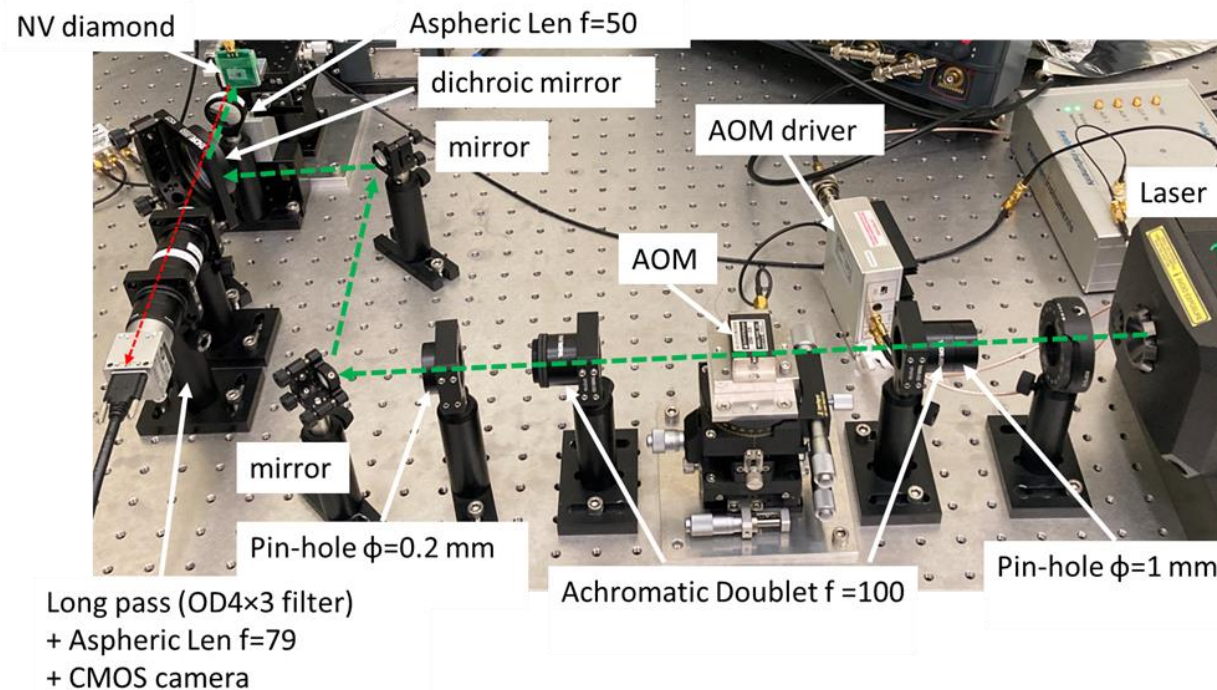




Massachusetts Institute of Technology



International Center for
Quantum-field Measurement Systems for
Studies of the Universe and Particles
WPI research center at KEK



Axion Dark Matter Search with NV Centers: Hybrid-spin decoupling

JHEP 03 (2025) 083
Phys.Rev.D 111 (2025) 7, 075028
APL Quantum 1 (2024) 4, 046106
+ Work in progress

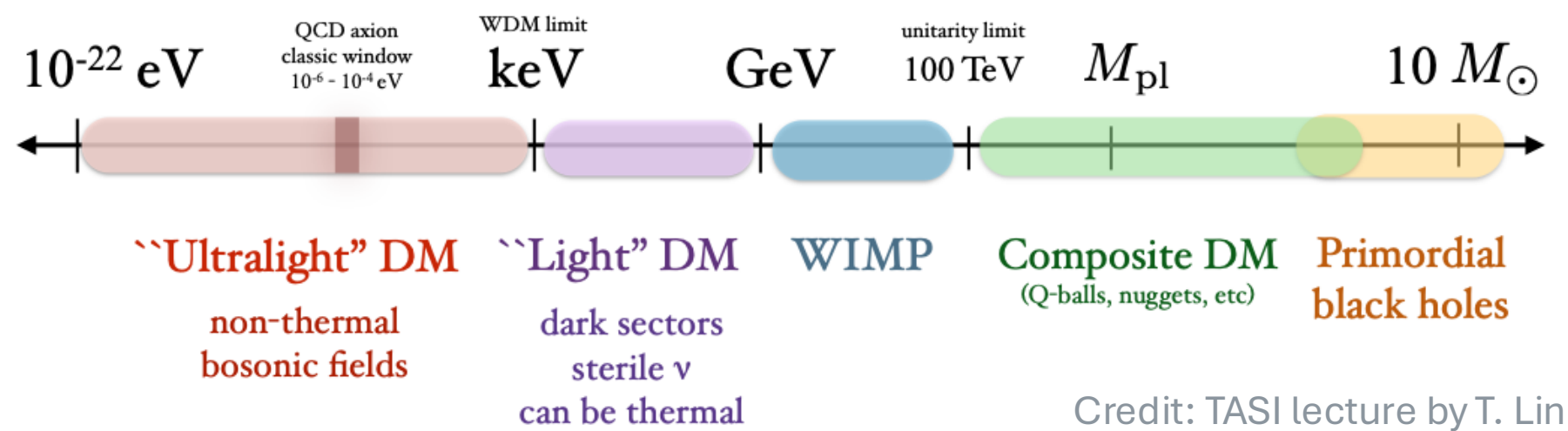
In collaboration with
M. Hazumi, E. D. Herbschleb, N. Mizuochi, K. Nakayama, Y. Matsuzaki

So Chigusa

10/23/2025 @ Brookhaven Forum 2025

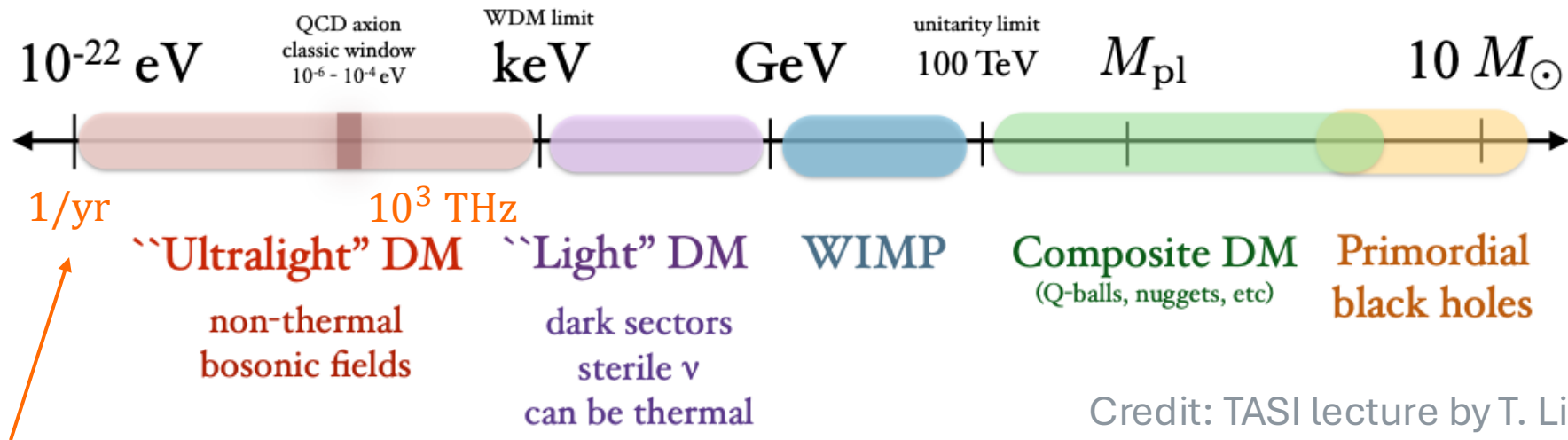
Challenges in DM direct detection

- Faint signal ↔ Need high sensitivity
- Wide mass range ↔ Broadband approaches are desirable



Challenges in DM direct detection

- Faint signal $\leftrightarrow$ Need high sensitivity
- Wide mass range $\leftrightarrow$ Broadband approaches are desirable

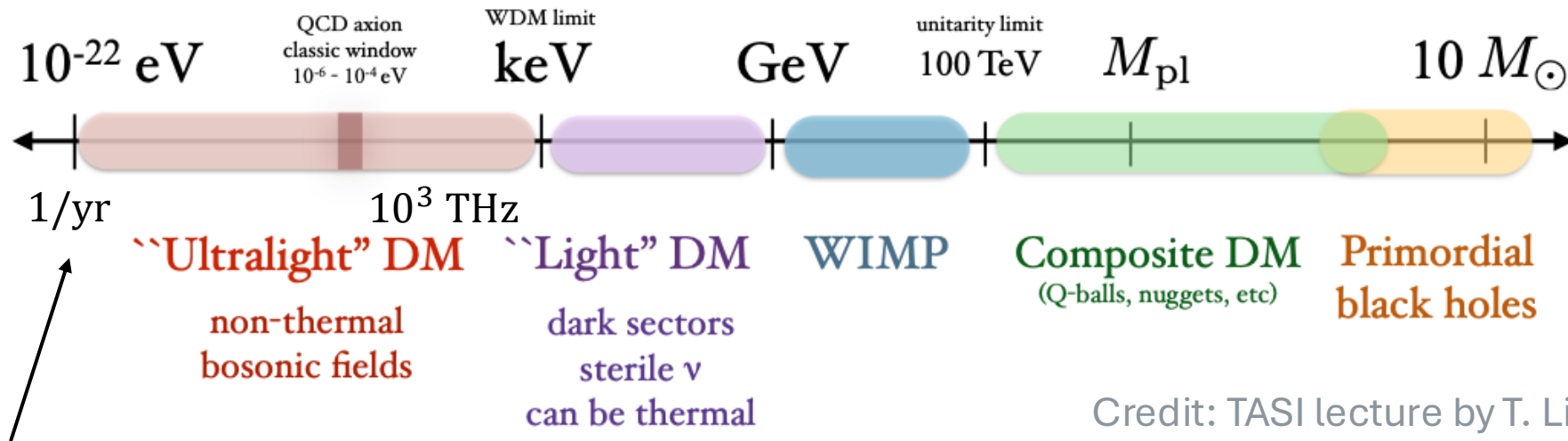


Ex) Axion-induced $\vec{B}_{\text{eff}}$

- $\mathcal{L} = g_{aff} \frac{\partial_\mu a}{2m_f} \bar{f} \gamma^\mu \gamma_5 f \leftrightarrow H_{eff} = \gamma_f \vec{B}_{\text{eff}} \cdot \vec{S}_f$
- $\gamma_f \vec{B}_{\text{eff}} \simeq \sqrt{2\rho_{DM}} \frac{g_{aff}}{m_f} \vec{v}_{DM} \cos(m_a t + \delta)$

Challenges in DM direct detection

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Ex) Axion-induced $\vec{B}_{\text{eff}}$

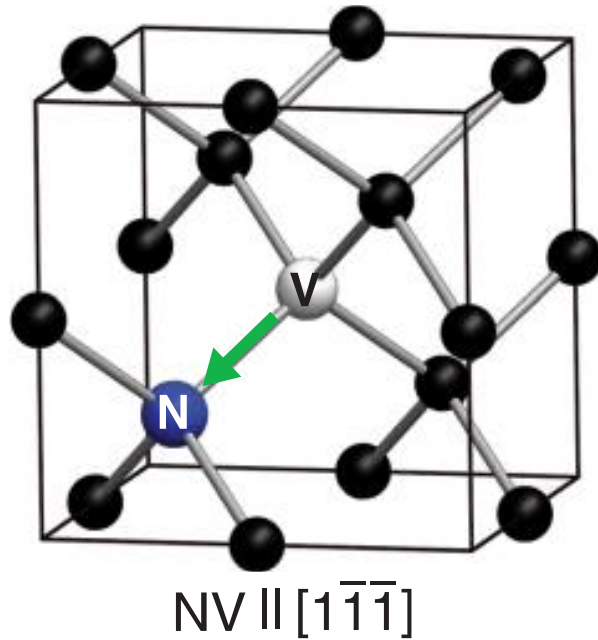
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Can we consider DM-specific “quantum sensing protocols” to overcome these challenges?

NV center in diamond

(a)

L. M. Pham '13



- 2-qutrit system made of e^- -spin and ^{14}N -spin

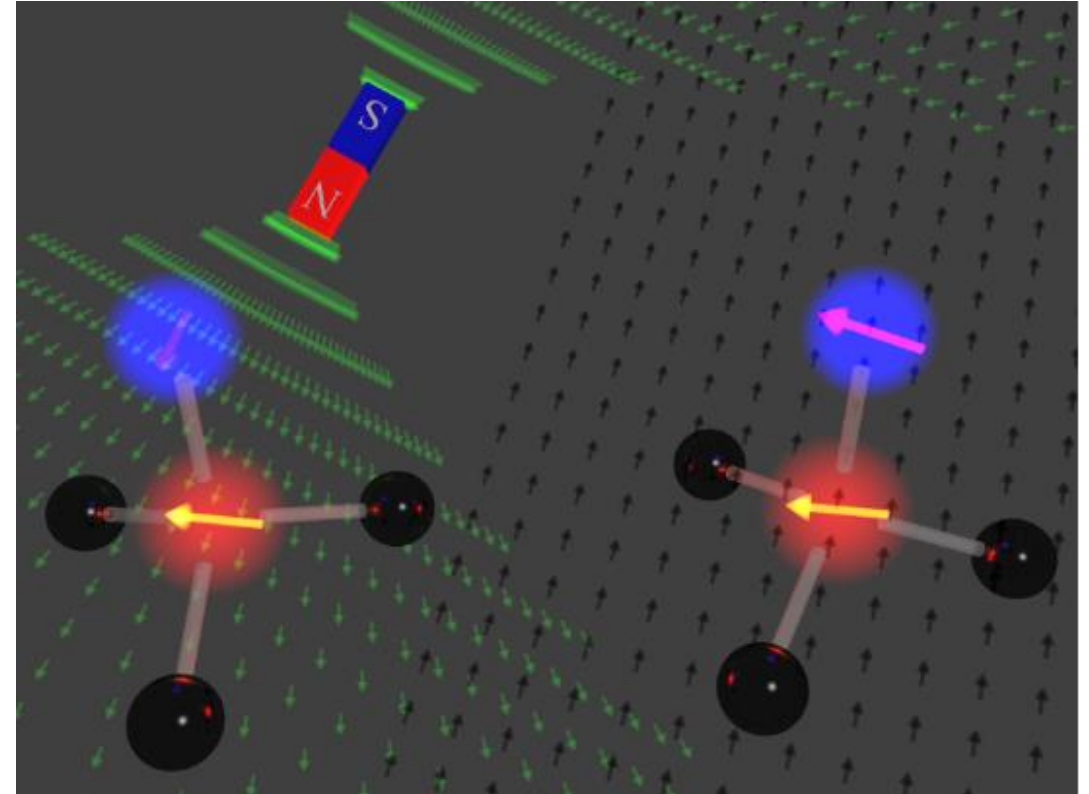
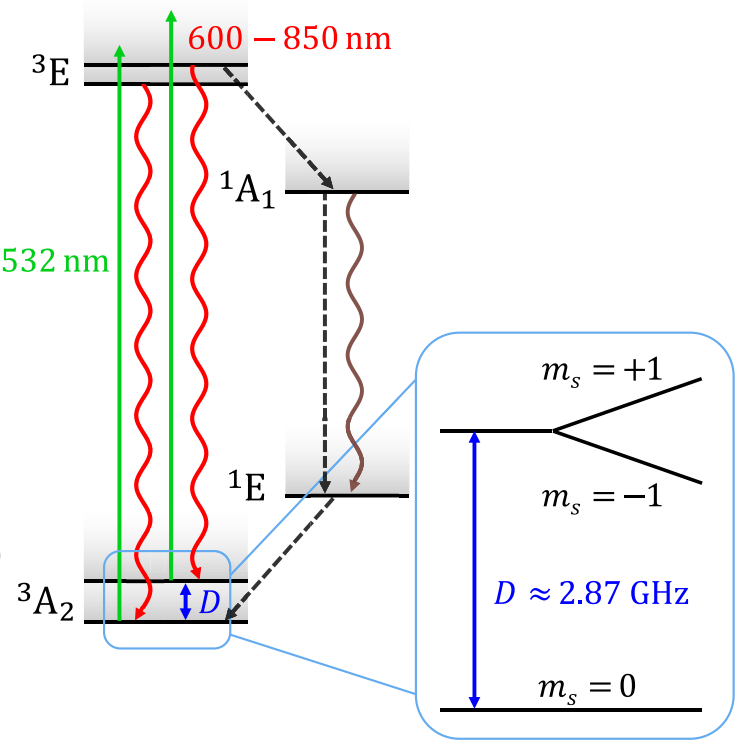


Image credit: [press release from Kyoto University](#)

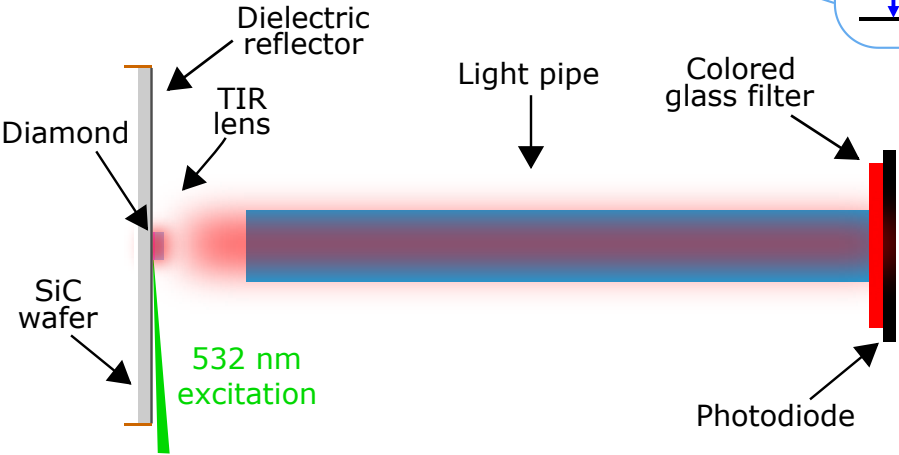


Quantum sensor requisites: measurement & operation

- Fluorescence measurement

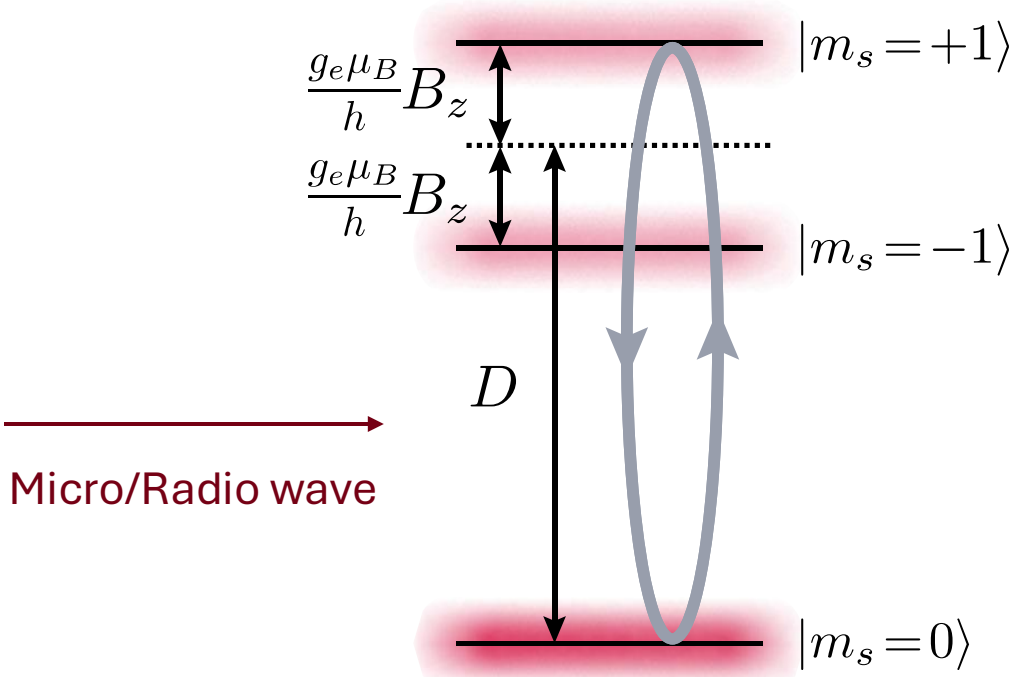


J. M. Schloss, et al. ‘18



J. F. Barry, et al. ‘23

- Rabi oscillation

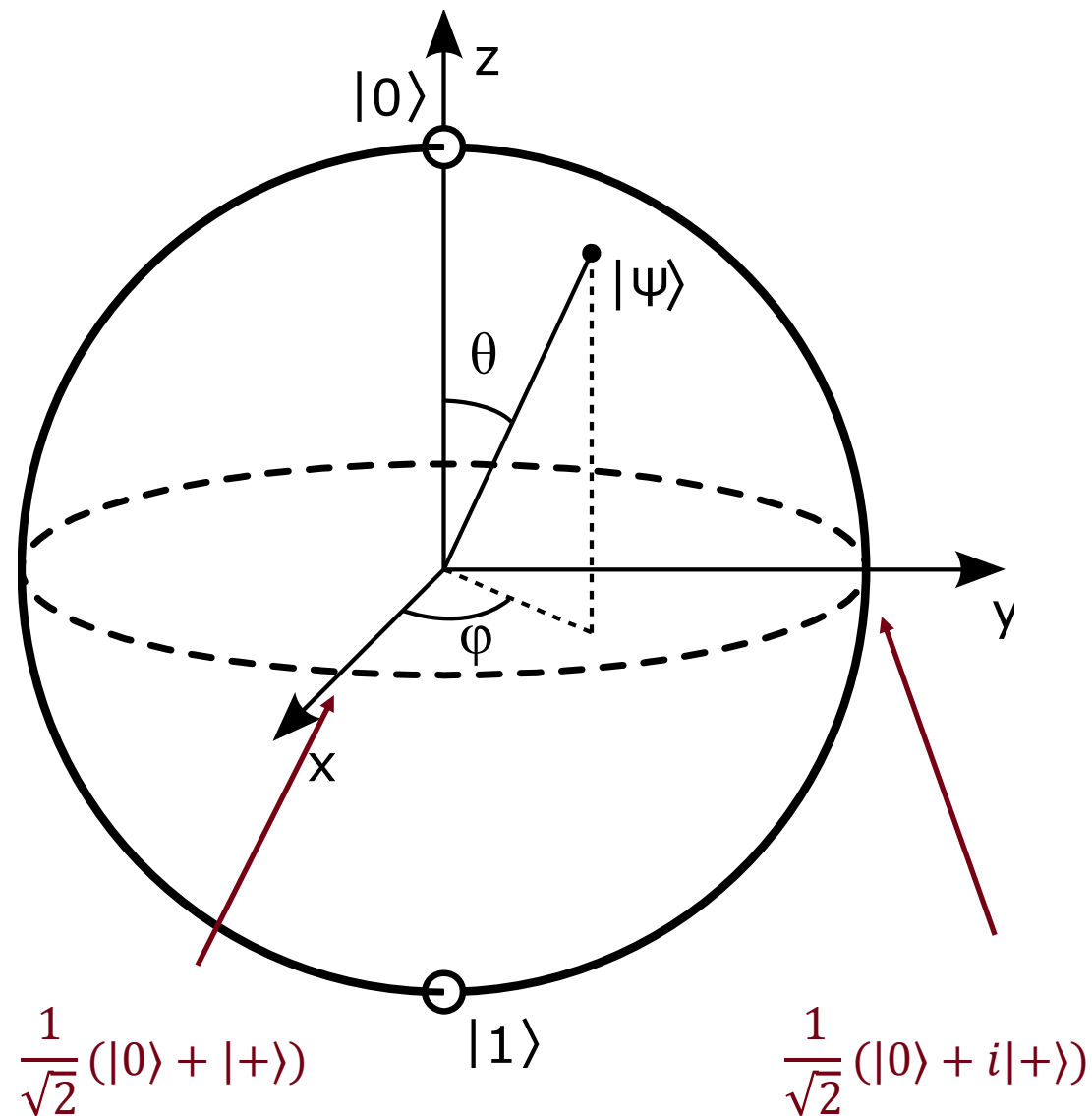


J. F. Barry, et al. ‘20

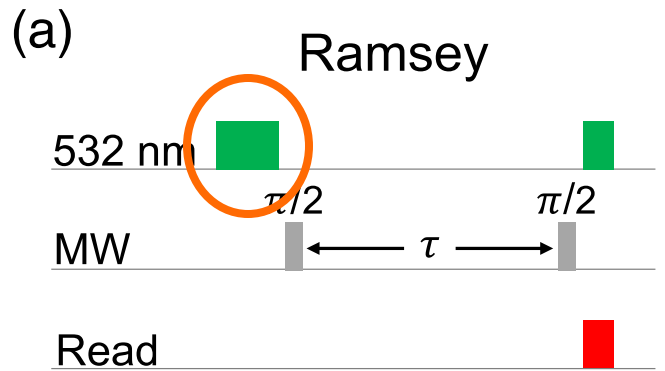
Illustration by Bloch sphere

- A qubit state = A point on Bloch sphere

$$|\psi\rangle = \cos\frac{\theta}{2} |0\rangle + \sin\frac{\theta}{2} e^{i\phi} |+\rangle$$

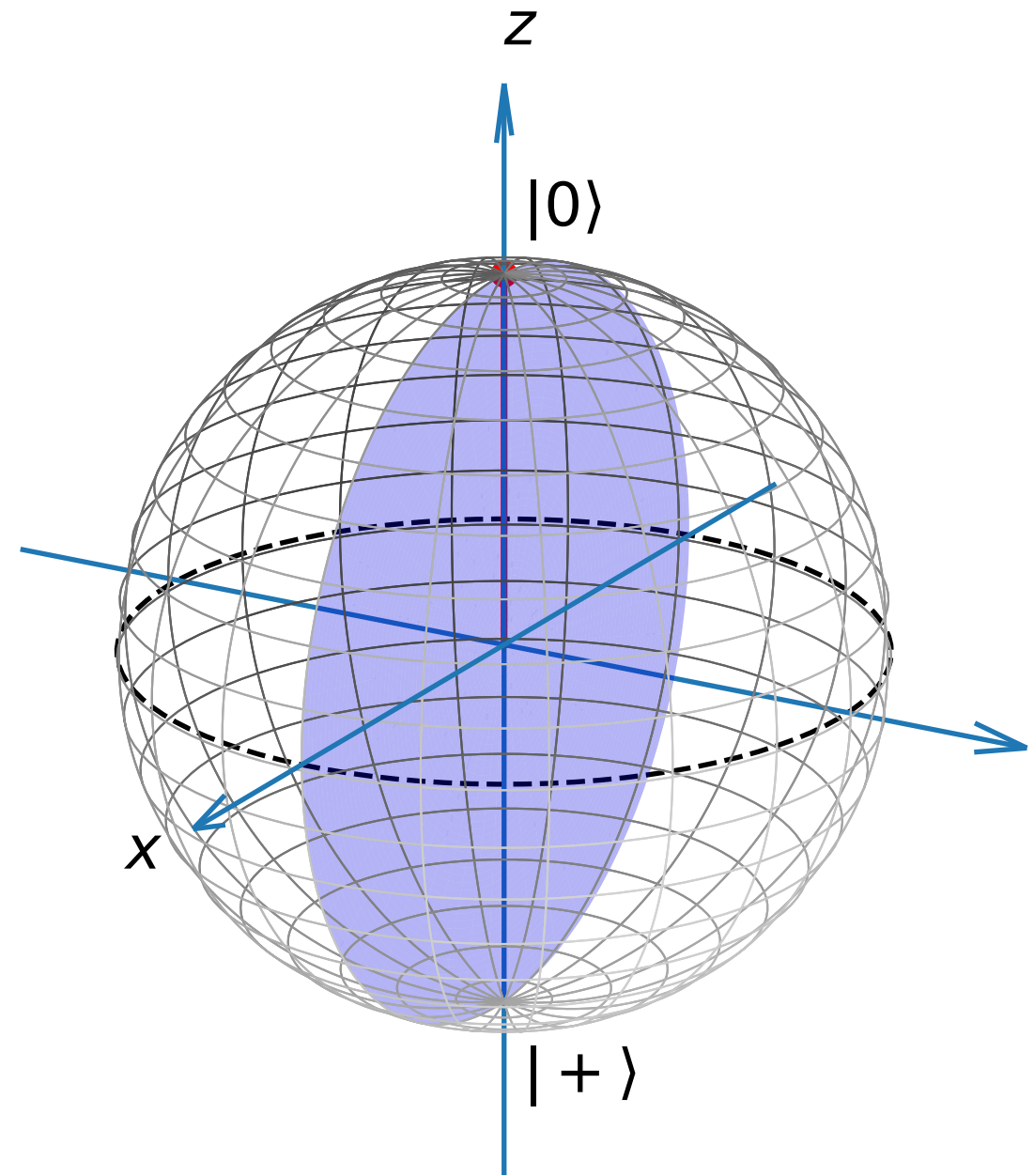
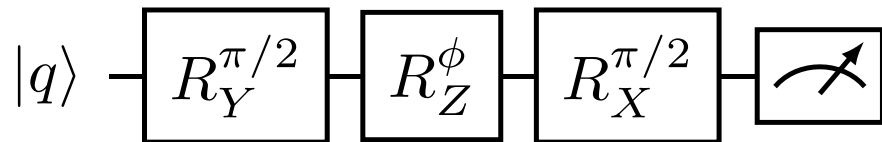


Ramsey protocol

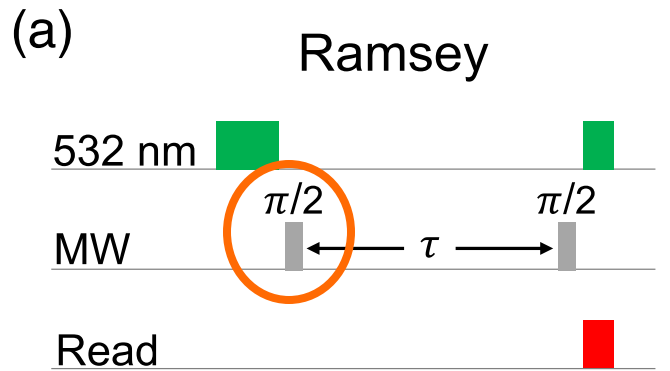


Ramsey

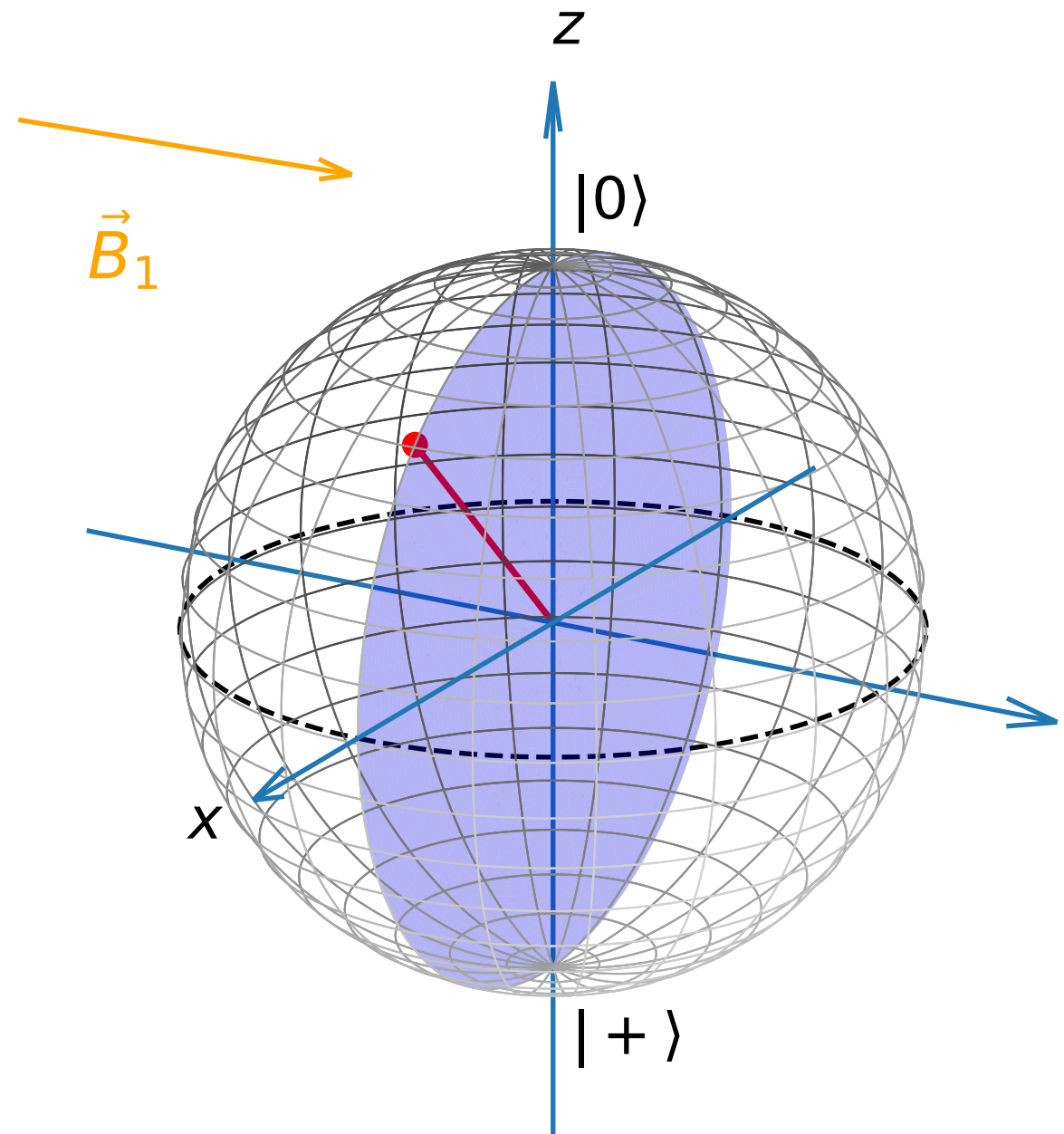
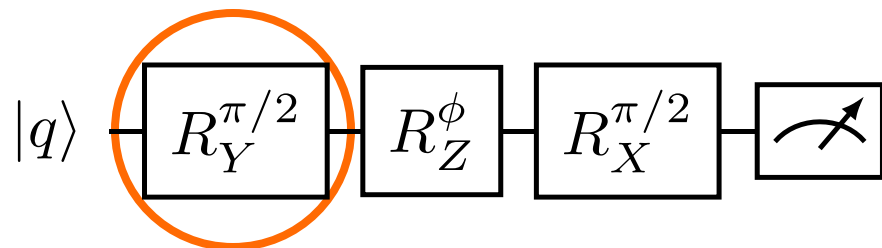
J. F. Barry, et al. '20



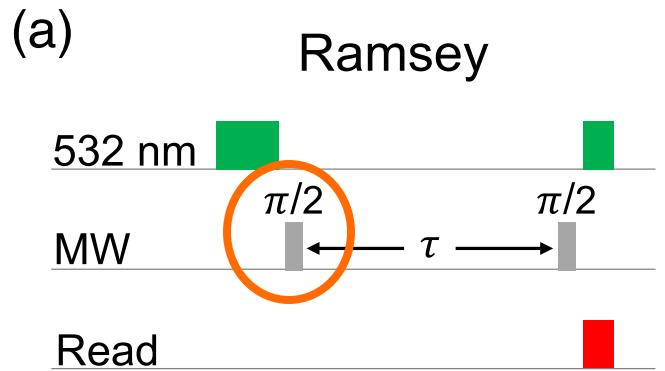
Ramsey protocol



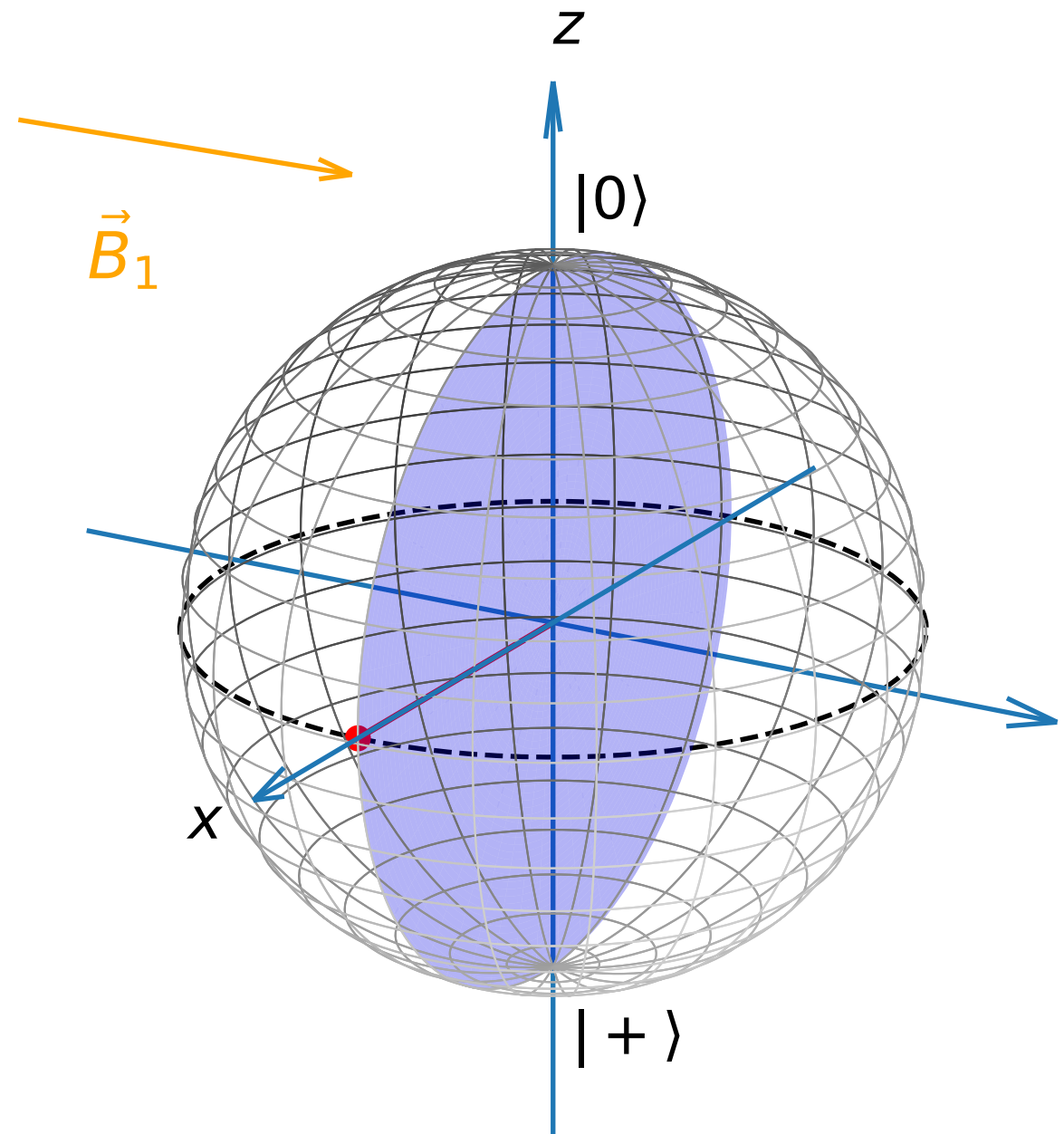
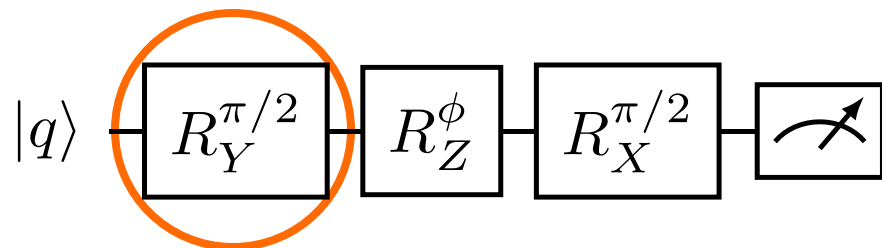
J. F. Barry, et al. '20



Ramsey protocol



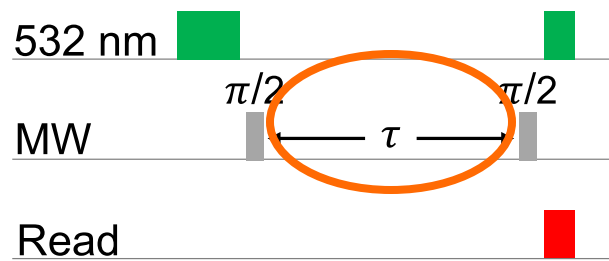
J. F. Barry, et al. '20



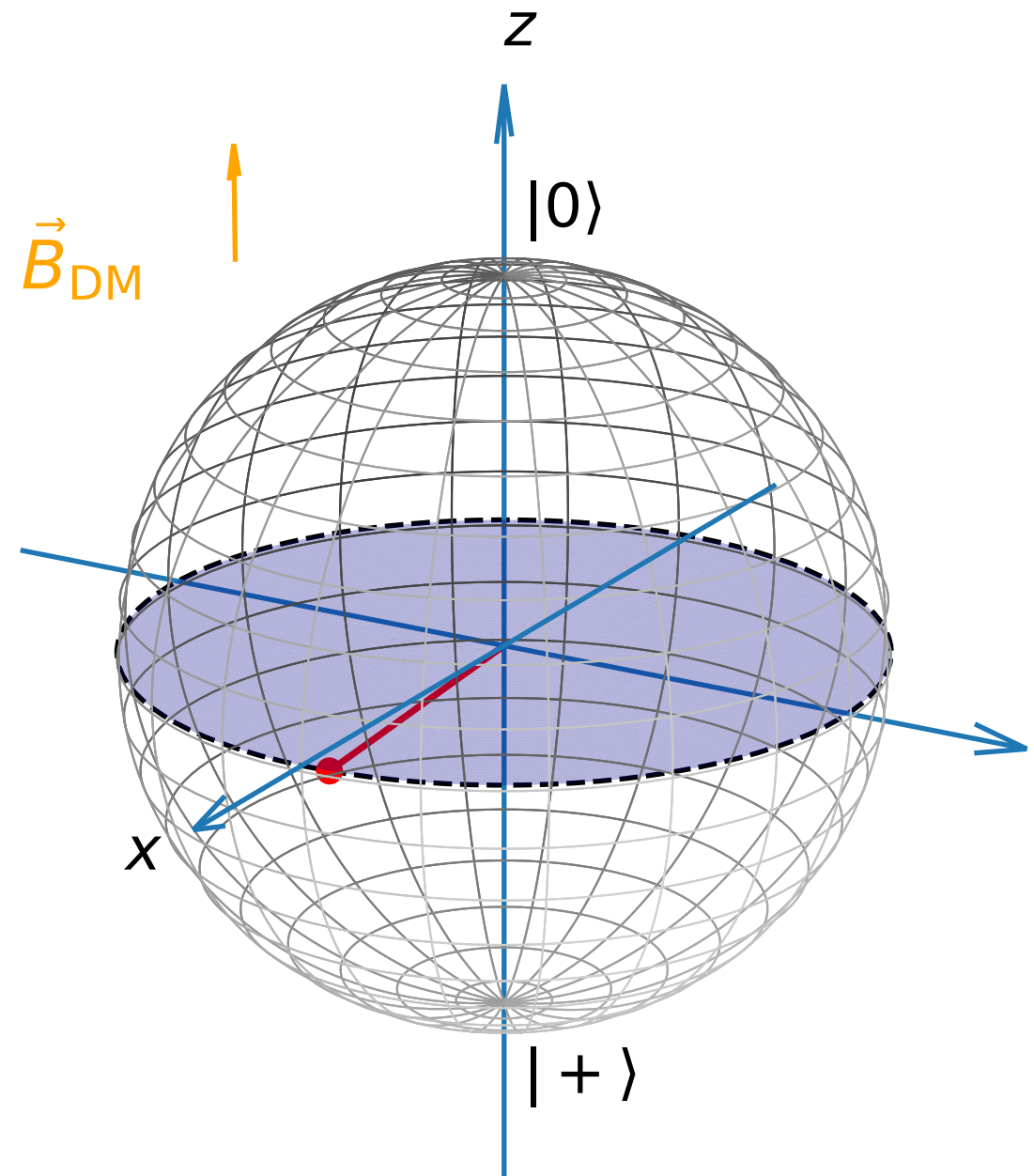
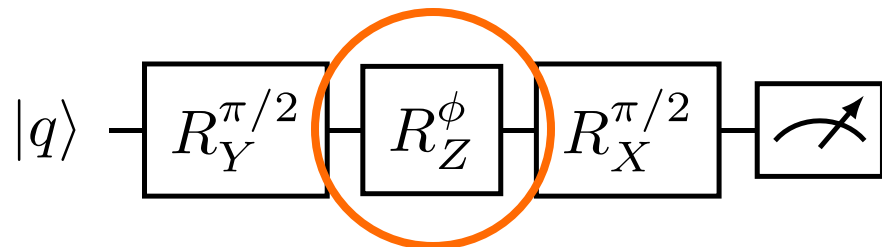
Ramsey protocol

(a)

Ramsey



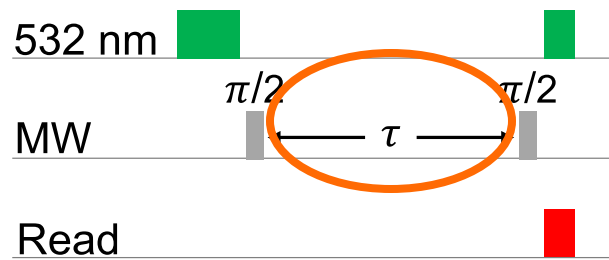
J. F. Barry, et al. '20



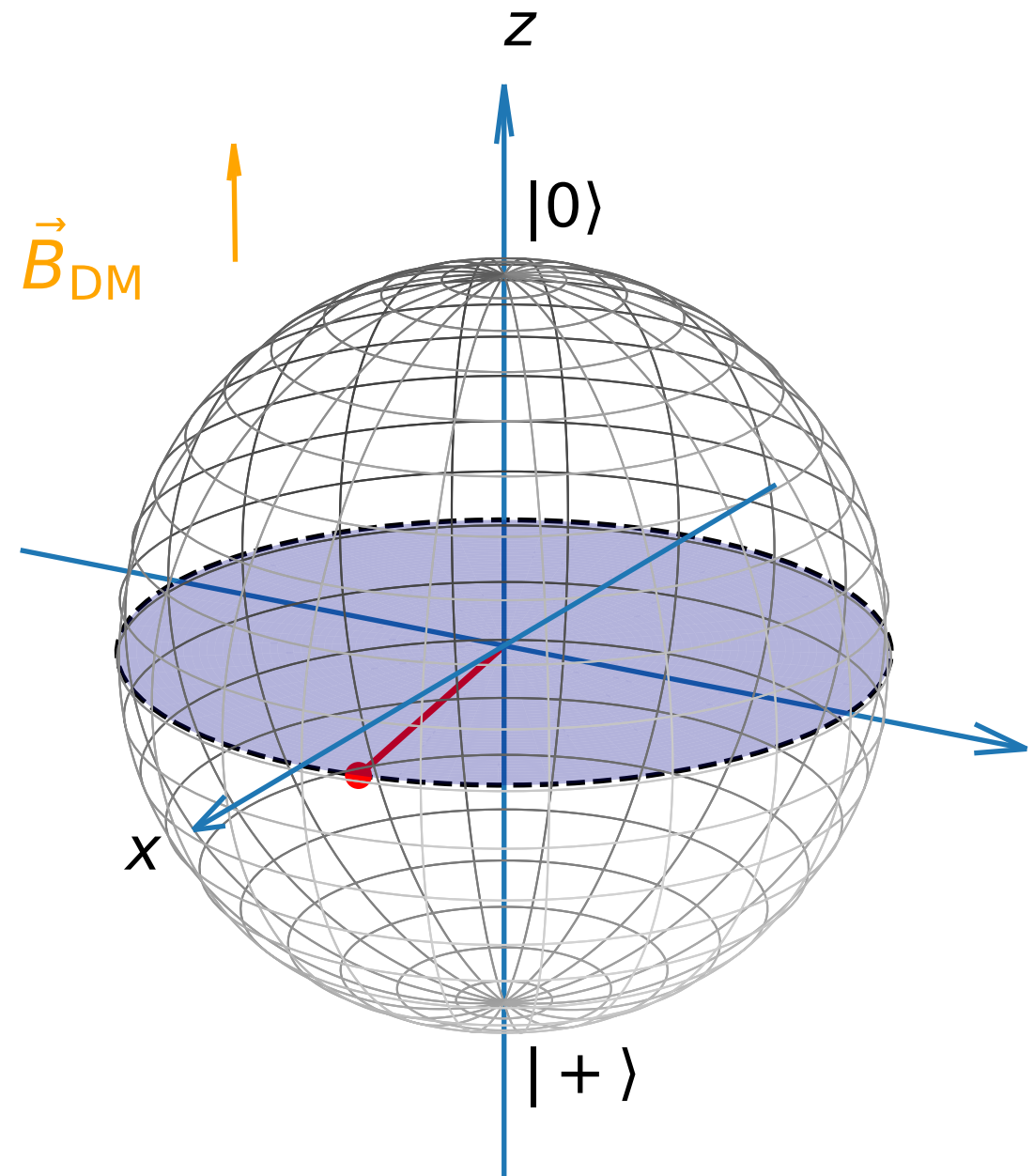
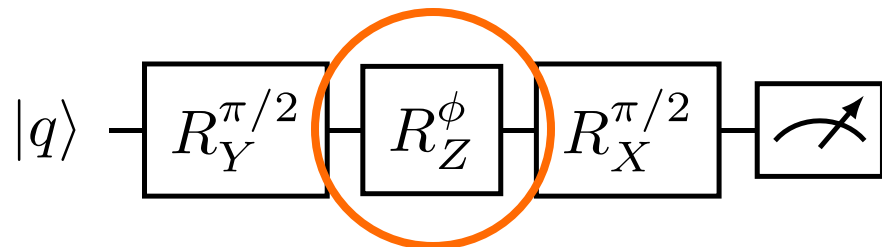
Ramsey protocol

(a)

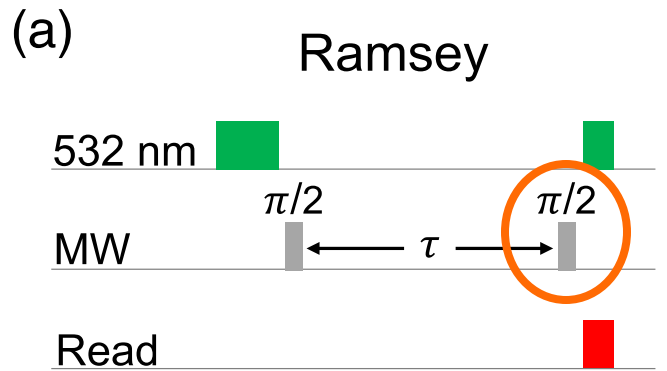
Ramsey



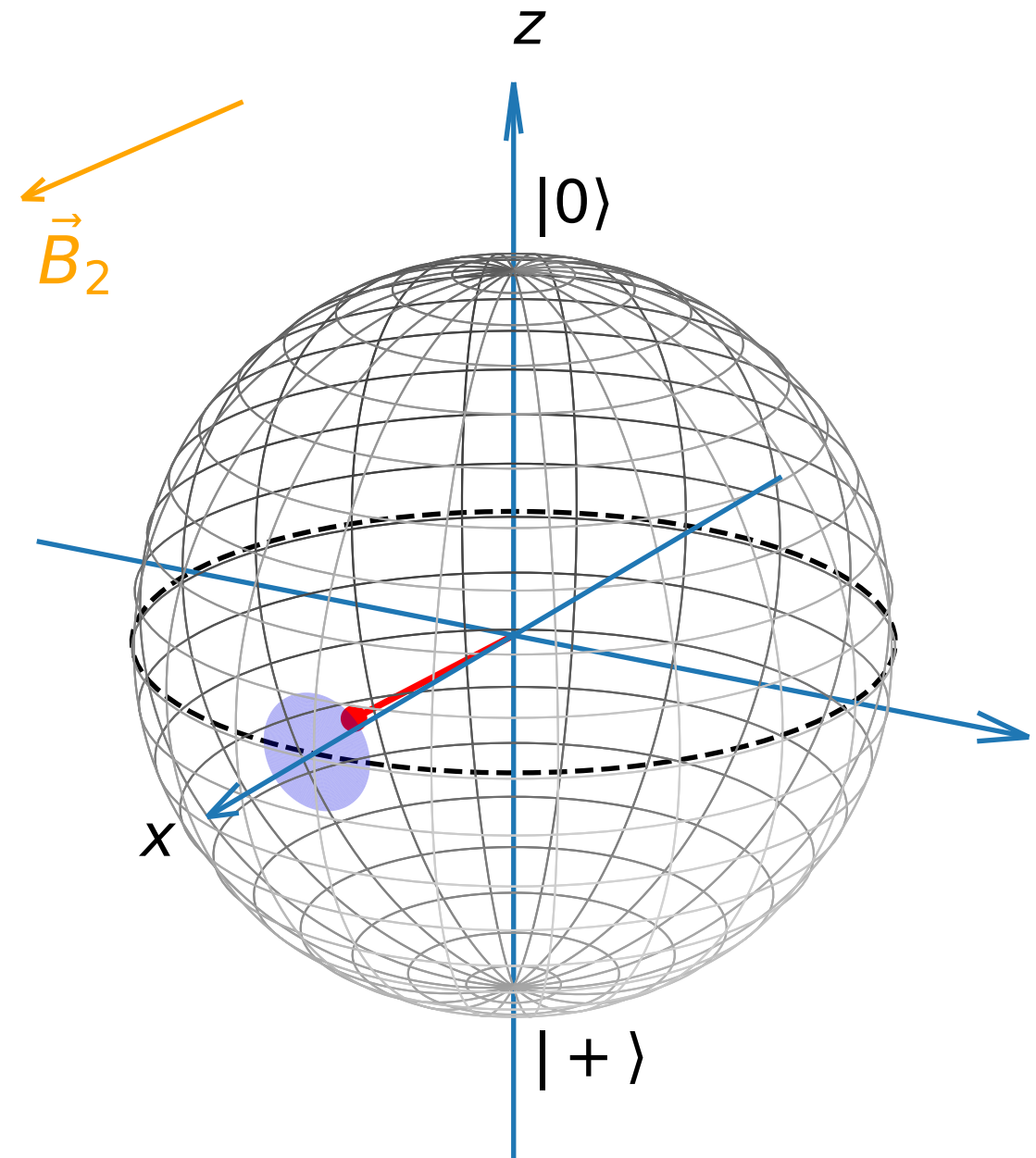
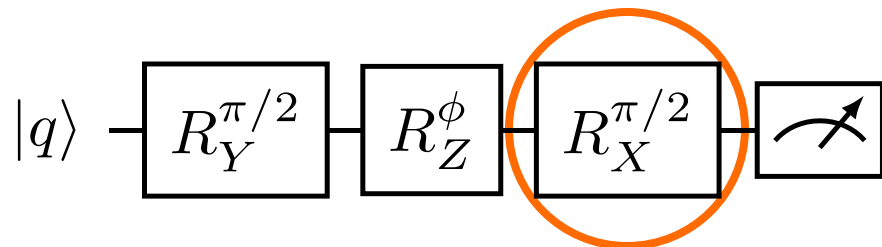
J. F. Barry, et al. '20



Ramsey protocol



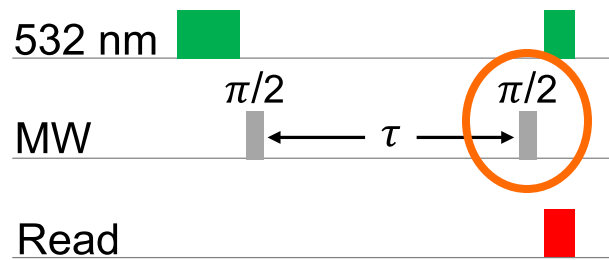
J. F. Barry, et al. '20



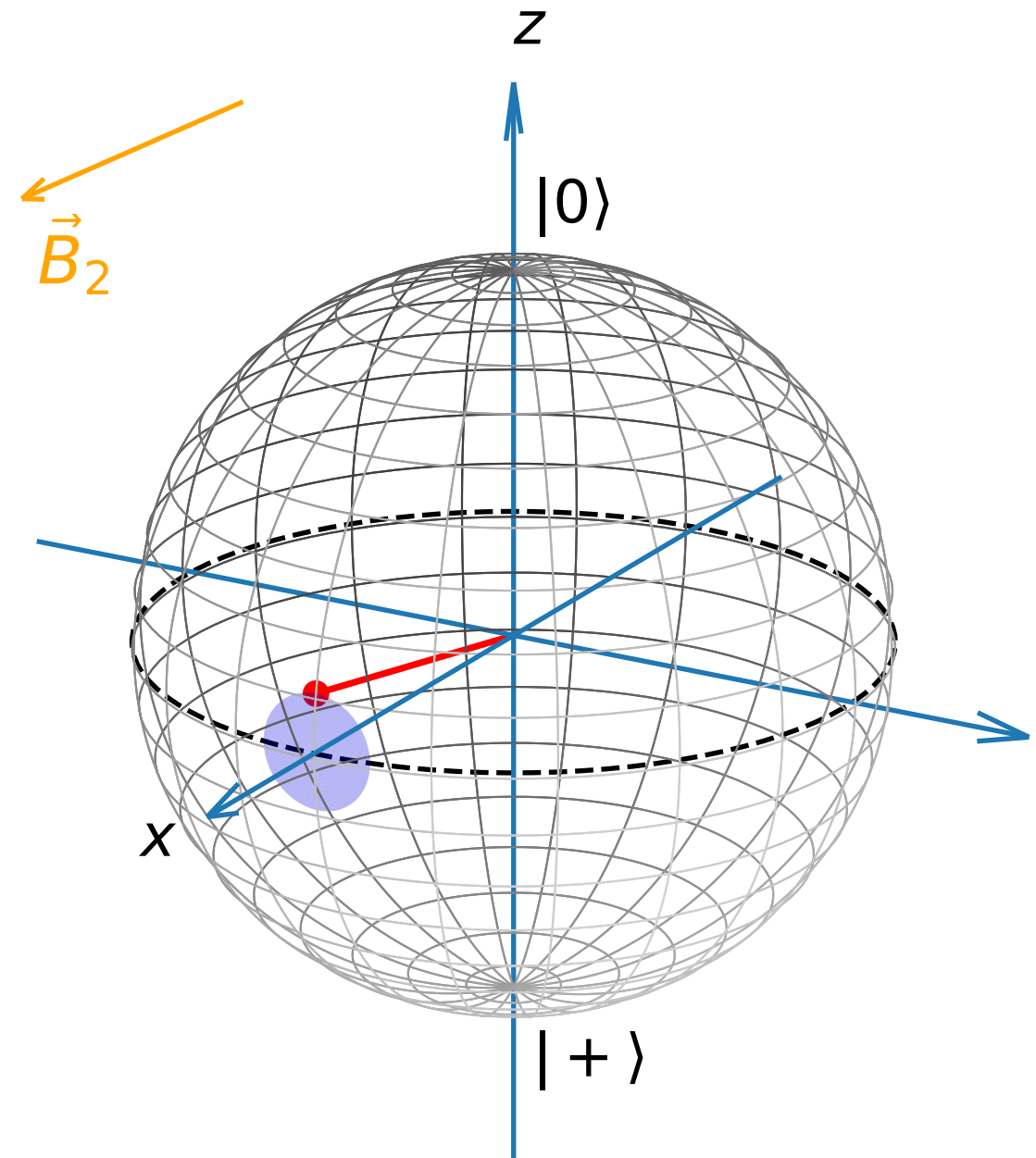
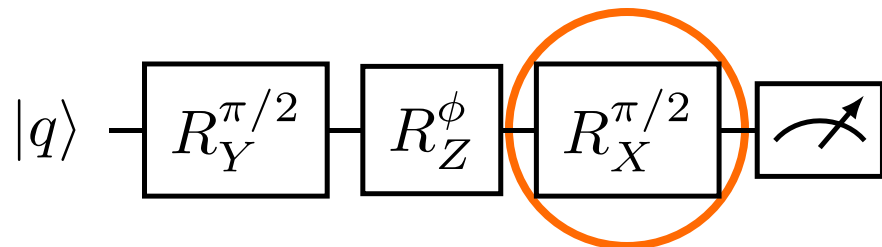
Ramsey protocol

(a)

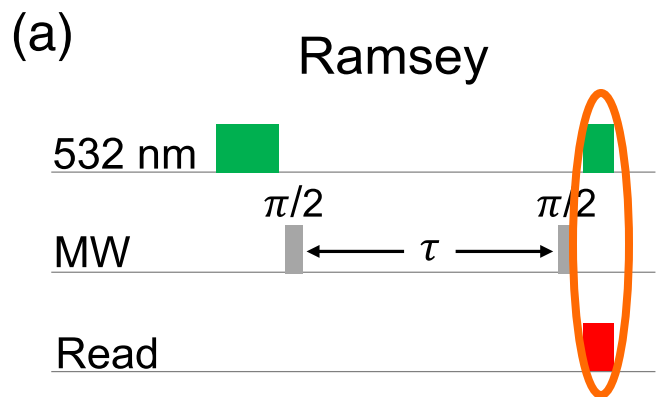
Ramsey



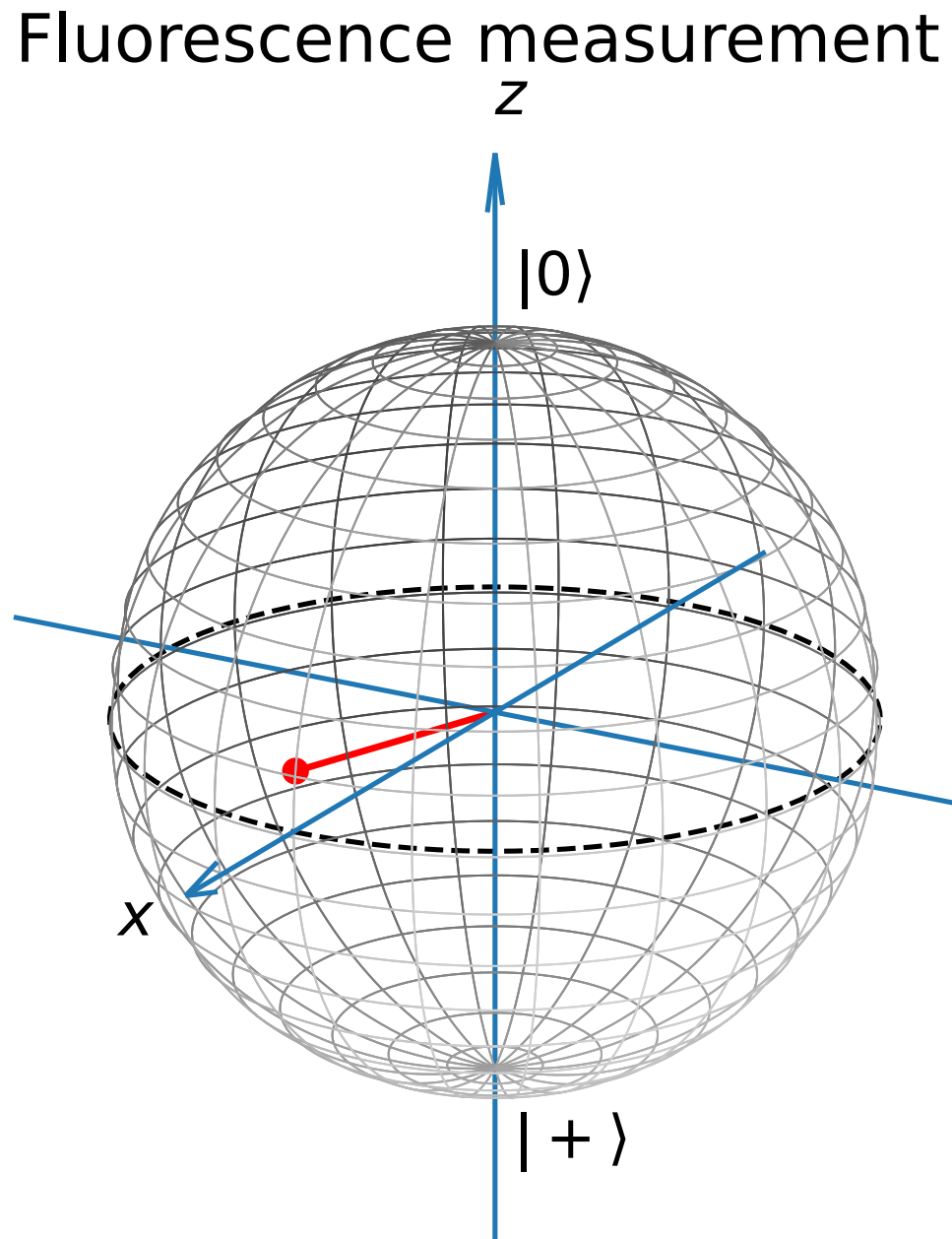
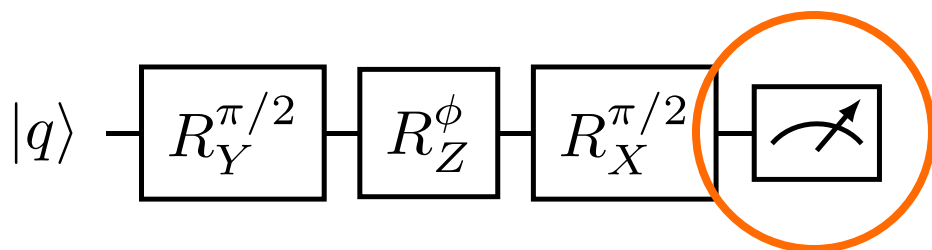
J. F. Barry, et al. '20



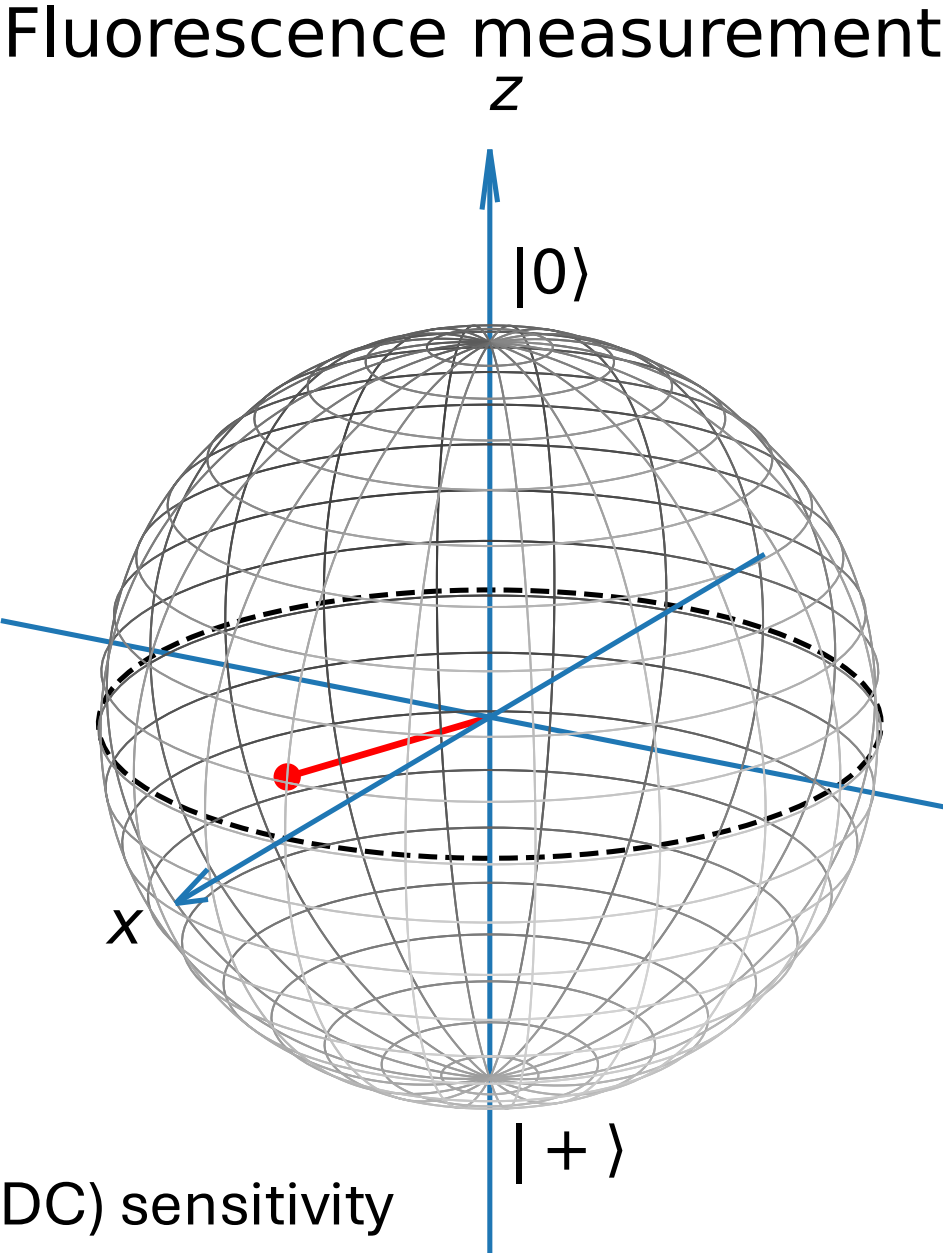
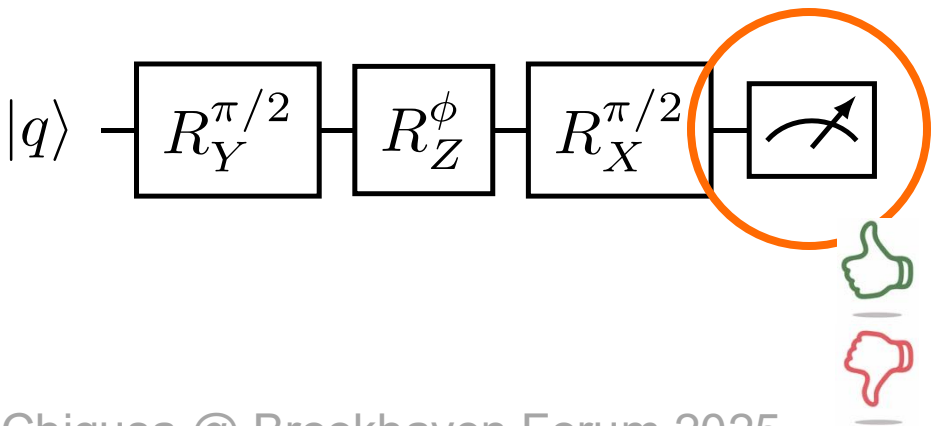
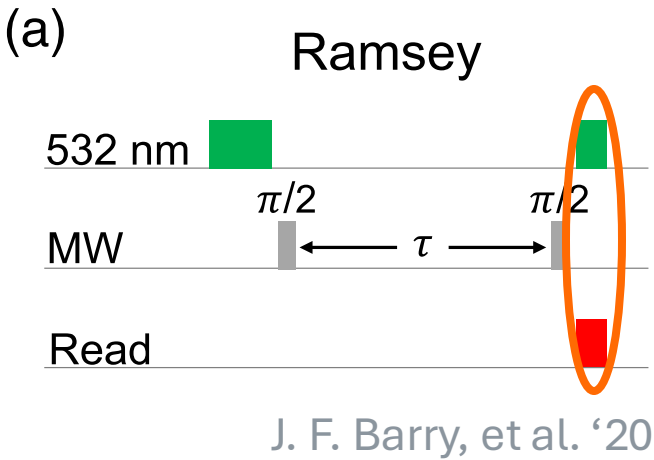
Ramsey protocol



J. F. Barry, et al. '20

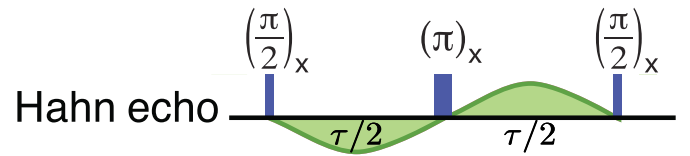


Ramsey protocol

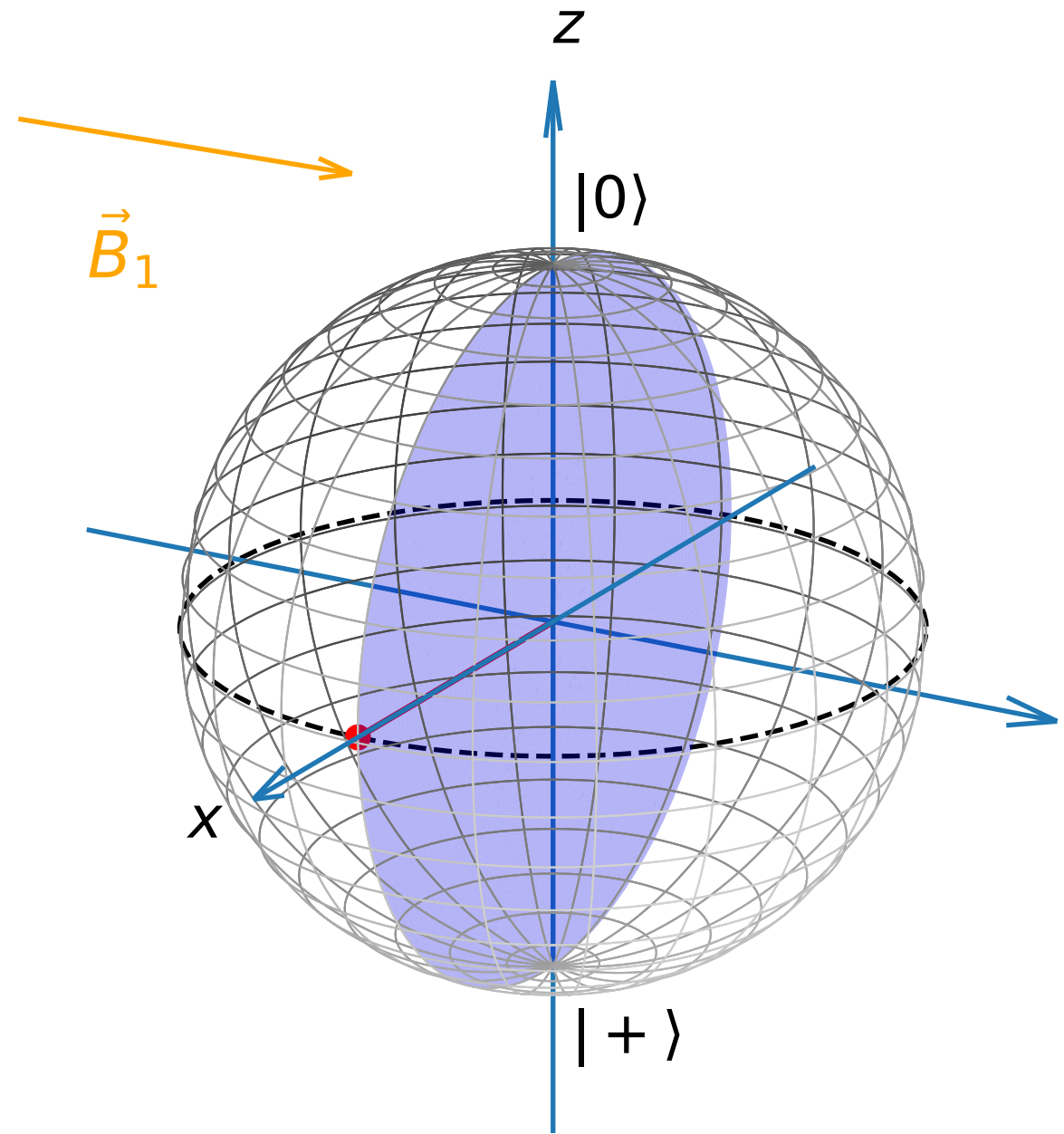
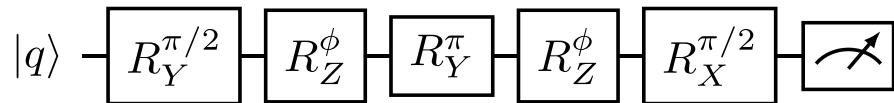


Broadband (DC) sensitivity
Vulnerable to noises $T_2^* \sim 1 \mu\text{s}$

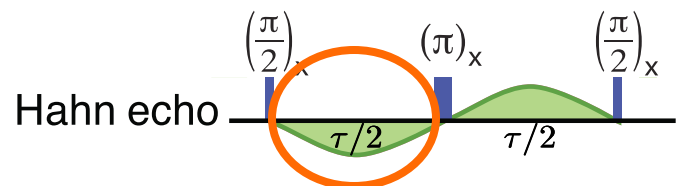
Spin echo and DC noise



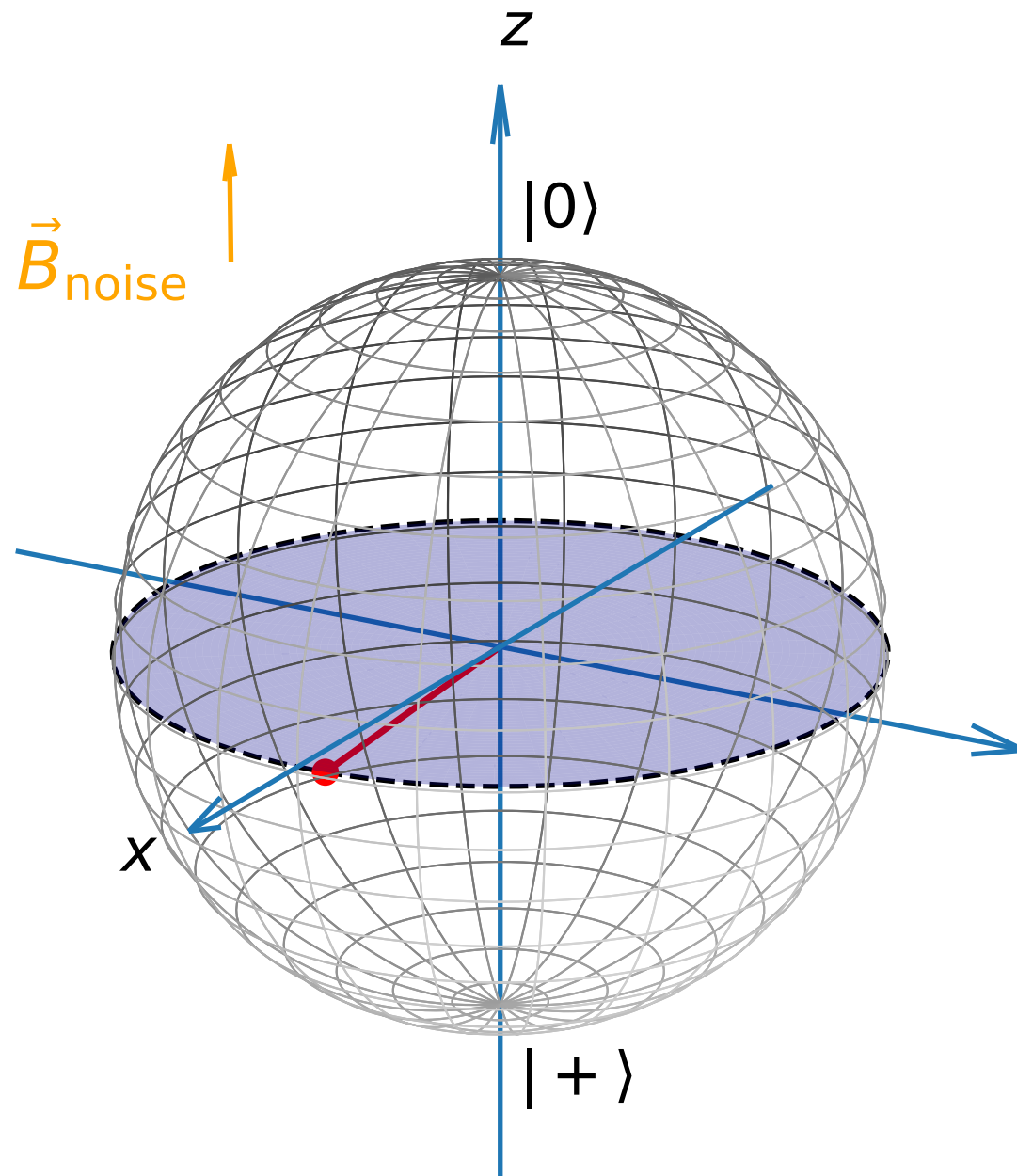
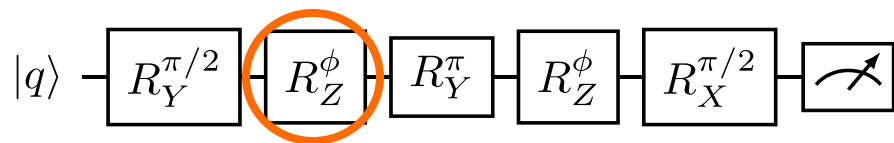
J. F. Barry, et al. '20



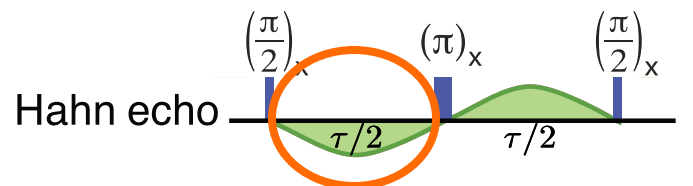
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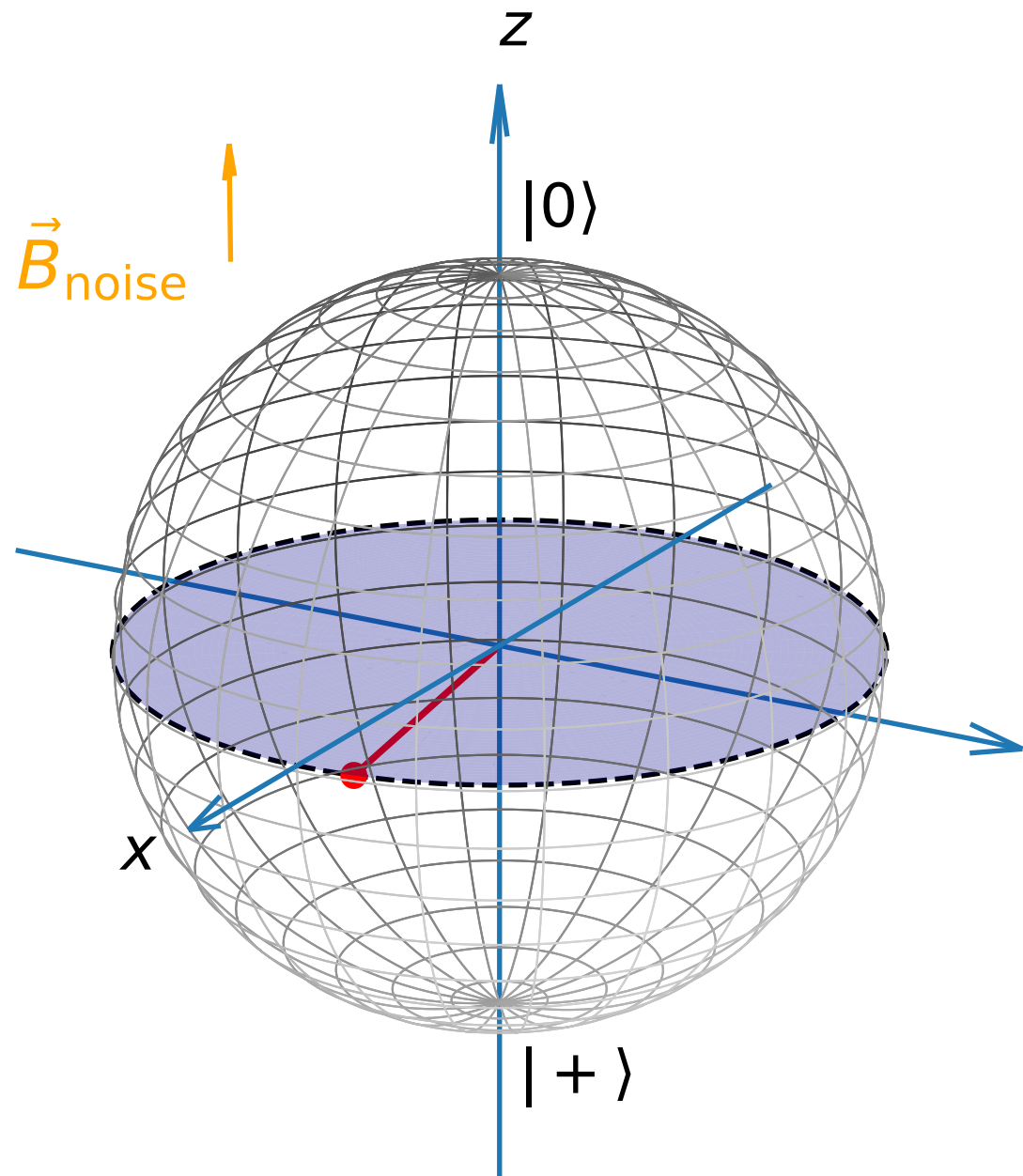
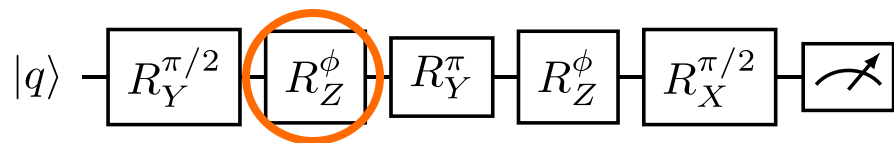
J. F. Barry, et al. '20



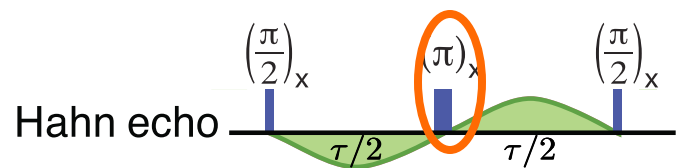
Spin echo and DC noise



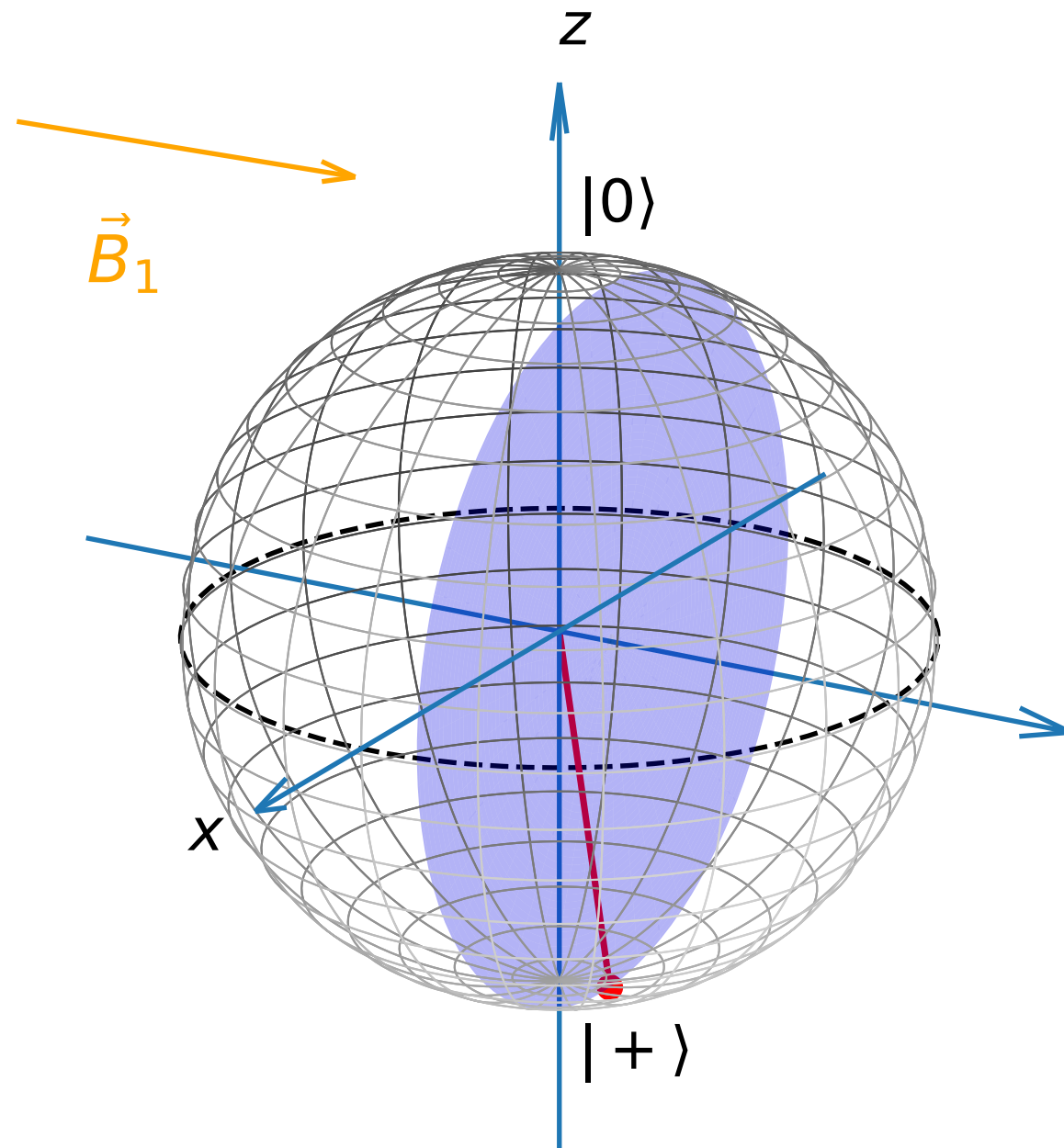
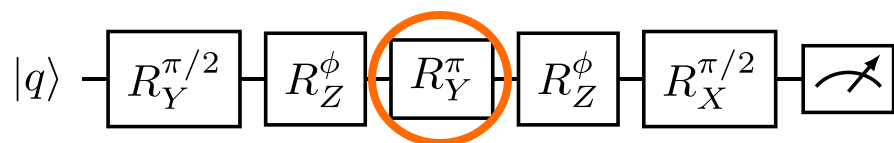
J. F. Barry, et al. '20



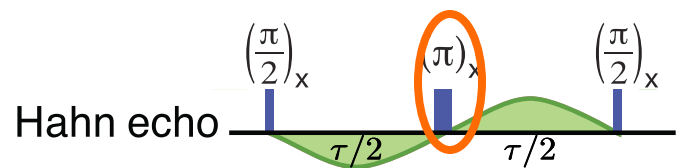
Spin echo and DC noise



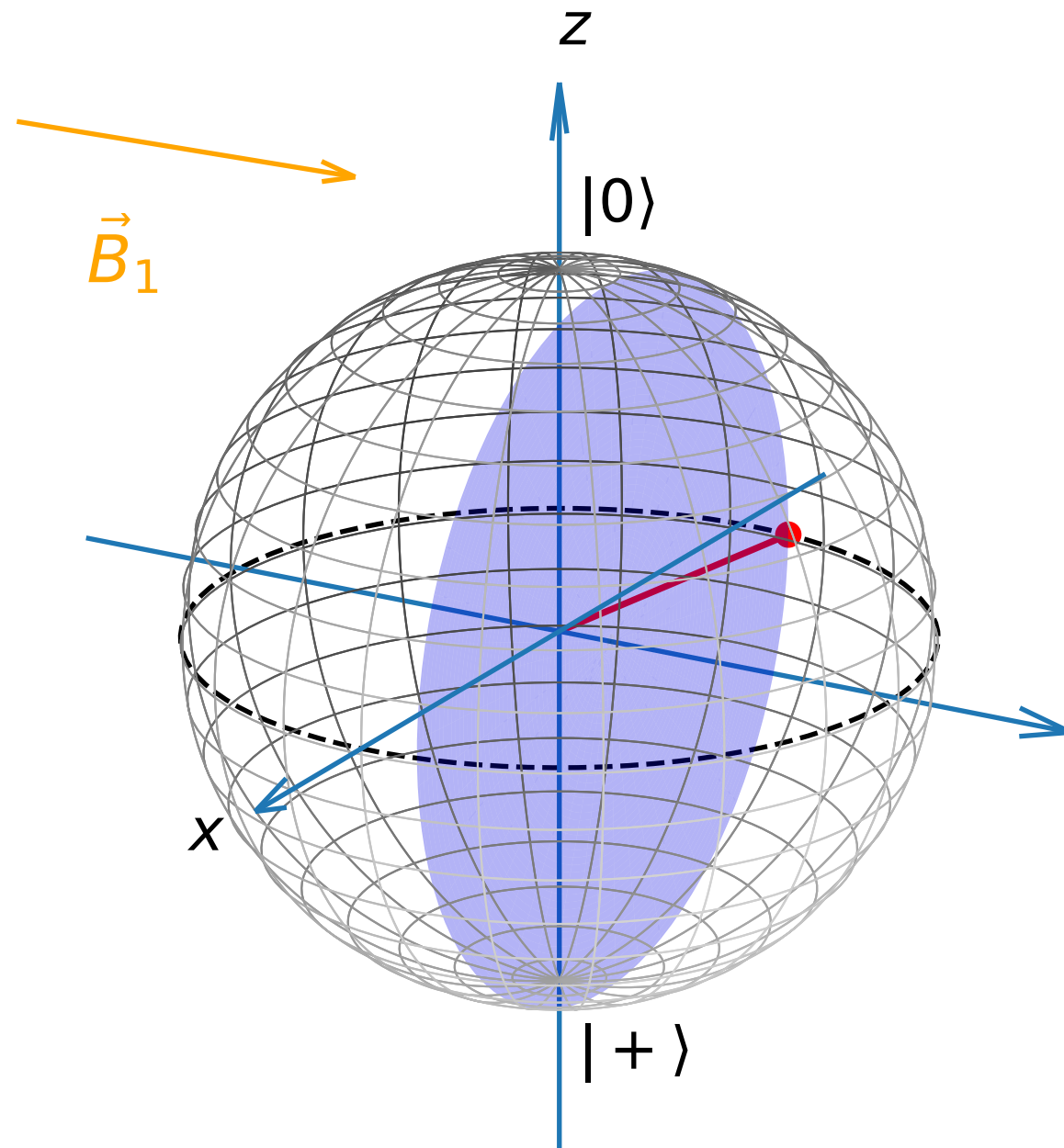
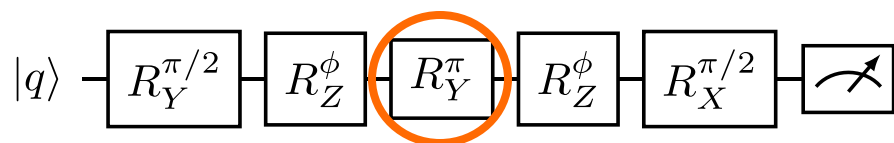
J. F. Barry, et al. '20



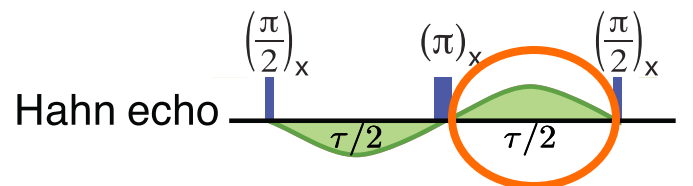
Spin echo and DC noise



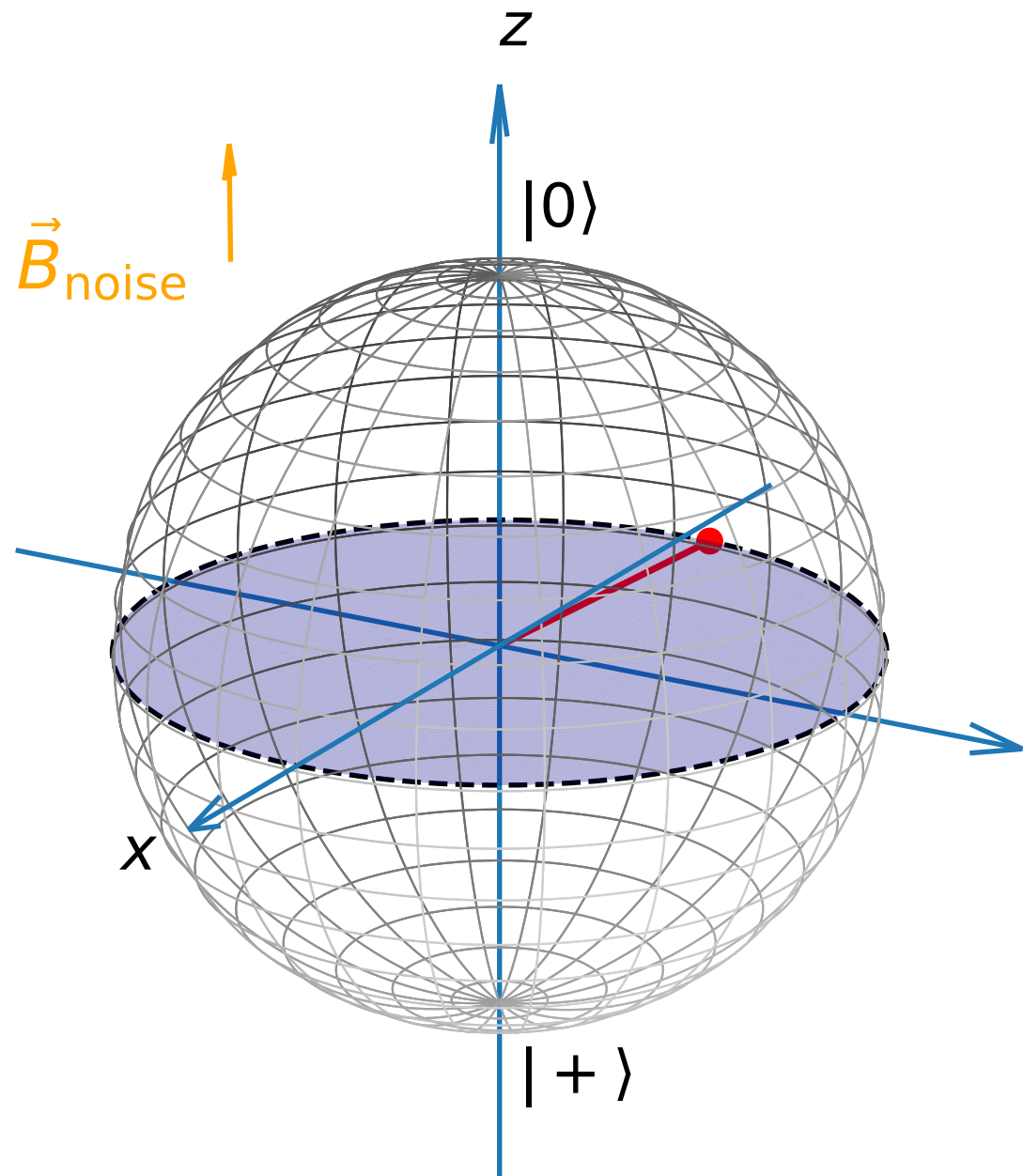
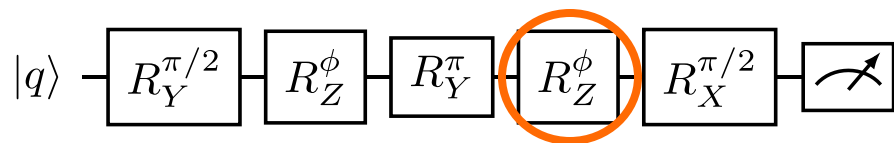
J. F. Barry, et al. '20



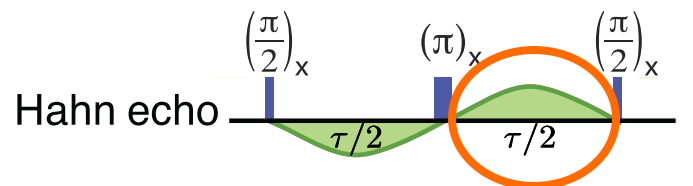
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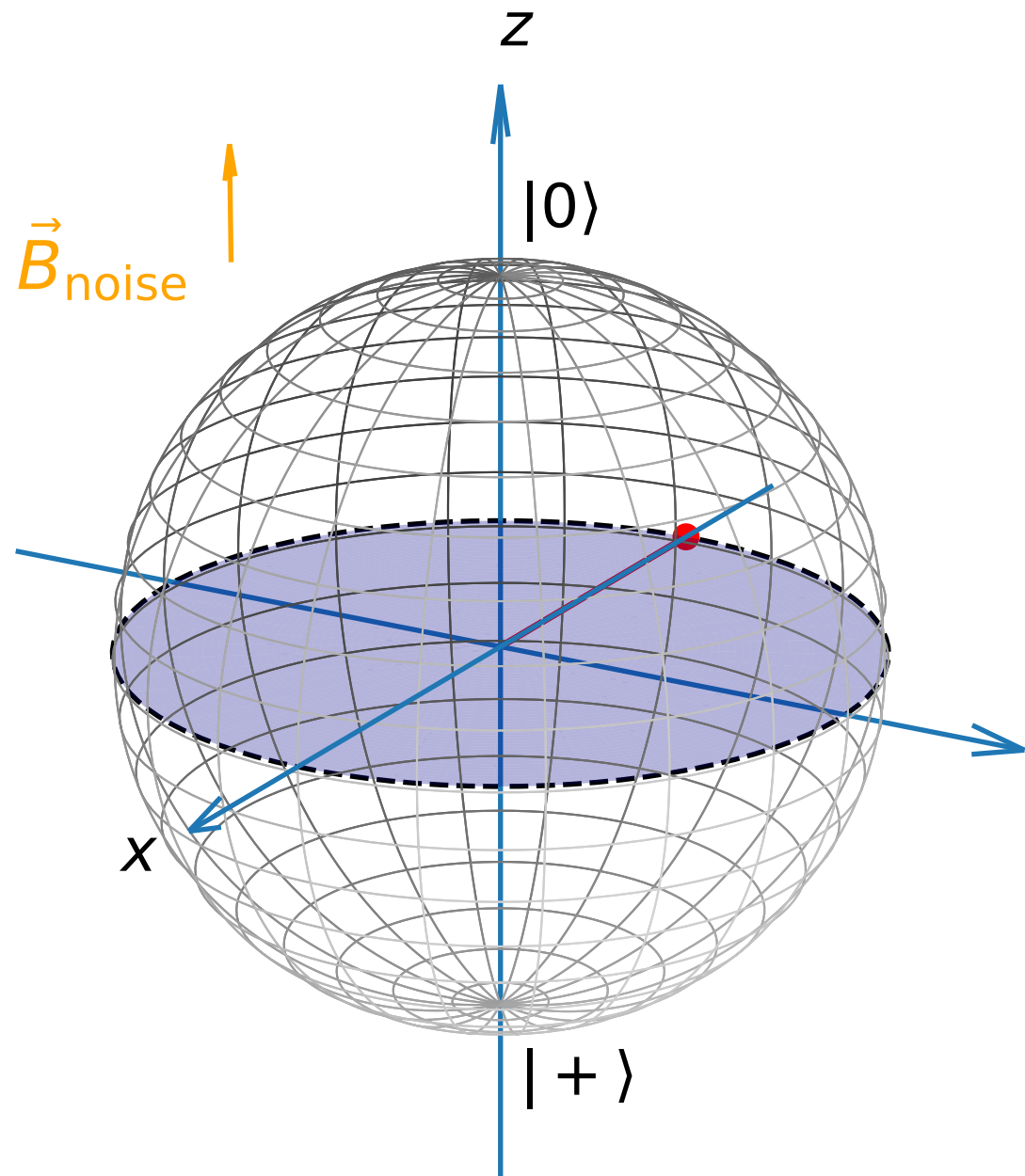
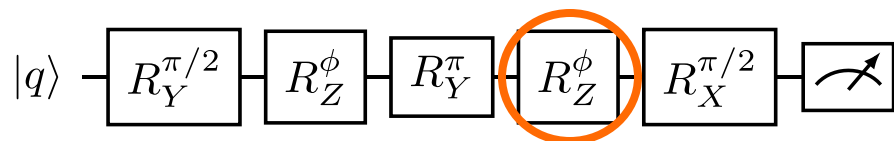
J. F. Barry, et al. '20



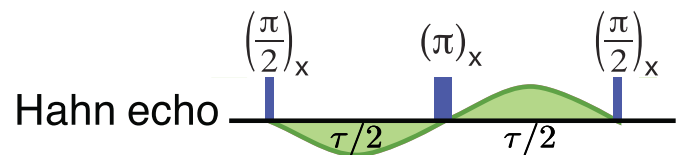
Spin echo and DC noise



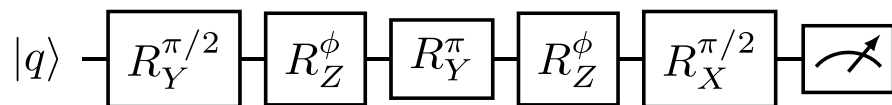
J. F. Barry, et al. '20



Spin echo and DC noise

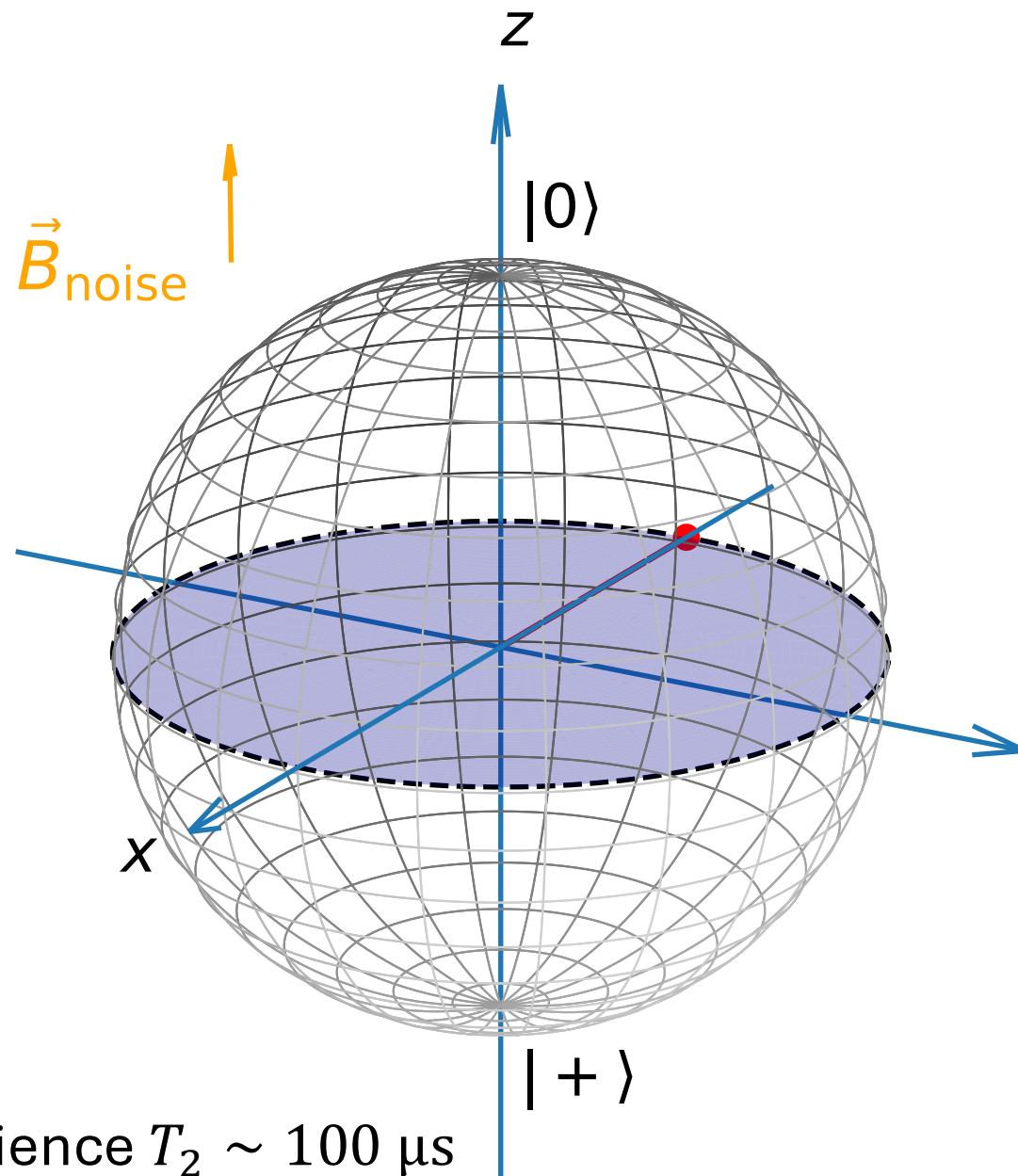


J. F. Barry, et al. '20

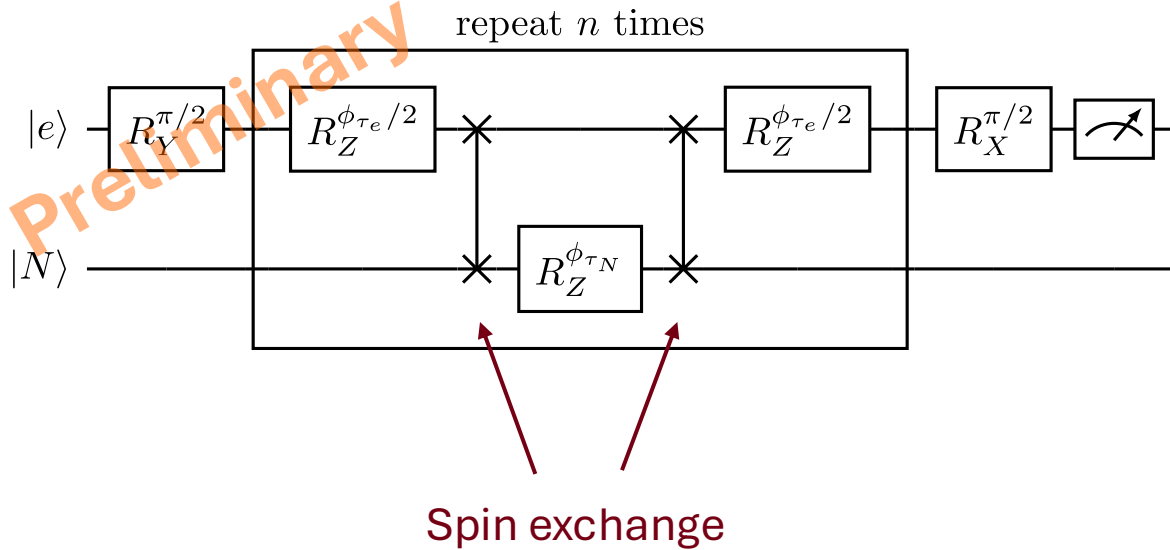


Noise resilience $T_2 \sim 100 \mu\text{s}$

Narrow-band sensitivity for $f \sim 1/\tau$



Hybrid spin decoupling



- DC Noise cancellation without π -pulses

$$B(\gamma_N \tau_N + \gamma_e \tau_e) = 0 \quad (\gamma_N \gamma_e < 0)$$

- Exotic spin interactions do not cancel

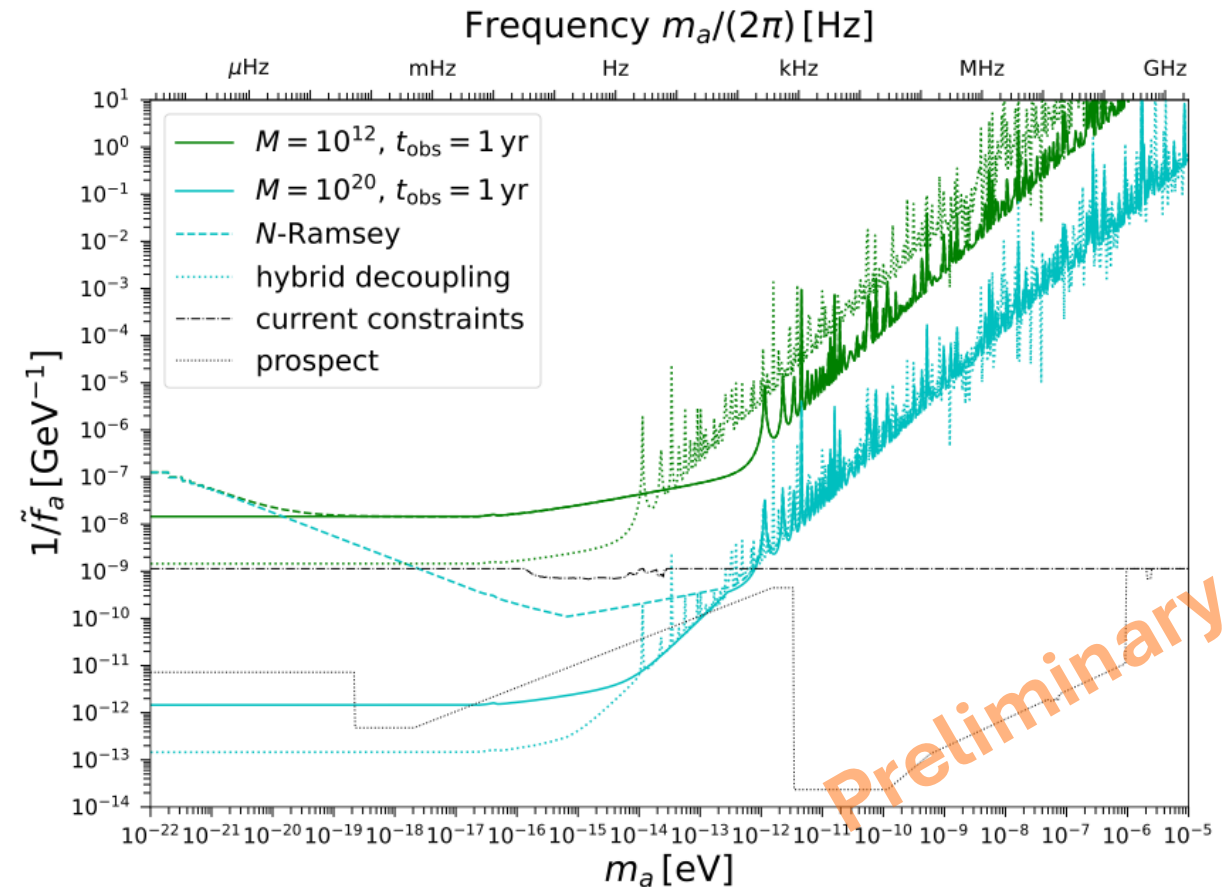
$$\frac{g_{aNN}}{m_N} \tau_N + \frac{g_{aee}}{m_e} \tau_e \neq 0$$



Longer T_2 with larger n , lower T

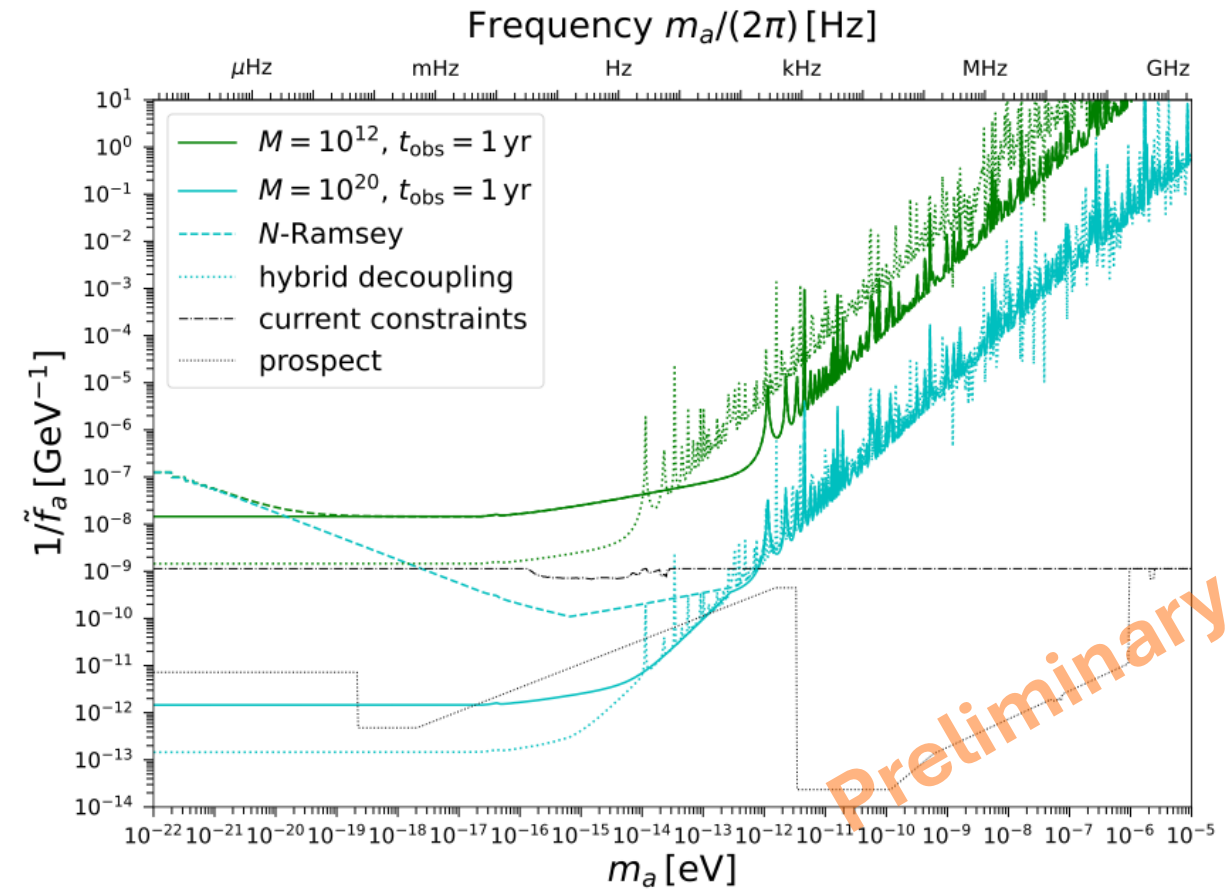
Comagnetometry setup to reduce external noise

Broadband sensitivity!



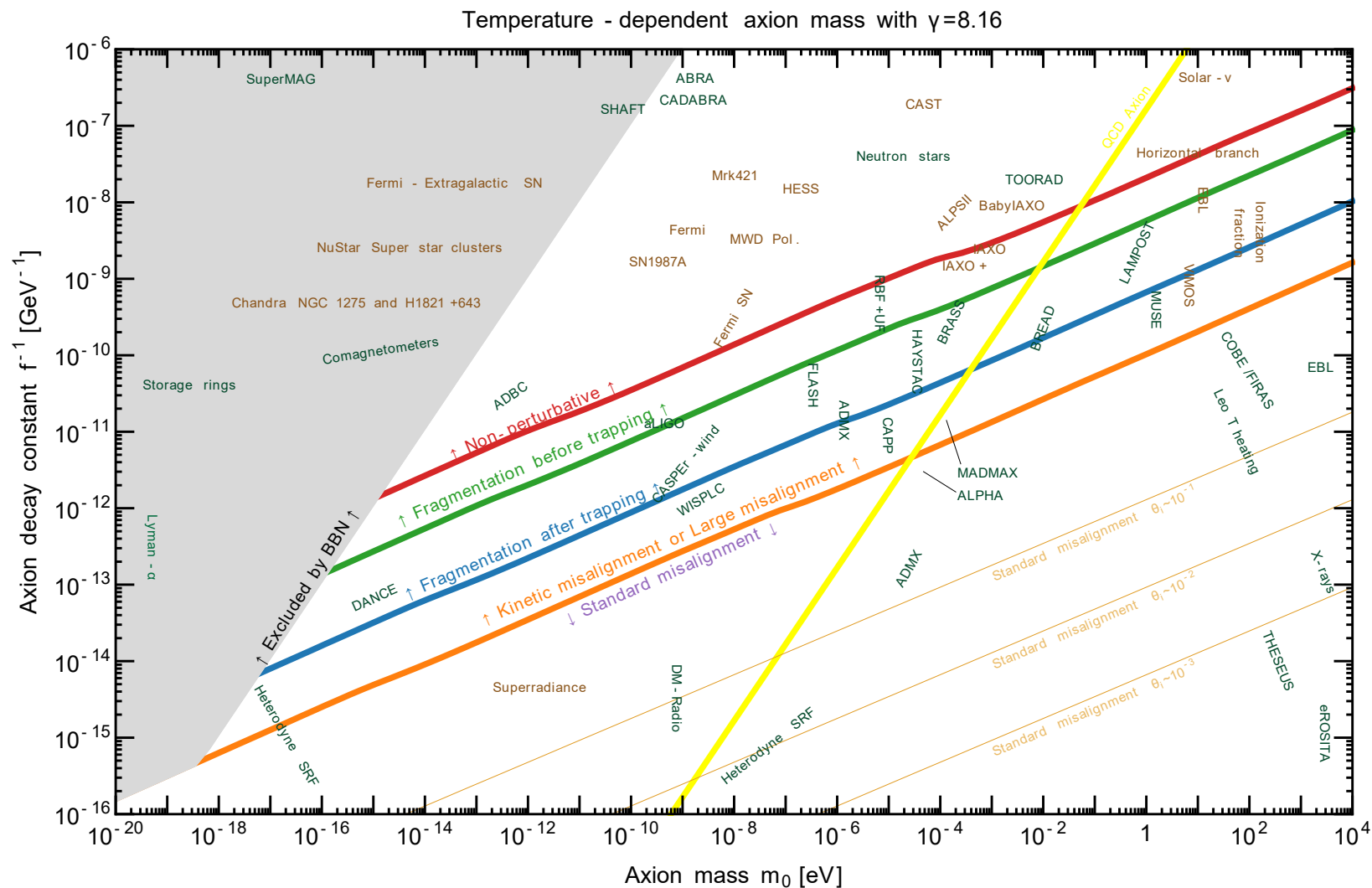
Discussions and Conclusion

- Axion detection with NV center
 - “Hybrid spin decoupling” quantum sensing protocol
- Benefits
 - Longer coherence time
 - Comagnetometry
 - Broadband sensing
- Setting up an experiment at QUP, KEK
 - NV + cryogenic



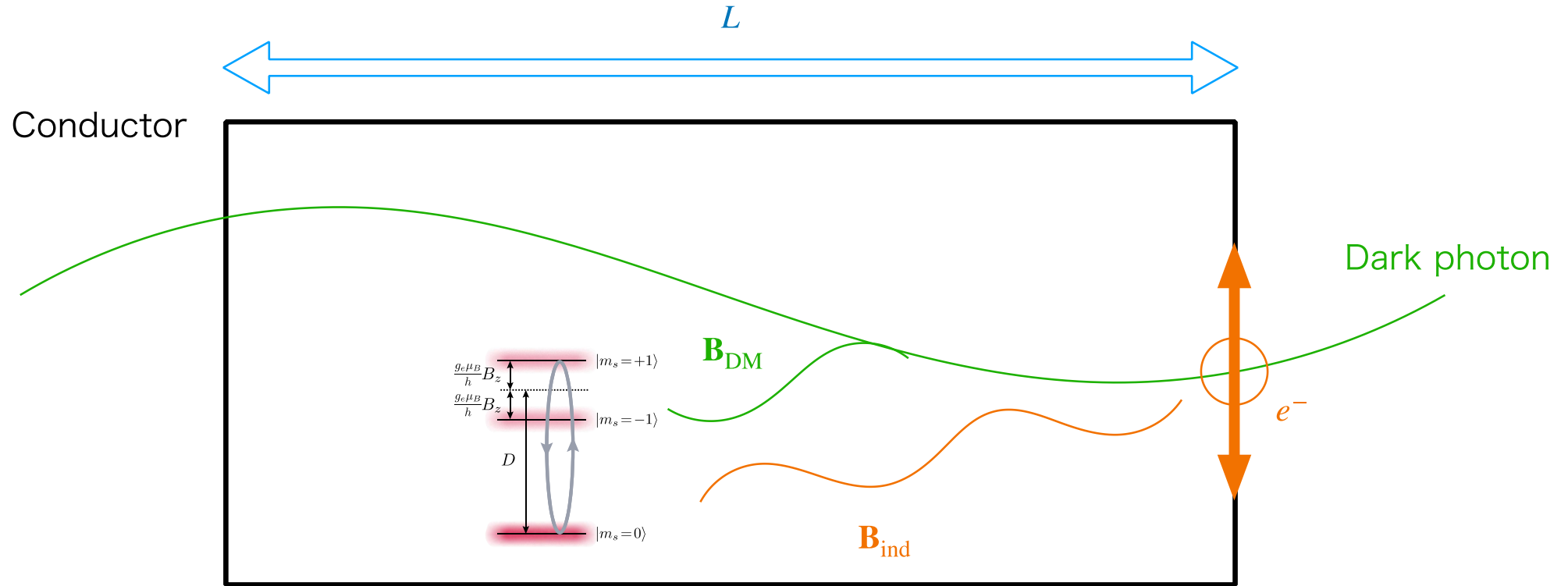
Backup slides

Axion DM parameter space



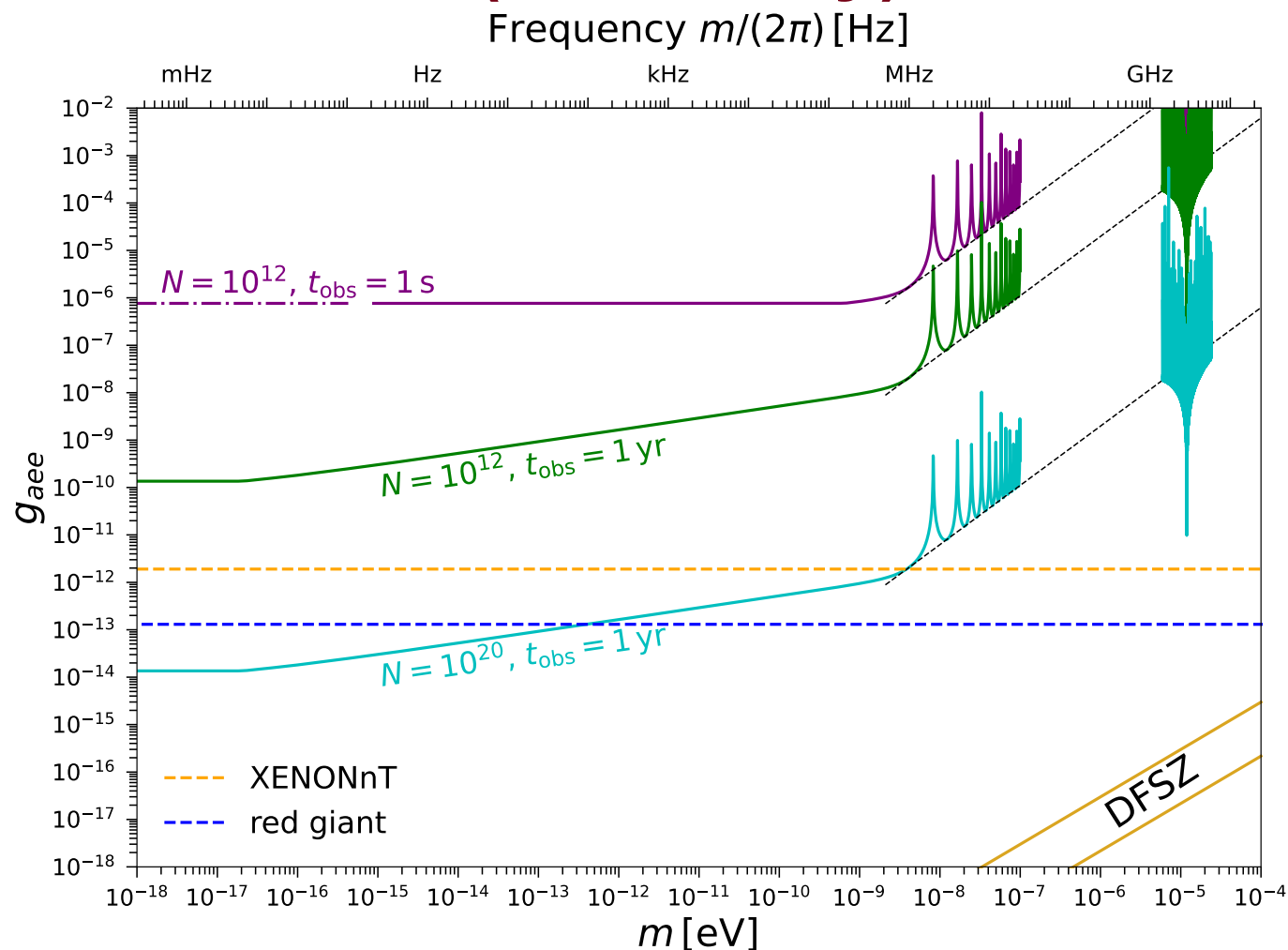
Eröncel+ [2206.14259]

Shielding effect



- ▶ Electric interaction of the dark photon creates current in the conductor and induces a magnetic field $\mathbf{B}_{\text{ind}}$
- ▶ The effective magnetic field may be canceled and “shielded” if $\lambda_{\text{DM}} > L$

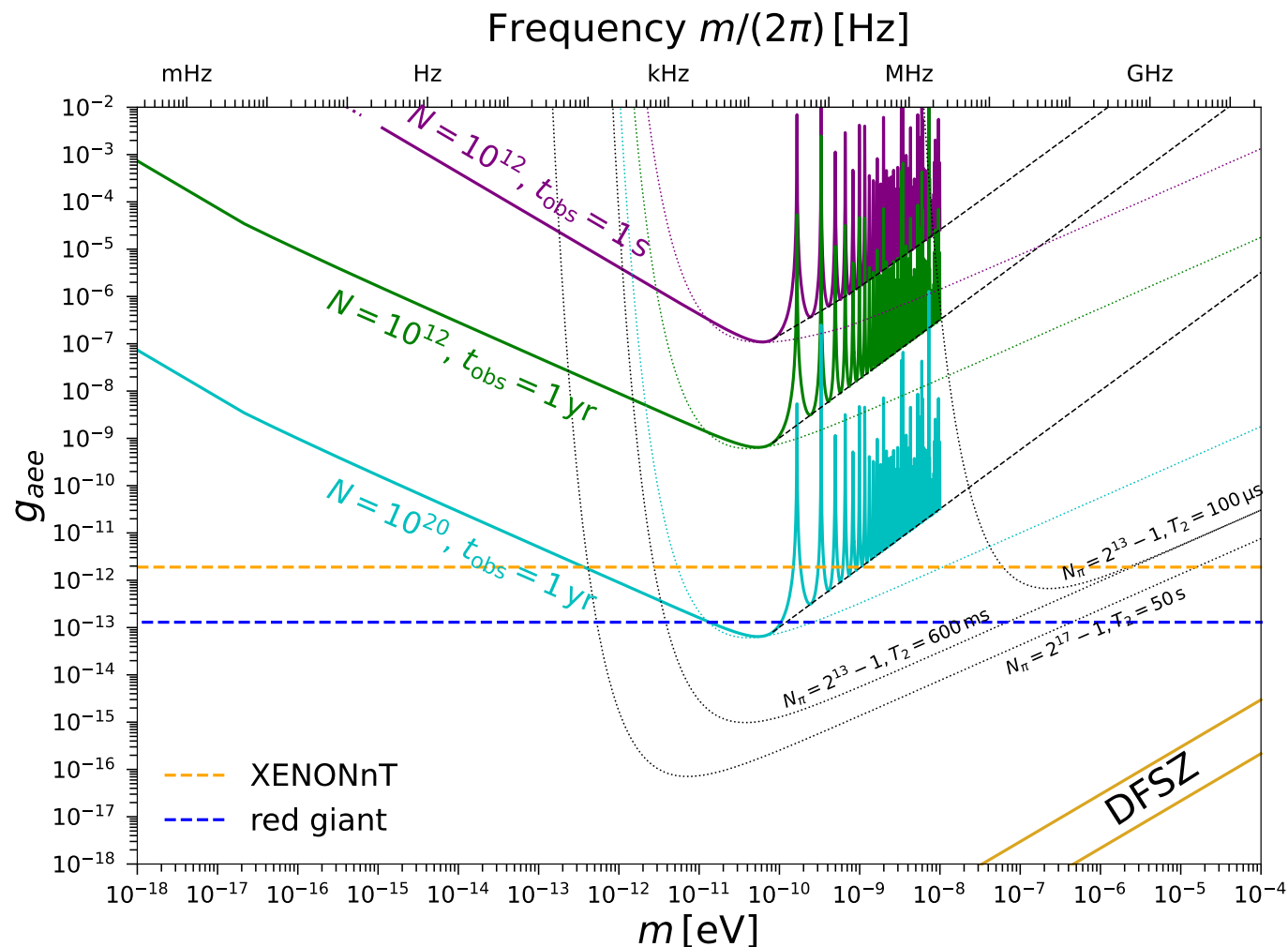
Sensitivity on axion DM (*e*-Ramsey)



SC, et al. [2302.12756]

- (Roughly) universal sensitivity to the dc-like region $m < 2\pi/T_2^* \sim 10^{-8} \text{ eV}$

Sensitivity on axion DM (spin echo)

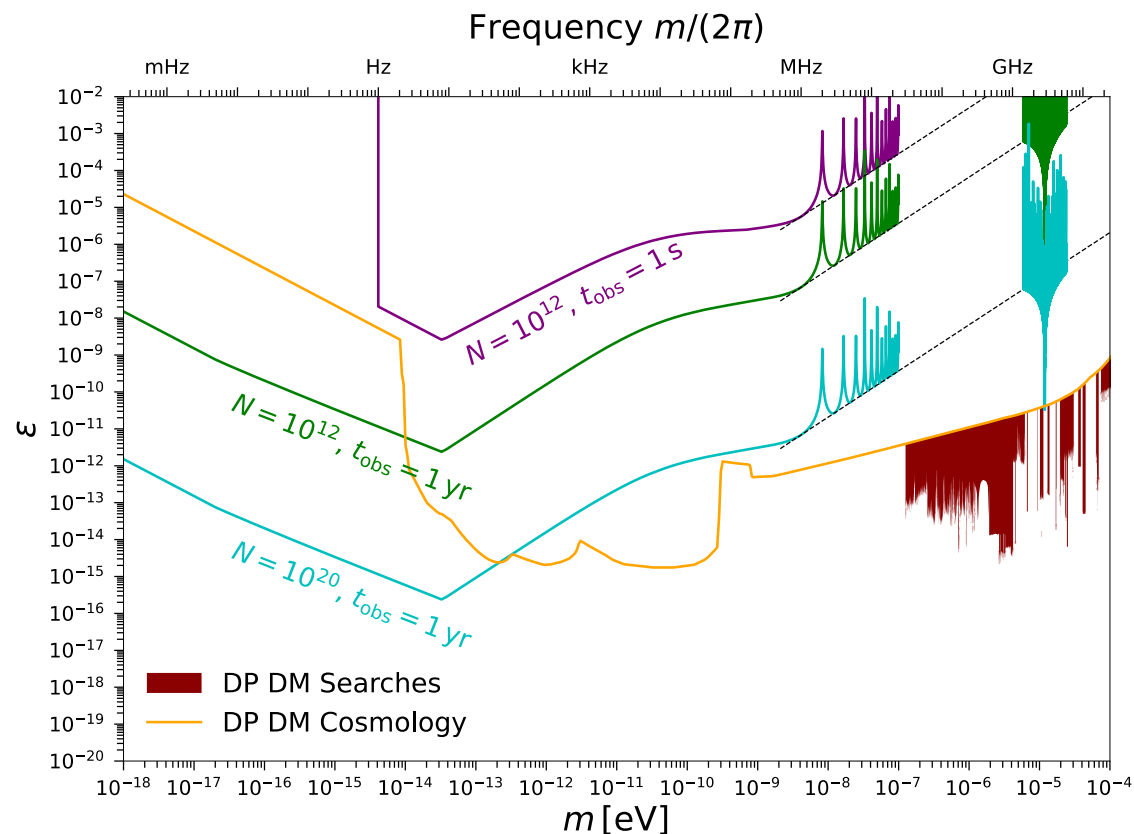


SC, et al. [2302.12756]

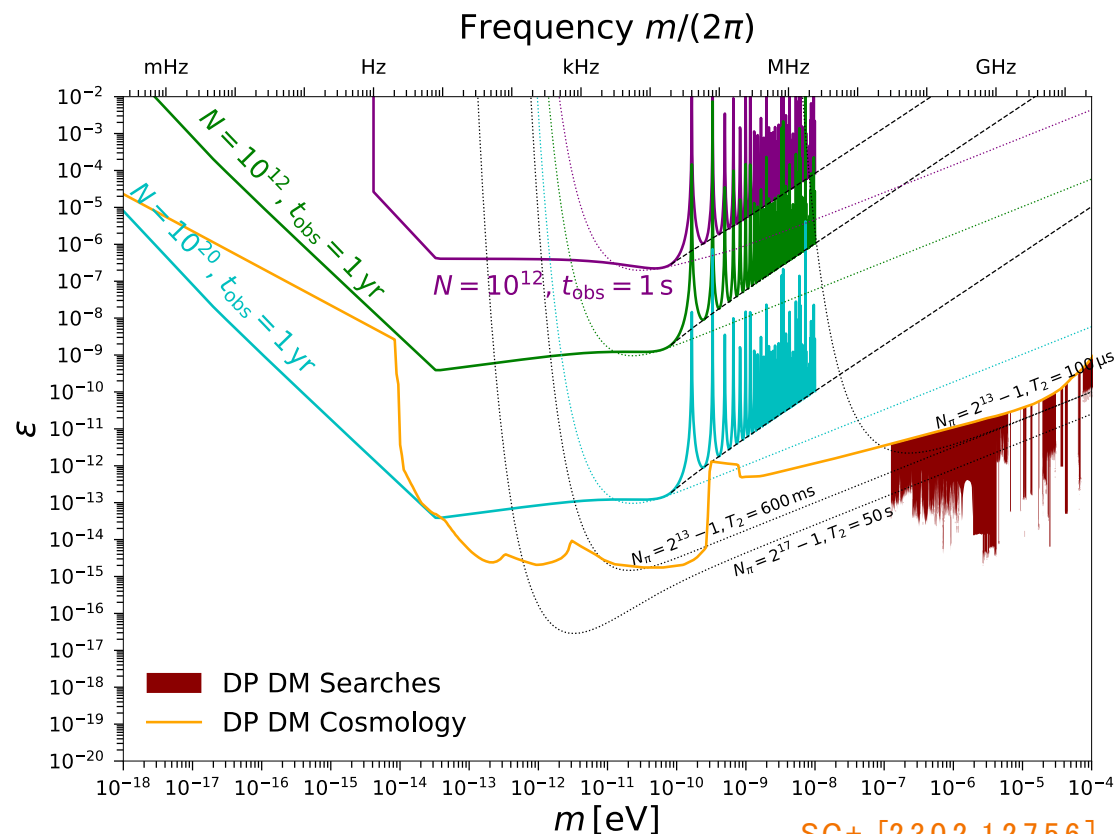
- Achieves sensitivities better than Ramsey for target frequency $\sim 1/T_2 \sim 10$ kHz

Sensitivities on dark photon DM

▸ DC magnetometry



▸ AC magnetometry



SC+ [2302.12756]

Axion- ^{14}N interaction

- A little algebra of spin synthesis

$$(2_{1/2} \otimes 3_1) \otimes (2_{1/2} \otimes 3_1)$$

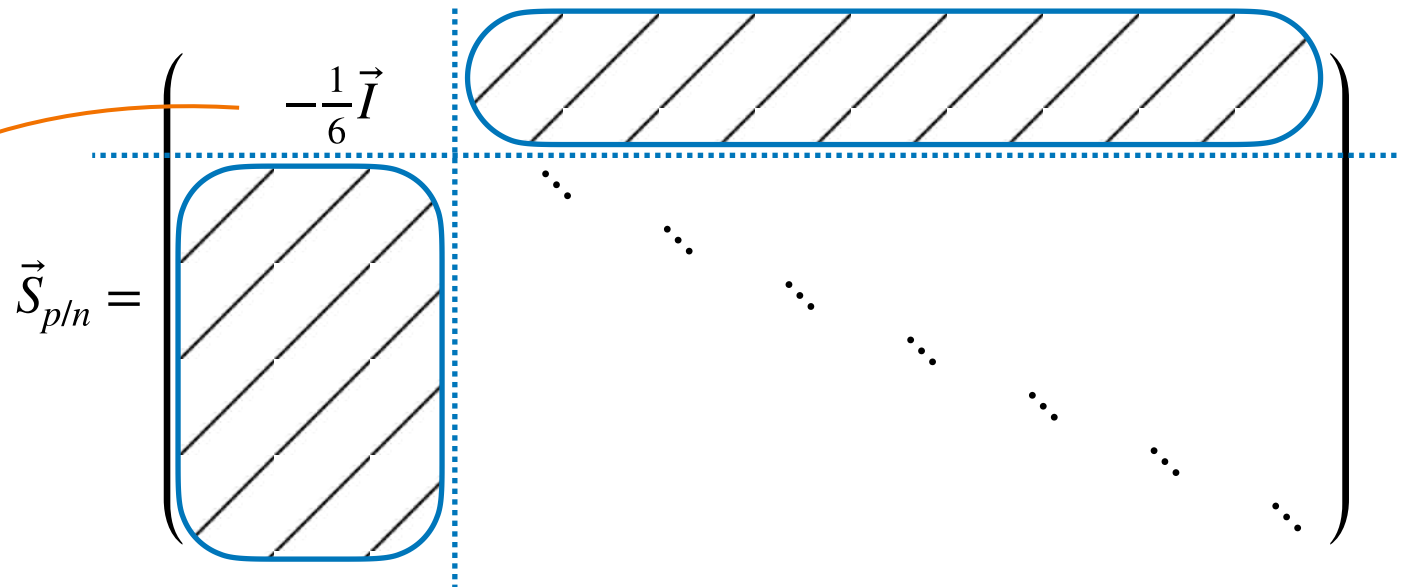
$$= (\boxed{2_{1/2}} \oplus 4_{3/2}) \otimes (\boxed{2_{1/2}} \oplus 4_{3/2})$$

$$= (1_0 \oplus \boxed{3_1}) \oplus (3_1 \oplus 5_2) \oplus (3_1 \oplus 5_2) \oplus (1_0 \oplus 3_1 \oplus 5_2 \oplus 7_3)$$

- $H_{\text{int}} = \gamma_n \vec{B}_a^{(n)} \cdot \vec{S}_n + \gamma_p \vec{B}_a^{(p)} \cdot \vec{S}_p$

$$= \gamma_{^{14}\text{N}} \vec{B}_a \cdot \vec{I} + \dots$$

$$|\vec{B}_a| \propto \frac{1}{6} \left(\frac{g_{\text{ann}}}{m_n} + \frac{g_{\text{app}}}{m_p} \right)$$



Full control of nuclear (^{14}N) spins

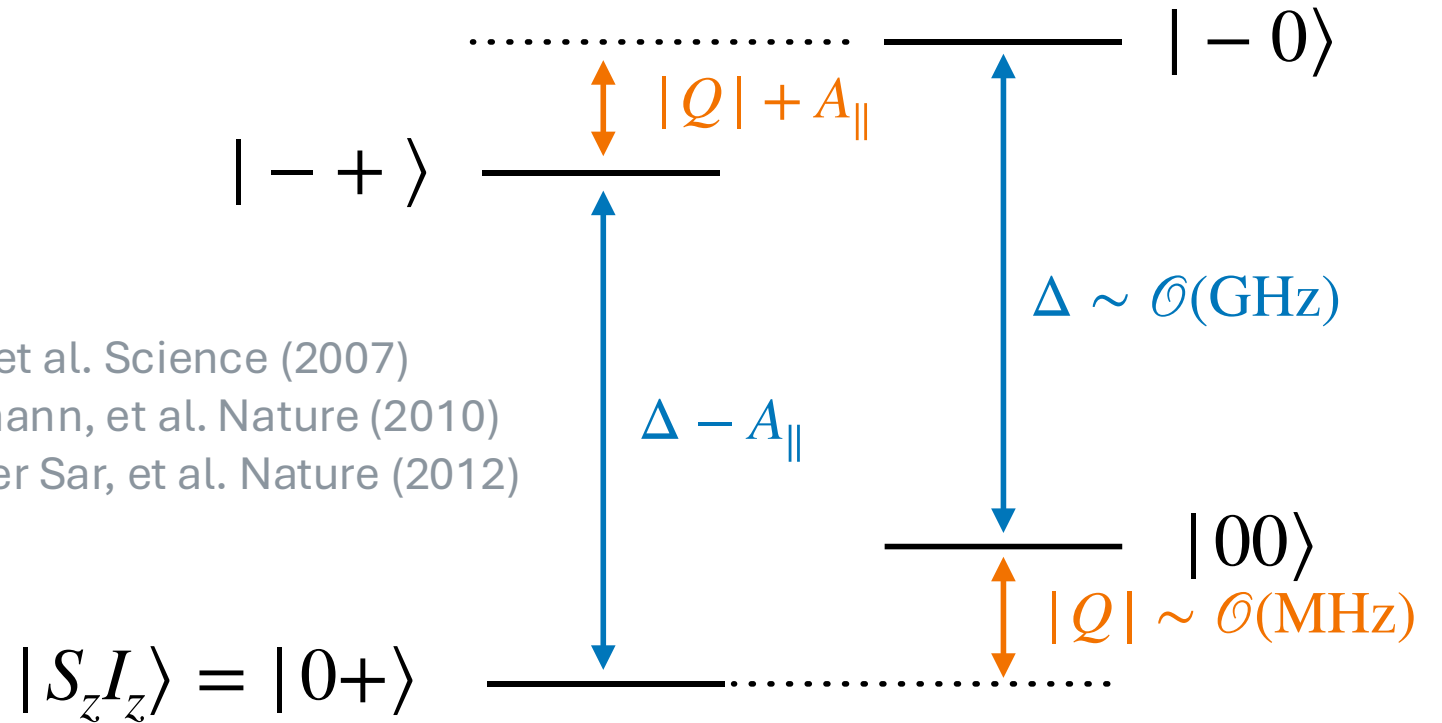
- Hyperfine interaction between e^- and ^{14}N spins ($I = 1$)

$$H_{hyp.} = A_{\parallel} S_z I_z$$

- Causes hyperfine splitting of energy levels

- Full control on two-qubit system of e^- and ^{14}N spins available

Dutt, et al. Science (2007)
Neumann, et al. Nature (2010)
van der Sar, et al. Nature (2012)



Full control of nuclear (^{14}N) spins

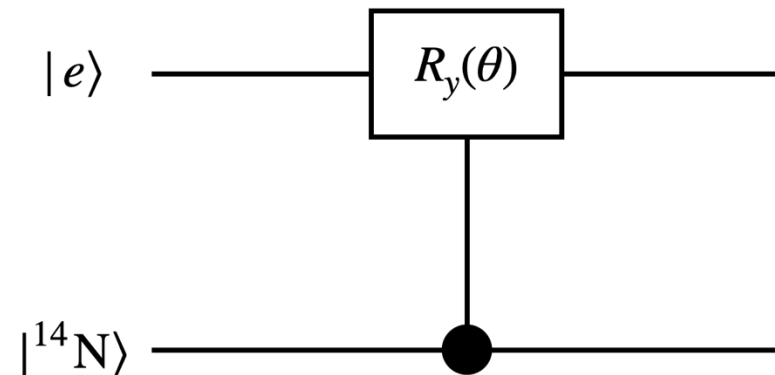
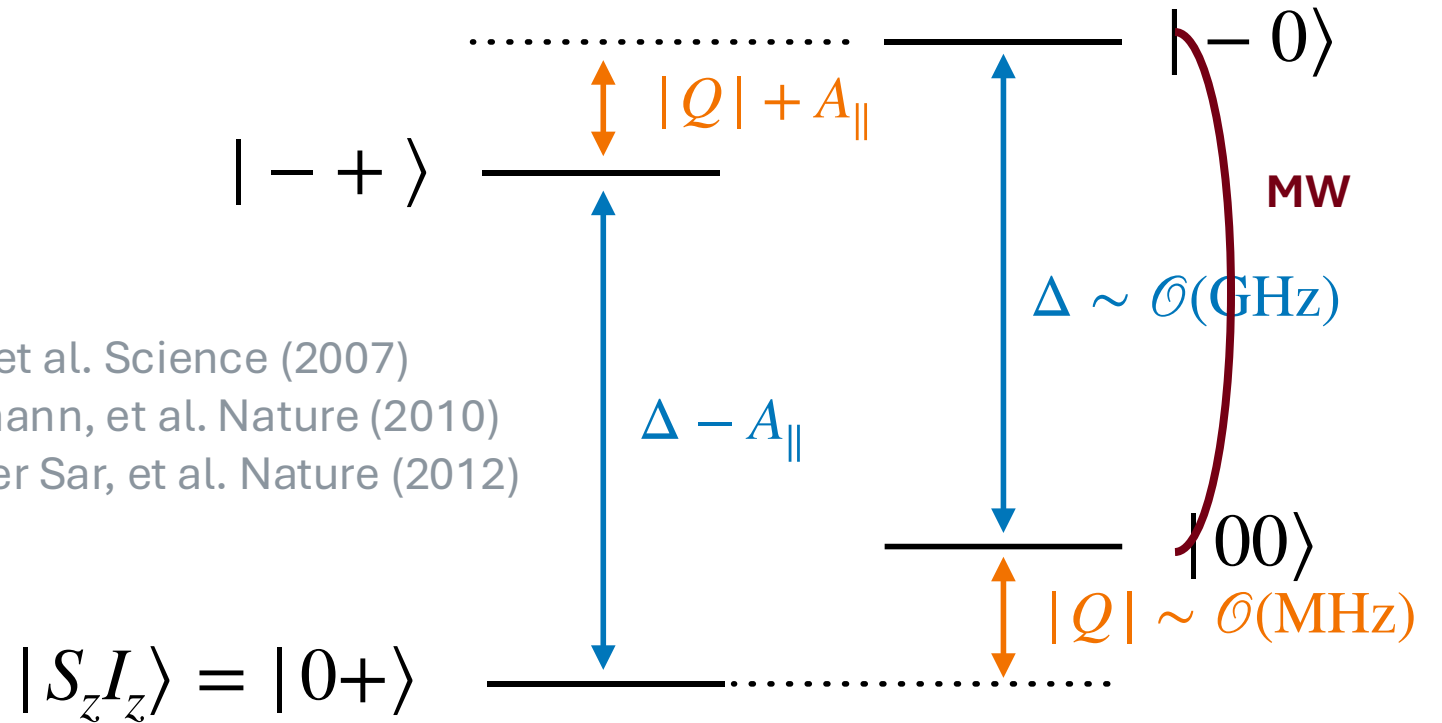
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Dutt, et al. Science (2007)
Neumann, et al. Nature (2010)
van der Sar, et al. Nature (2012)

- Causes hyperfine splitting of energy levels

- Full control on two-qubit system of e^- and ^{14}N spins available



Full control of nuclear (^{14}N) spins

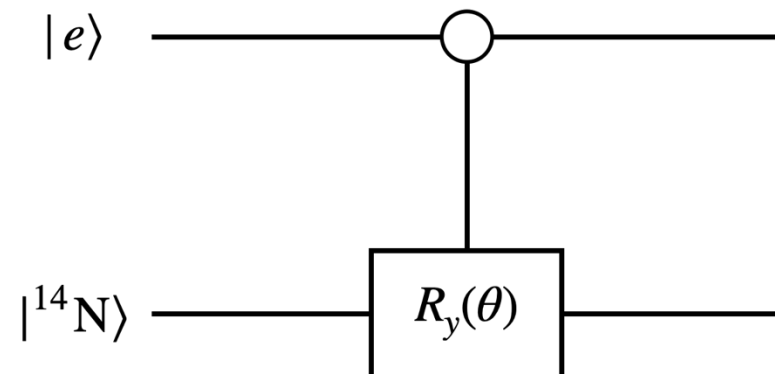
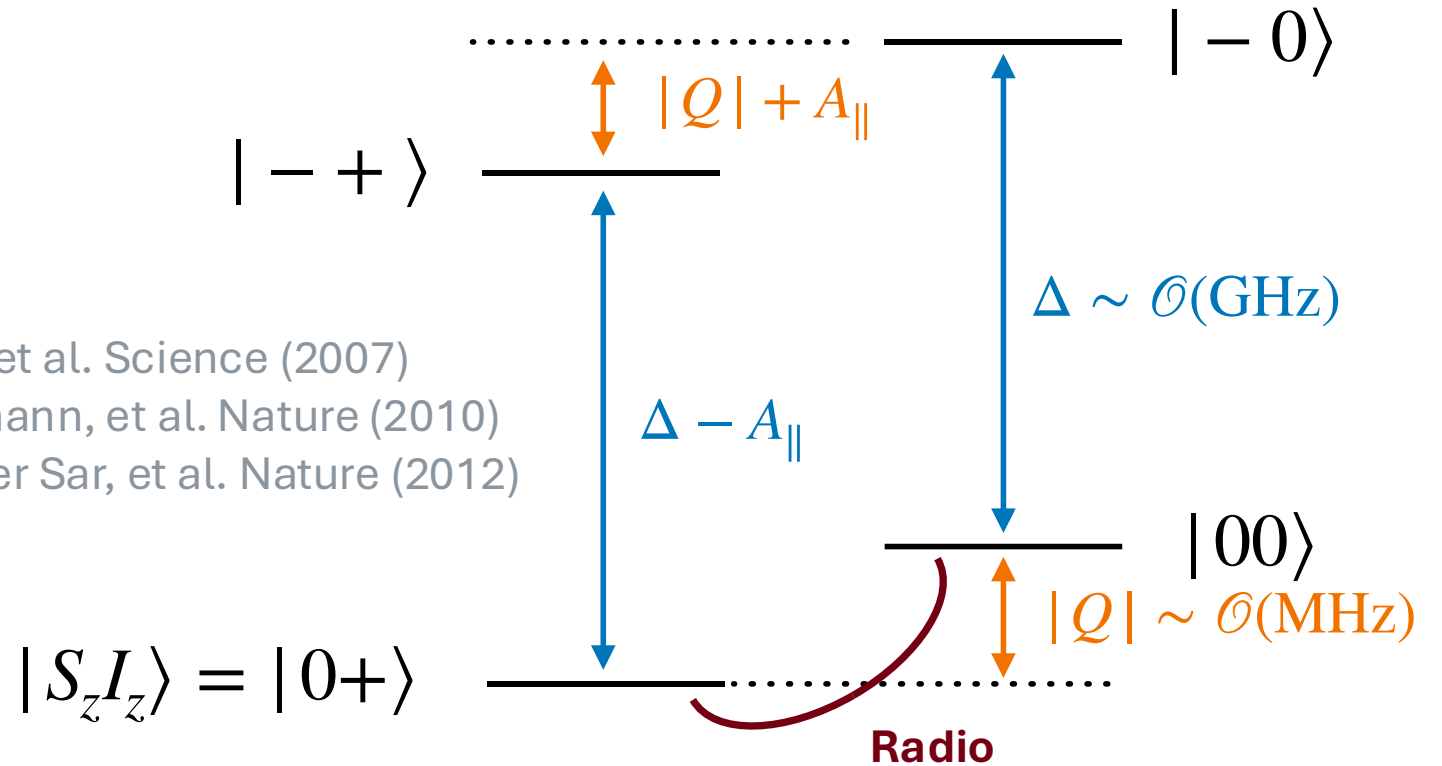
- Hyperfine interaction between e^- and ^{14}N spins ($I = 1$)

$$H_{hyp.} = A_{\parallel} S_z I_z$$

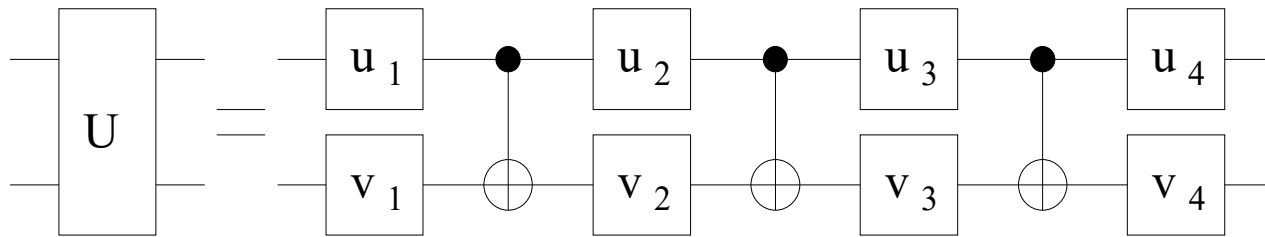
Dutt, et al. Science (2007)
Neumann, et al. Nature (2010)
van der Sar, et al. Nature (2012)

- Causes hyperfine splitting of energy levels

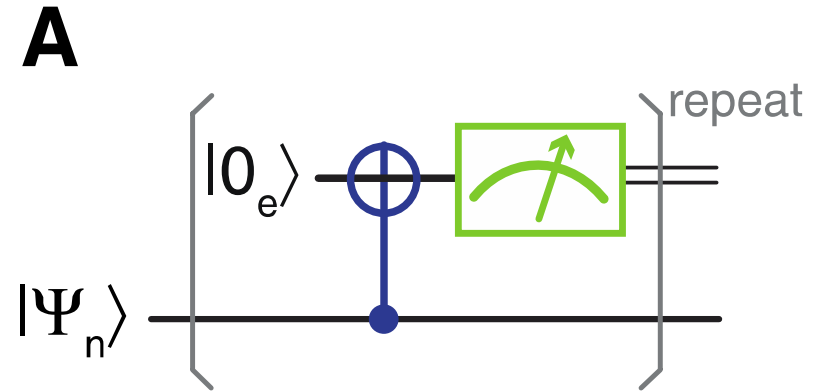
- Full control on two-qubit system of e^- and ^{14}N spins available



General manipulation and read out



Vidal & Dawson, PRA (2003)



Neumann, et al. Nature (2010)

- General $SU(4)$ with ≤ 3 CNOT gates

- Non-demolition measurement of nuclear spin

Axion interaction with ^{14}N spin

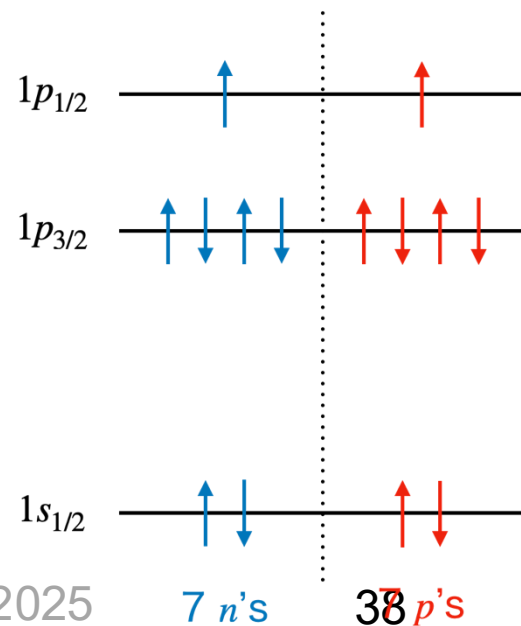
“Introductory Nuclear Physics” by K. S. Krane

- Axion interactions with
 - Orbital angular momentum: None
 - Neutron spins $\propto g_{ann}$
 - Proton spins $\propto g_{app}$
- Need to understand composition of ^{14}N spin
 - Odd-odd nucleus

$$H_{int} = \gamma_{^{14}\text{N}} \vec{B}_a \cdot \vec{I}$$

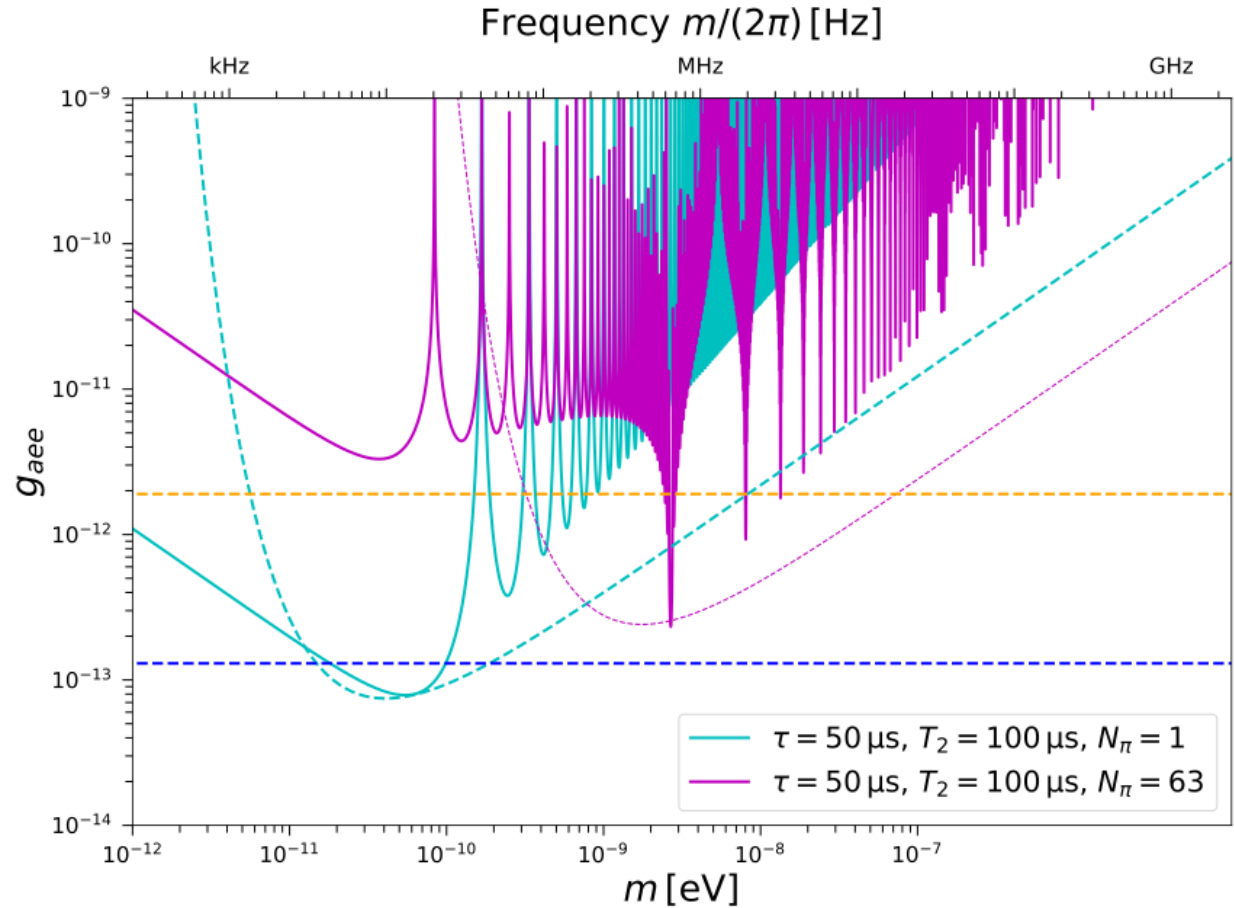
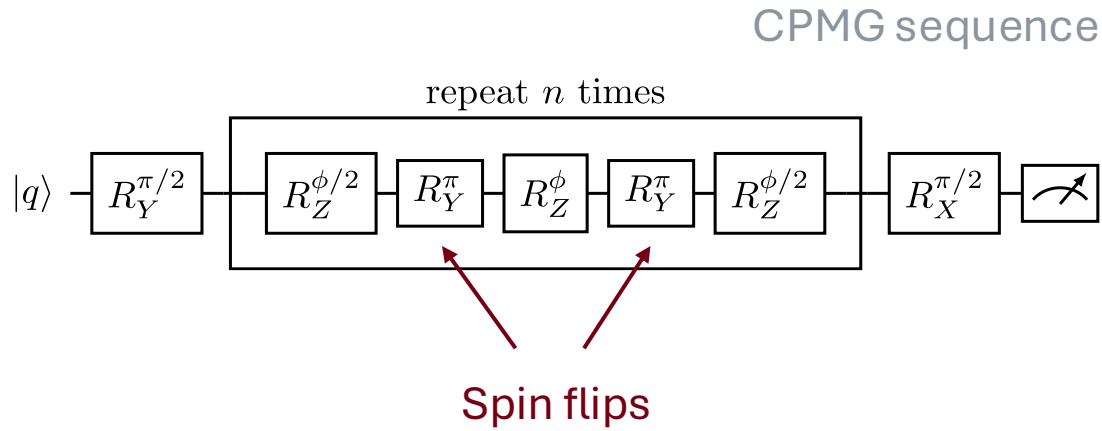
$$\vec{B}_a \propto \frac{1}{6} \left(\frac{g_{ann}}{m_n} + \frac{g_{app}}{m_p} \right)$$

$$\equiv \frac{1}{3\tilde{f}_a}$$



Harmonic Oscillator			Spin-Orbit Potential		
N	ℓ	Spectroscopic Notation	Spin-orbit $\mathcal{O}$	Magic Number	
6	0	4s	$\vdots$	58	184
	2	3d			
	4	2g			
	6	1i			
5	1	3p	$\vdots$	44	126
	3	2f			
	5	1h			
	7	1i			
4	0	3s	$\vdots$	32	82
	2	2d			
	4	1g			
	6	1i			
3	1	2p	$\vdots$	22	50
	3	1f			
	5	1h			
	7	1i			
2	0	2s	$\vdots$	8	28
	2	1d			
	4	1g			
	6	1i			
1	1	1p	$\vdots$	6	8
	3	1f			
	5	1h			
	7	1i			
0	0	1s	$\vdots$	2	2

Decoupling protocols



Longer T_2 with larger n

Longer T_2 with lower T (temperature)



Even narrower-band sensitivity

Sensitivity on g_{aee} (hybrid spin decoupling)

