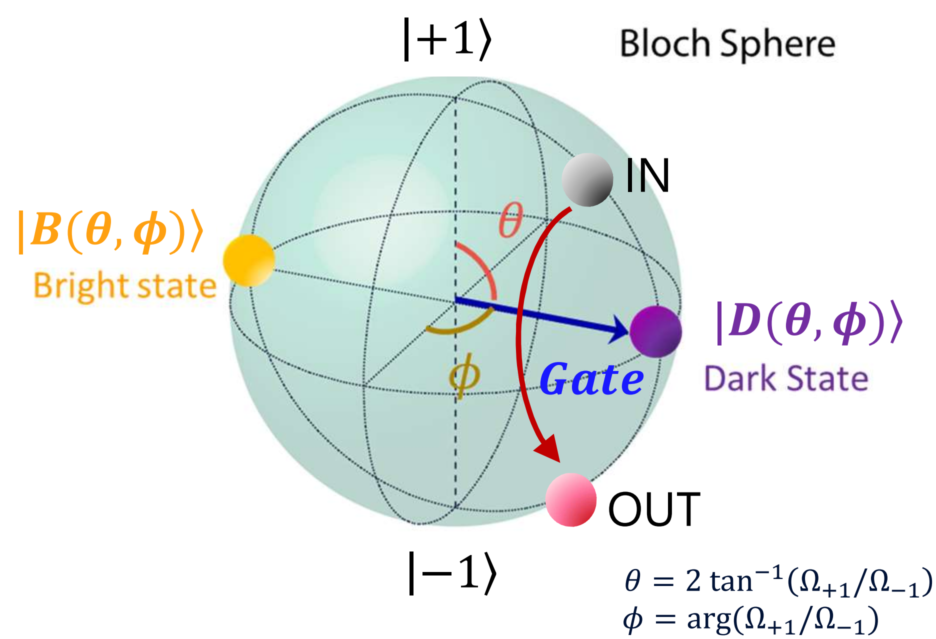
Matrix-valued geometric phase:

$$G = |D\rangle\langle D| + e^{i\gamma}\,|B\rangle\langle B|$$

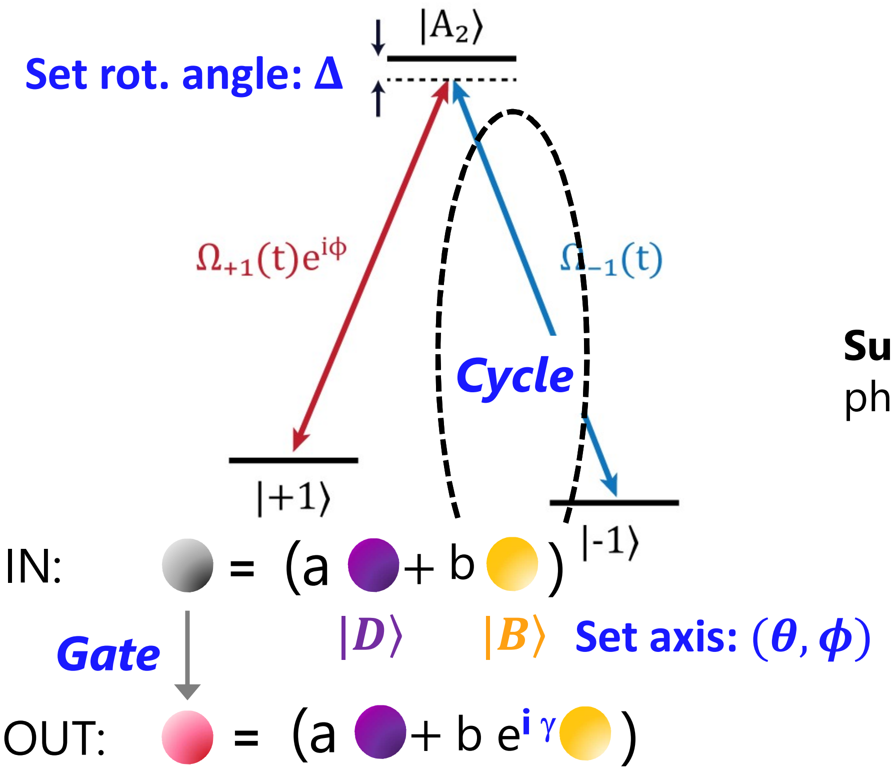
E. Sjöqvist, *Phys. Lett. A* ***380***, 65 (2016):

Use non-adiabatic geometric phase from an optical excitation cycle (in time).

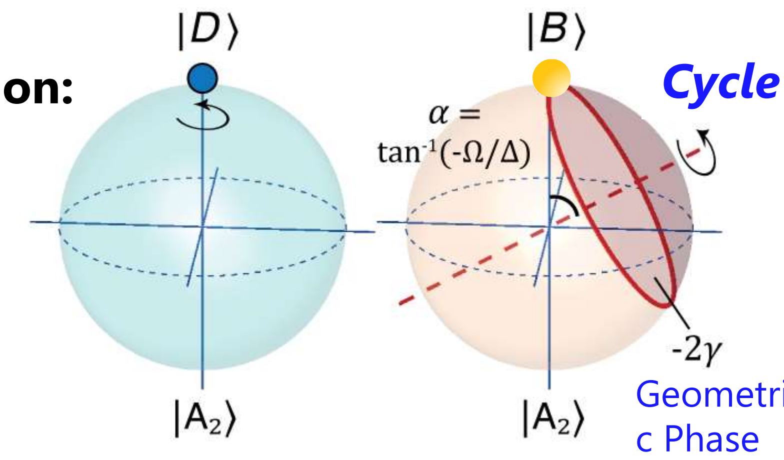
Result is rotation by arbitrary angle around any desired $|B\rangle/|D\rangle$ axis.



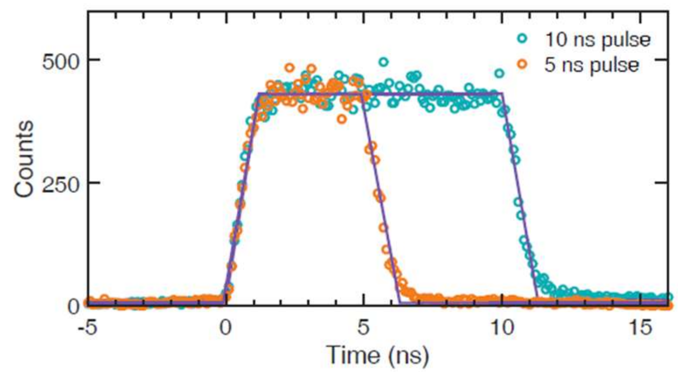
Non-Adiabatic Holonomic Quantum Gates



Geometric interpretation:



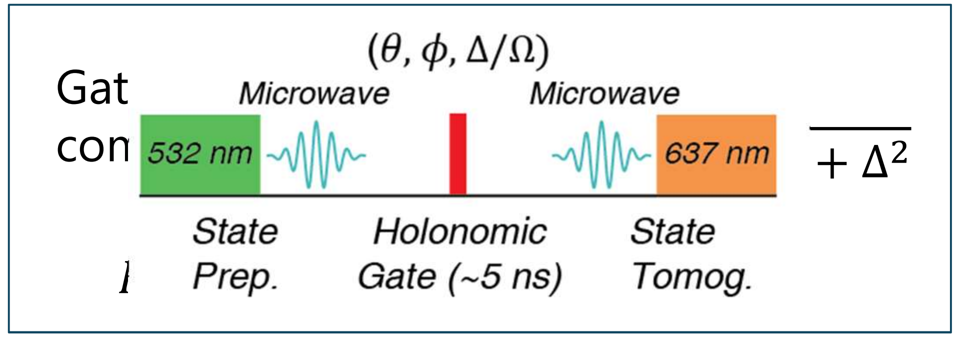
Subtle point: dynamic phases are zero for two-photon resonance and square optical pulses



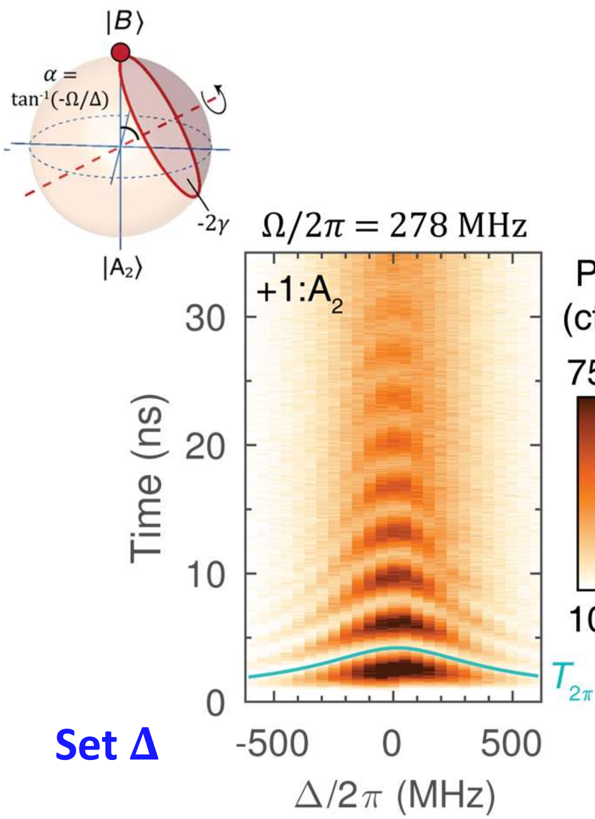
amplitude electro-optic modulator (~1 ns rise time)

Since transformation is **purely geometric** and **non-commuting (non-Abelian)**, they are known as "holonomic" quantum gates.

Experimental

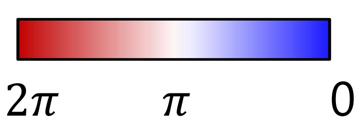


Control over rotation angle:



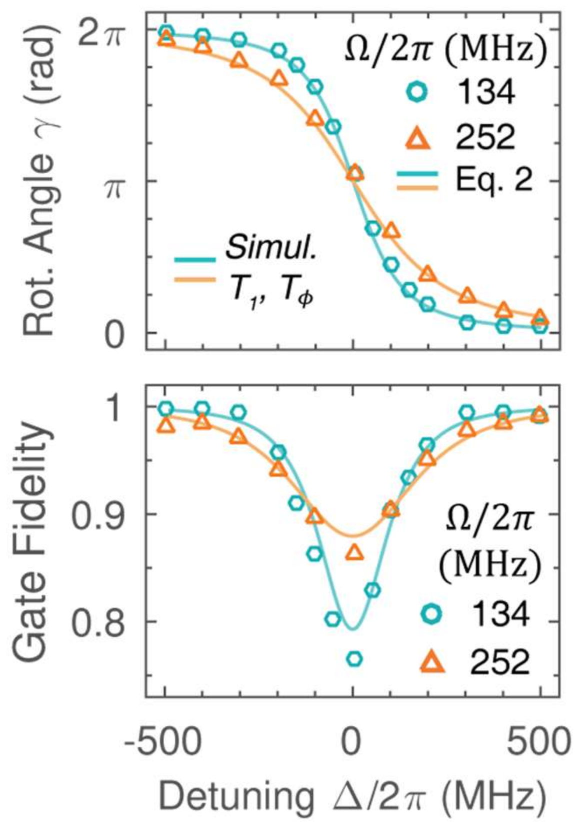
Set Δ

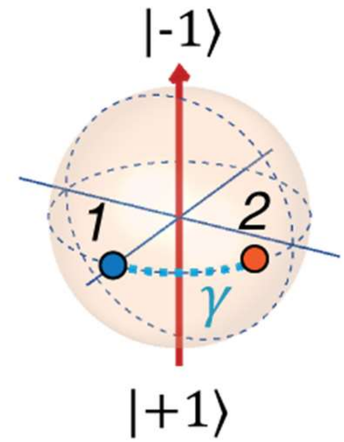
Rotation angle γ



Phase-Shift Gates $Z(\gamma)$

$\theta = 0$





$$\gamma = \pi\left(1 - \frac{\Delta}{\sqrt{\Omega^2 + \Delta^2}}\right)$$

Detuned gates (less maximal excitation, shorter gate time) achieve higher fidelities.

Full Quantum Process Tomography

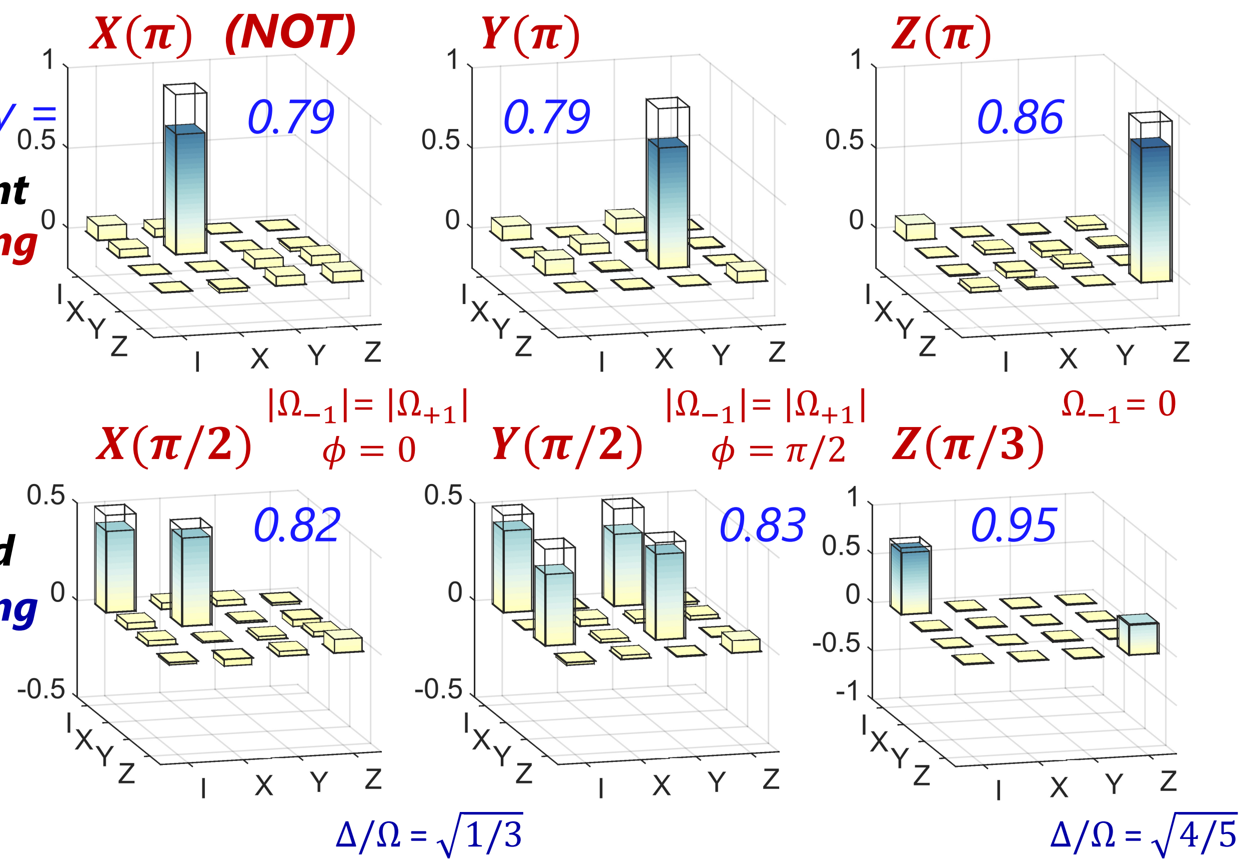
Full control over rotation axis and angle:

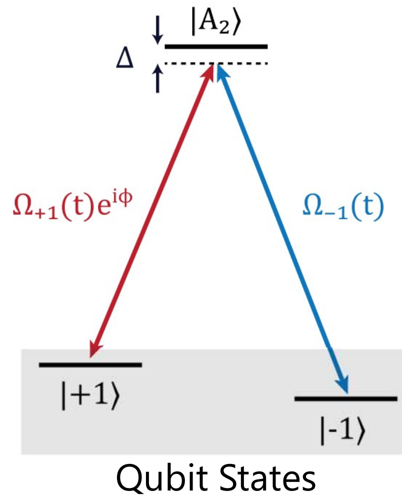
Maximal fidelities F

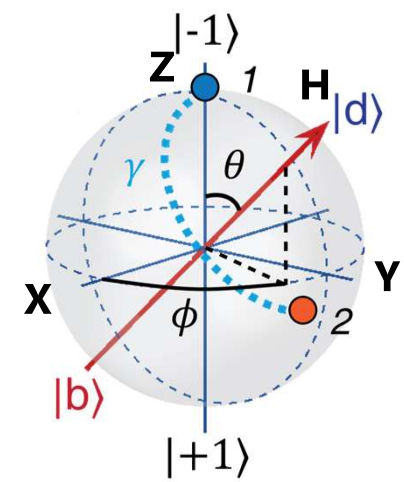
Fidelity =

Resonant Changing (θ, ϕ)

Detuned Changing Δ/Ω







- Gate fidelities limited by excited state decoherence (~12 ns).
- Current gate speeds < 6 ns. Relatively fast/efficient!
- Detuned gates achieve higher fidelities.

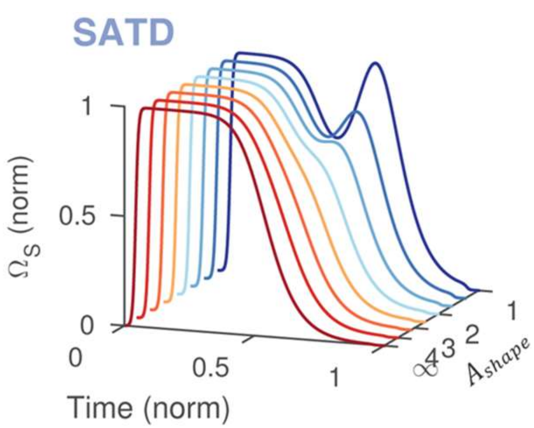
B. B. Zhou et al. *Phys. Rev. Lett.* **119**, 150403 (2017).
See also Sekiguchi et al. *Nat. Photon.* **11**, 309 (2017).

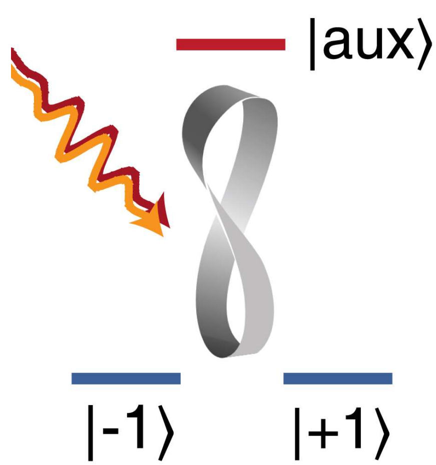
Conclusions

Positions available!

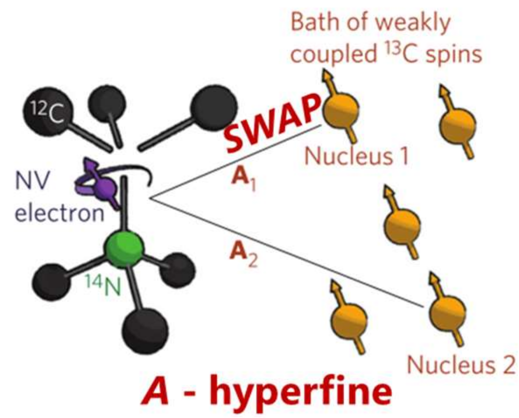
All-optical quantum control with engineered dynamics

- **Accelerated** adiabatic passage (~3x speed-up for STIRAP, fidelities > 0.90)
- **Robust** Berry phases and **efficient/arbitrary** single-qubit gates via geometric phases

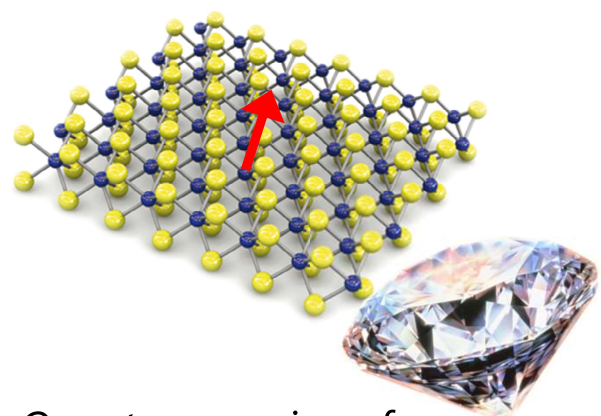




B. B. Zhou et al., *Nat. Phys.* **13,** 330 (2017).
B. B. Zhou et al., *Phys. Rev. Lett.* **119,** 150401 (2017).
C. G. Yale*, F. J. Heremans*, B. B. Zhou*, et al, *Nat. Phot.* **10**, 184 (2016).



Quantum control over multi-qubit registers



Quantum sensing of condensed matter systems