ECE 550/650 – Intro to Quantum Computing

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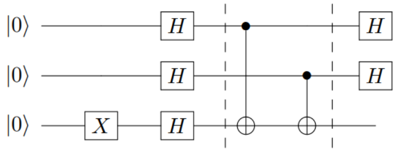
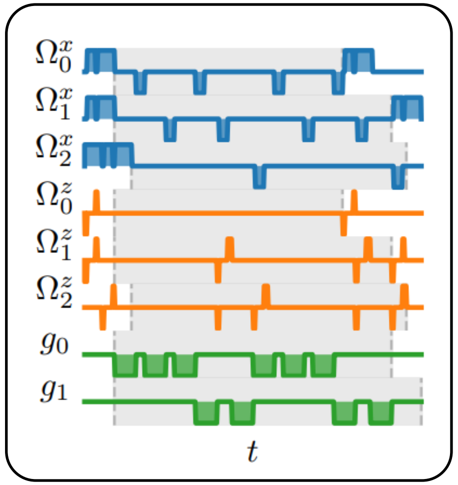
Outline of the course

- Quantum Optics
  - What is interference (classical vs. single particle)
  - Superposition of states
  - Measurement and measurement basis
- Atomic physics
  - Spin states in magnetic fields and spin transitions
  - Transitions between atomic states (Rabi oscillations of qubits)
- Single qubits
  - Single qubit gates (electro-magnetic pulses, RF, MW, phase)
  - Error sources (dephasing, spontaneous decay)
  - Ramsey pulses and Spin echo pulse sequences
  - Calibration (finding resonance and verifying pulse time and amplitudes)
- Two qubit gates
  - Two qubit interactions – gate speed vs. error rates
  - Entanglement – correlation at a distance
  - Bell states and the Bell basis
  - XX gates, Controlled Phase gates, Swap




```
qc = QubitCircuit(3)
qc.add_gate("X", targets=2)
qc.add_gate("SNOT", targets=0)
qc.add_gate("SNOT", targets=1)
qc.add_gate("SNOT", targets=2)

# Oracle function f(x)
qc.add_gate(
    "CNOT", controls=0, targets=2)
qc.add_gate(
    "CNOT", controls=1, targets=2)

qc.add_gate("SNOT", targets=0)
qc.add_gate("SNOT", targets=1)
```



- Quantum Hardware
  - Photonics – nonlinear phase shifts
  - Transmons – charge noise, SWAP gate
- Quantum Circuits
  - Single and two qubit gates
  - Hadamard gate , CNOT gate
- Quantum Algorithms
  - Amplitude amplification
  - Grover's Search
  - Oracle - Deutsch Jozsa
  - Bernstein Vazirani
  - Quantum Fourier Transform and period finding
  - Shor's algorithm

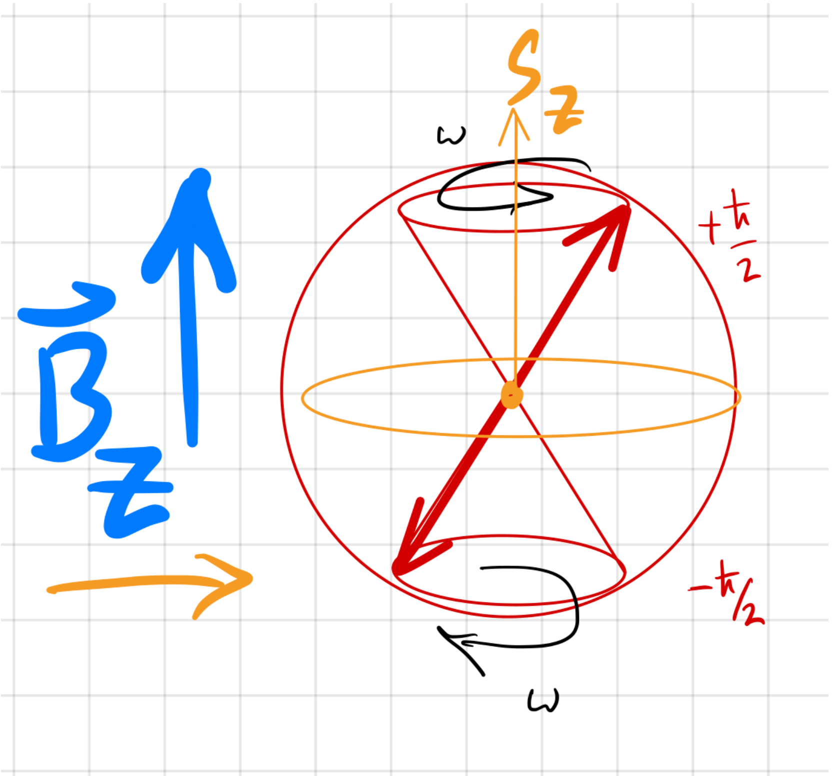
If time permits

- Error Correction
  - Repetition codes
  - Color Codes
  - Surface code

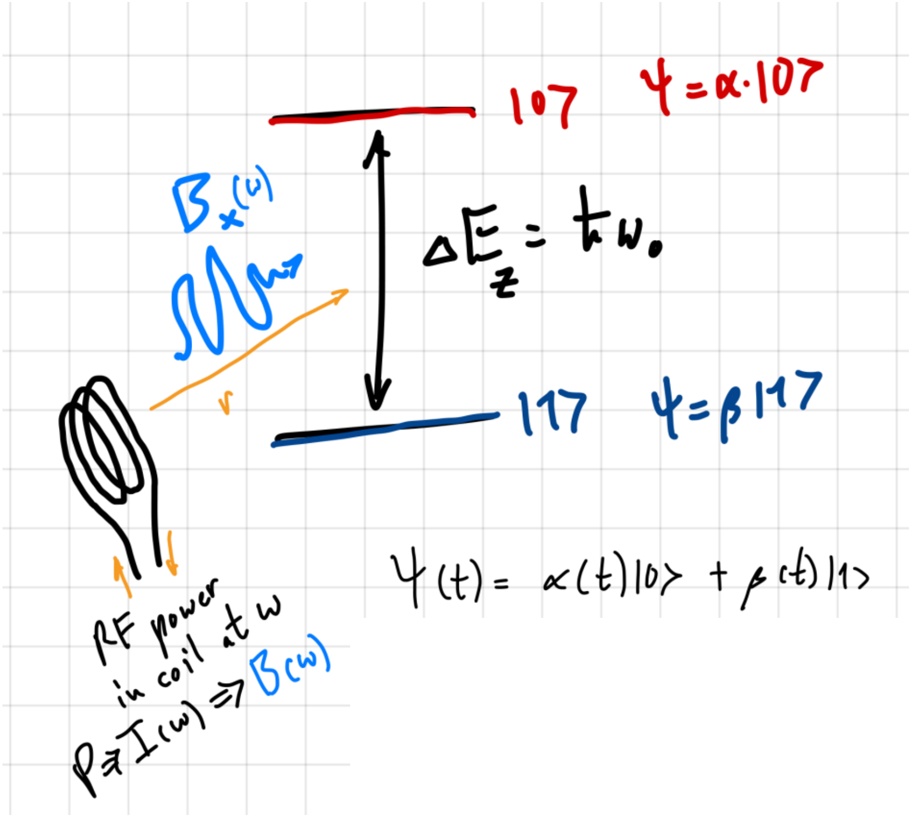
Lecture 3/3

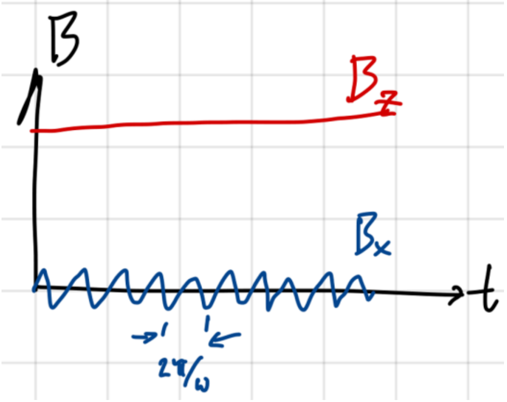
Applying Radiation (B_x) to Control Qubit State

Strong applied Field ($\overrightarrow{B_z}$) = Defines Basis

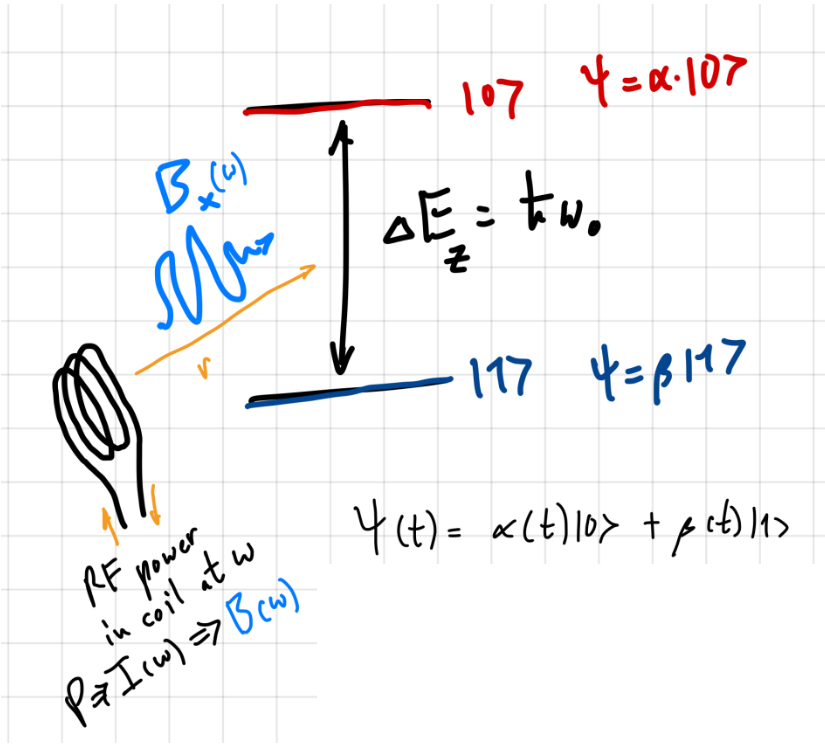


Smaller perturbation($\overrightarrow{B_X}(t)$)
→ Rotates state in stronger fields basis





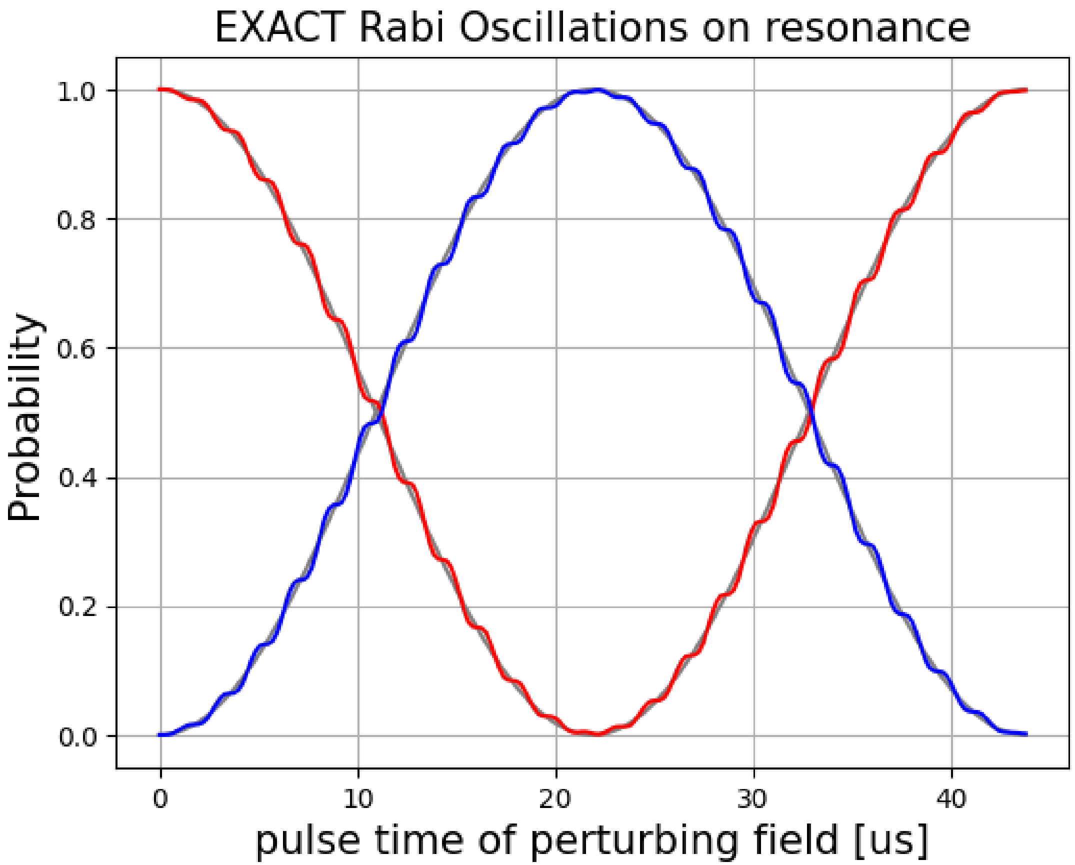
Calculate Coupling with realistic experimental parameters

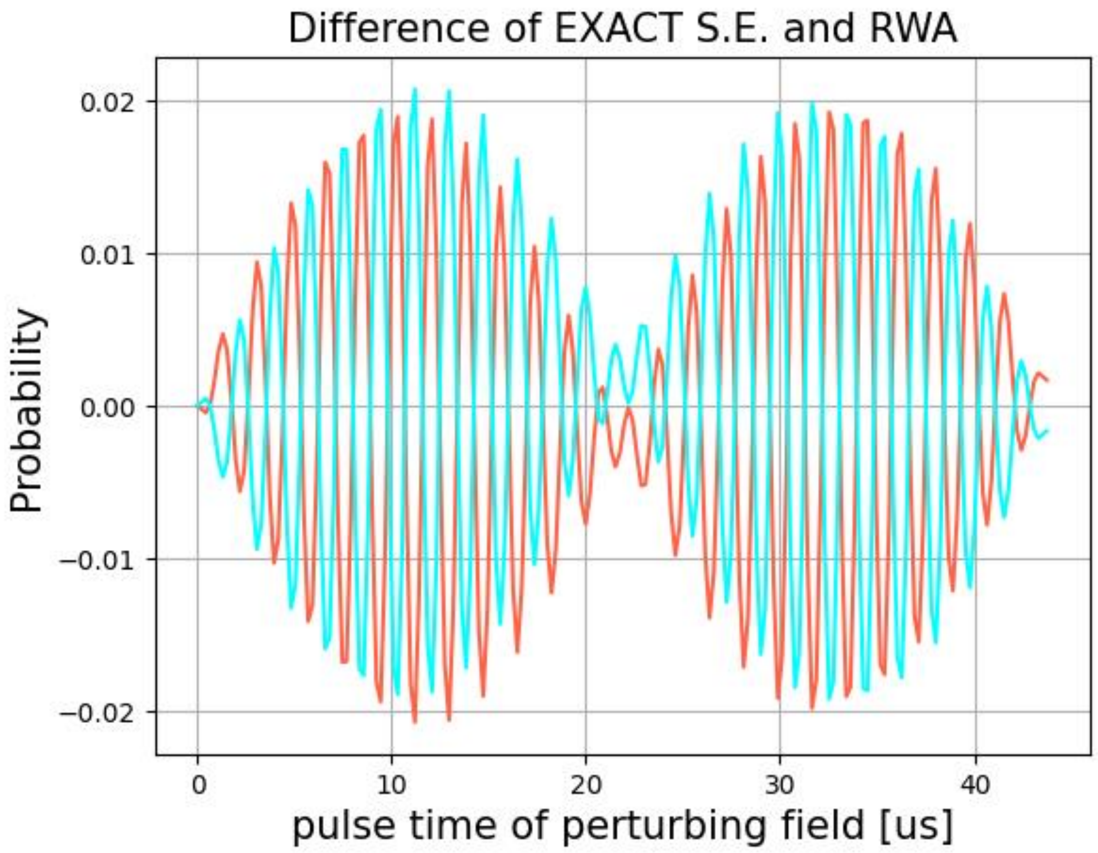



```python
'''Calculate the Rabi coupling rate from first principles'''
from scipy import constants as const
g_s = 2 # Land´e g-factor of the spin ( ~2)

'''Specify the geometry of the antenna applying the radiation to the spin'''
power = 0.05 # applied RF power in Watts ( 50 mW )
print('Applied Power = ', round(power,3) , '[W]')

r = 0.01 # Distance from antenna in meters ( 10 cm )
print('Distance from antenna to spin = ', round(r,3) , '[m]')

irradiance = power/(4*pi*r**2) #Irradiance from the antenna at the spin spreads out over a sphere
print('Irradiance = ', round(irradiance,3) , '[W/m^2]')

Bfield_AC = 2* sqrt( const.mu_0 / const.c * irradiance)
print('Bfield_AC =', round(Bfield_AC*1e4,4), '[Gauss]')

'''Omega_Rabi coupling from the applied perturbing magnetic field'''
Omega_Rabi_rads = const.value('Bohr magneton')*g_s*Bfield_AC / const.hbar #units of radians/second
Omega_Rabi_freq = Omega_Rabi_rads / (2*pi) # Convert from radians/second to revolutions/second (Hz)
period_Omega_Rabi = 1 / Omega_Rabi_freq # Calculating the period of a full oscillation in seconds

print('Rabi coupling rate= ', round(Omega_Rabi_freq/1e3,2),'[kHz]')
print('Period of Rabi flopping = ', round(period_Omega_Rabi*1e6,2) ,'[us]')
```

```
Applied Power =  0.05 [W]
Distance from antenna to spin =  0.01 [m]
Irradiance =  39.789 [W/m^2]
Bfield_AC = 0.0082 [Gauss]
Rabi coupling rate=  22.86 [kHz]
Period of Rabi flopping =  43.74 [us]
```

RWA – vs – Exact integration of the Schrodinger Equation





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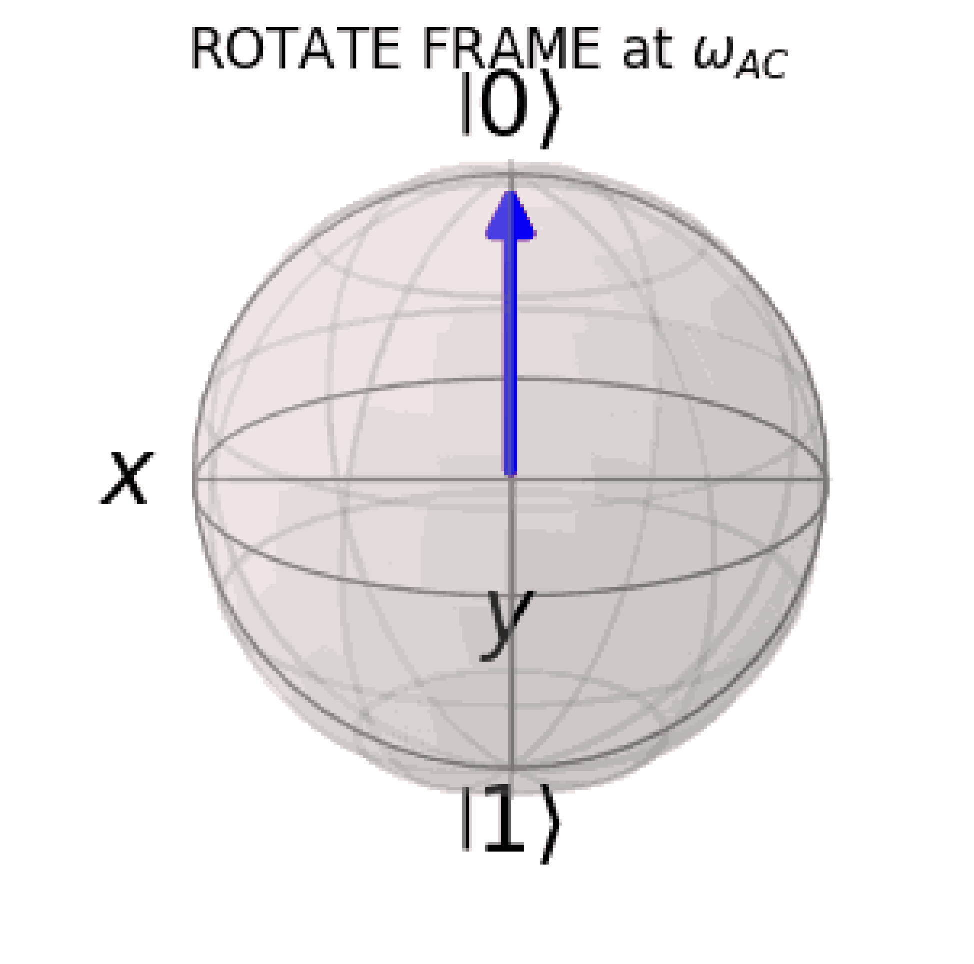
Rotating Frame - with residual relative rotation (***detuning***!)



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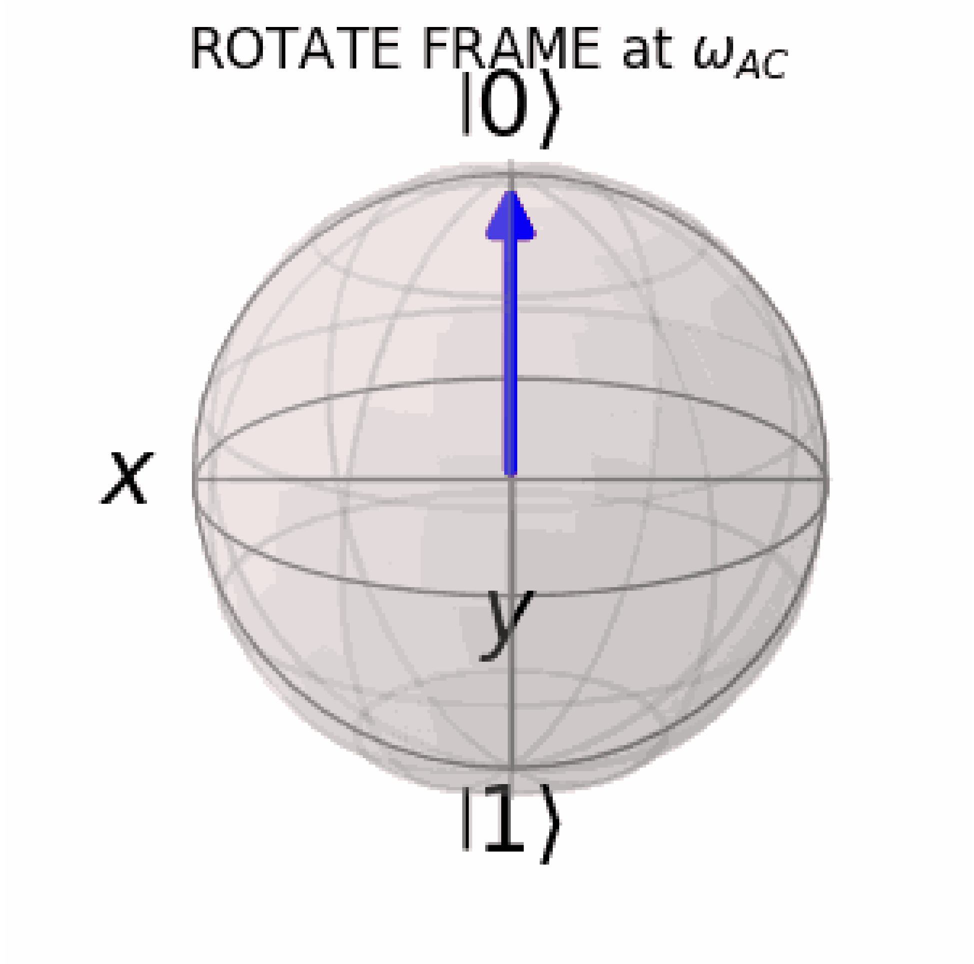
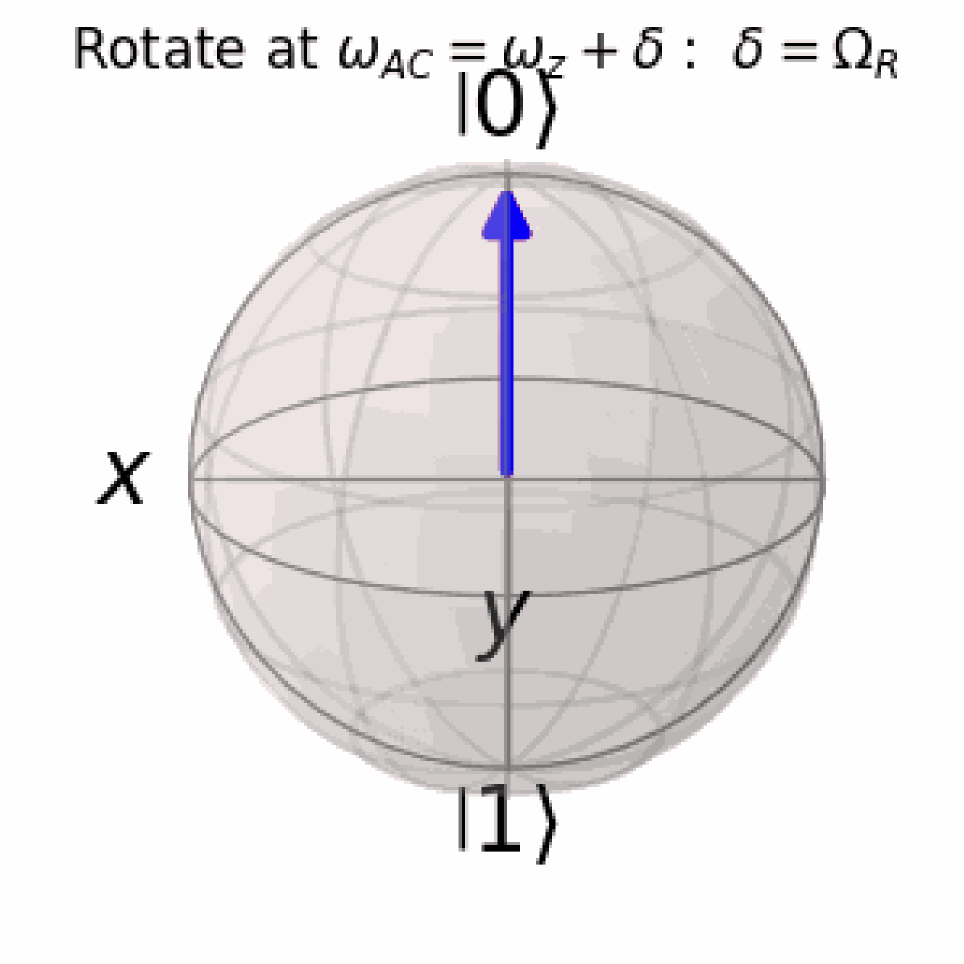
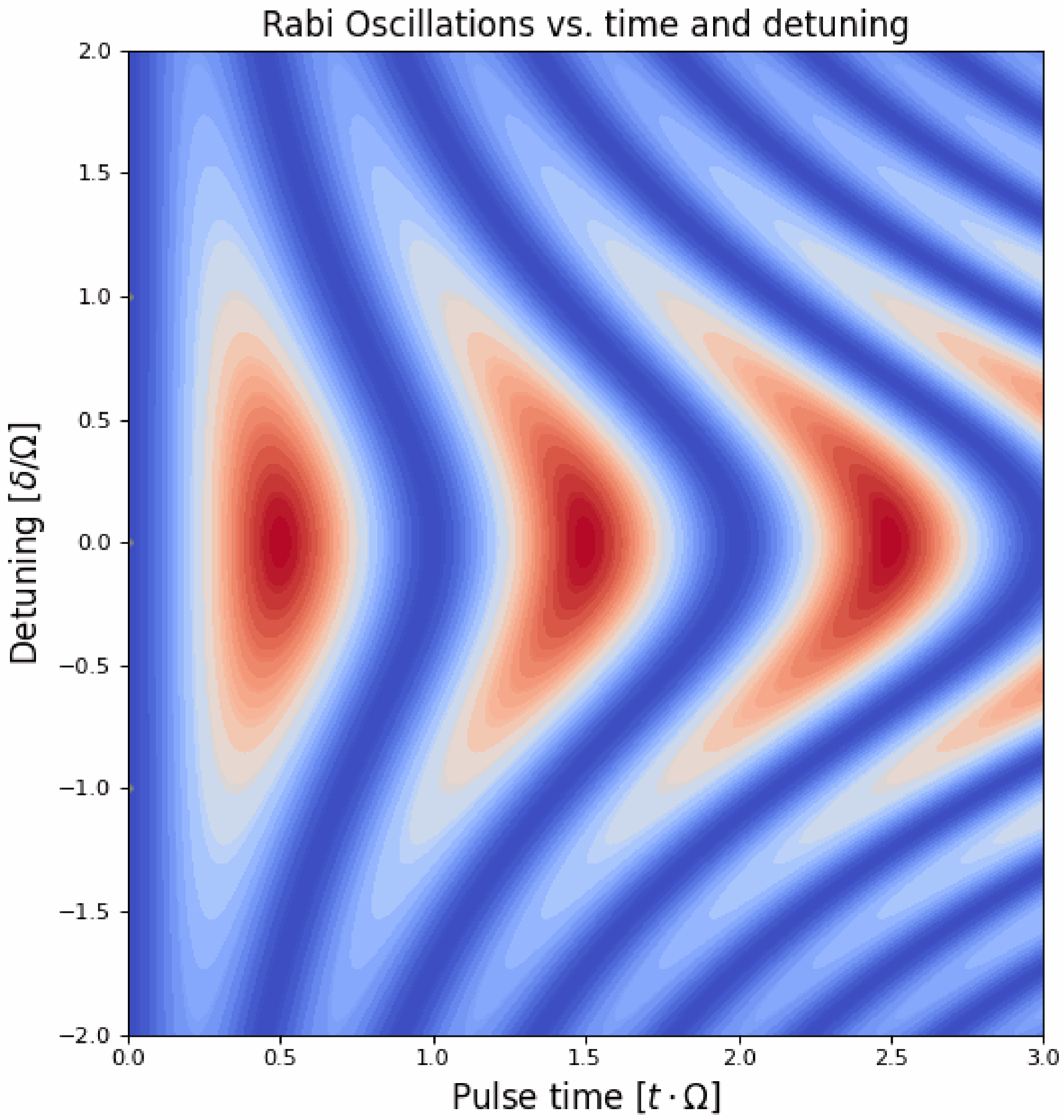
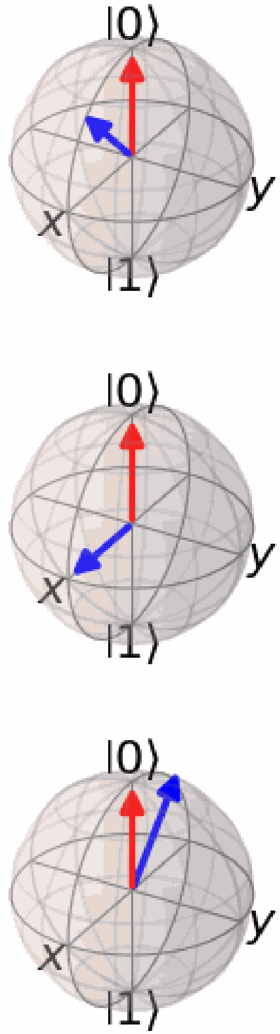
Rotating Frame - with residual relative rotation (***detuning***!)







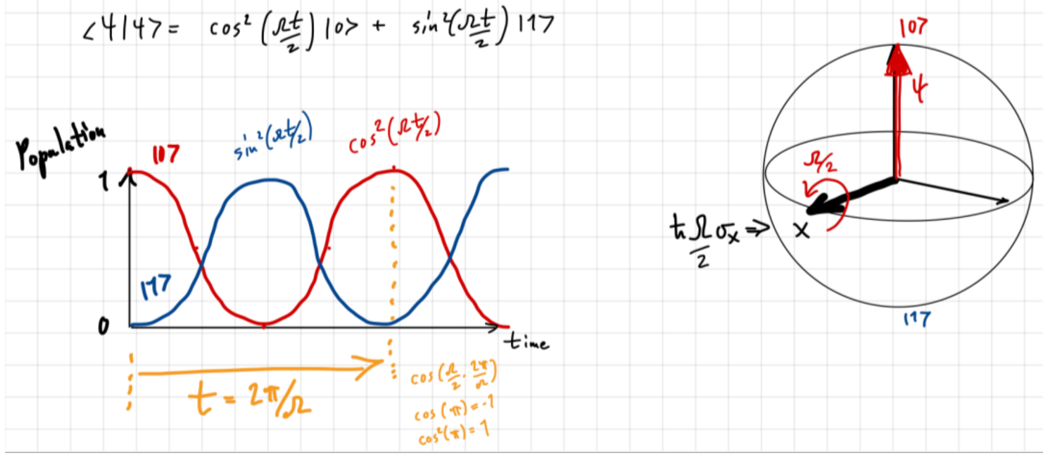
Rabi Oscillations vs. time and detuning
Detuning [δ/Ω]
Pulse time [$t \cdot \Omega$]
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0

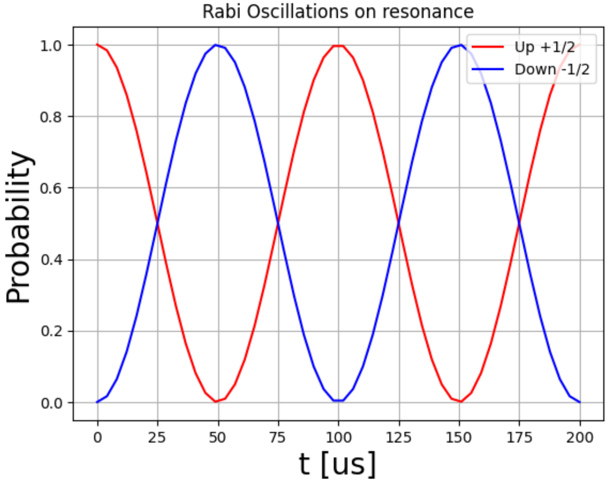


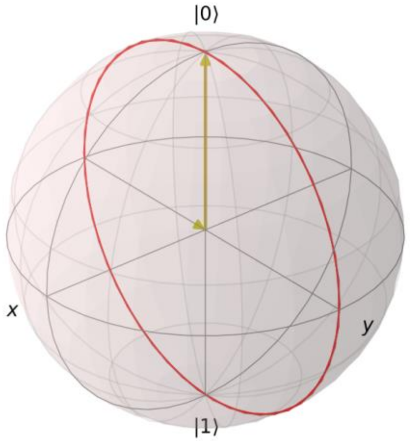
$|0\rangle$
$|1\rangle$
x
y
$|0\rangle$
$|1\rangle$
x
y
$|0\rangle$
$|1\rangle$
x
y

Pulses vs. Detuning

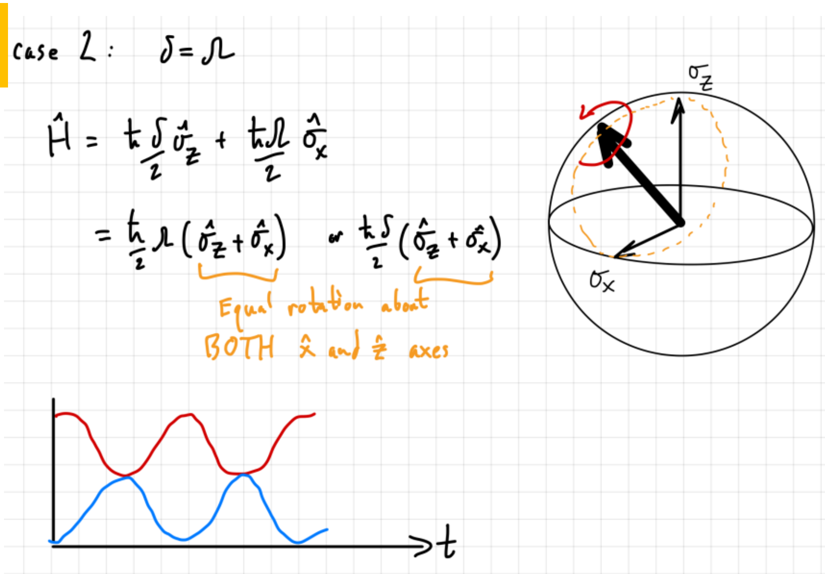
$\delta = 0$

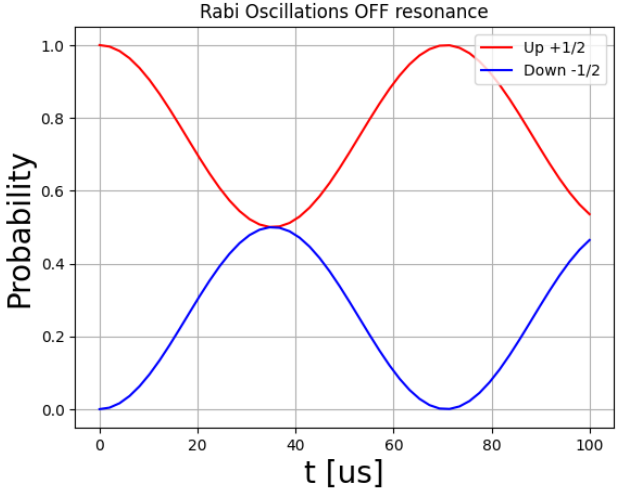


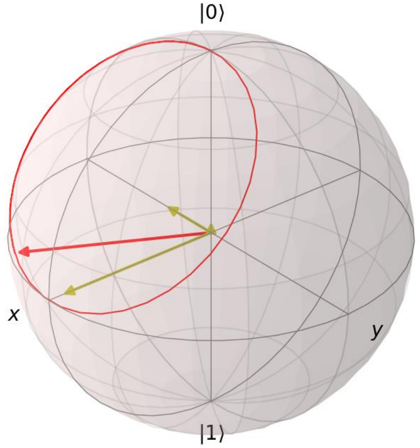




$\delta = \Omega$







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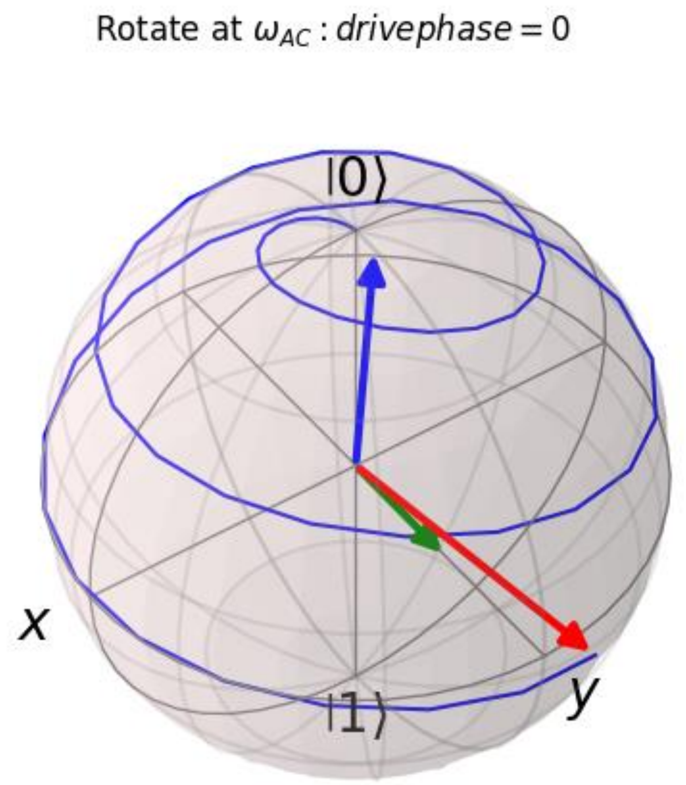
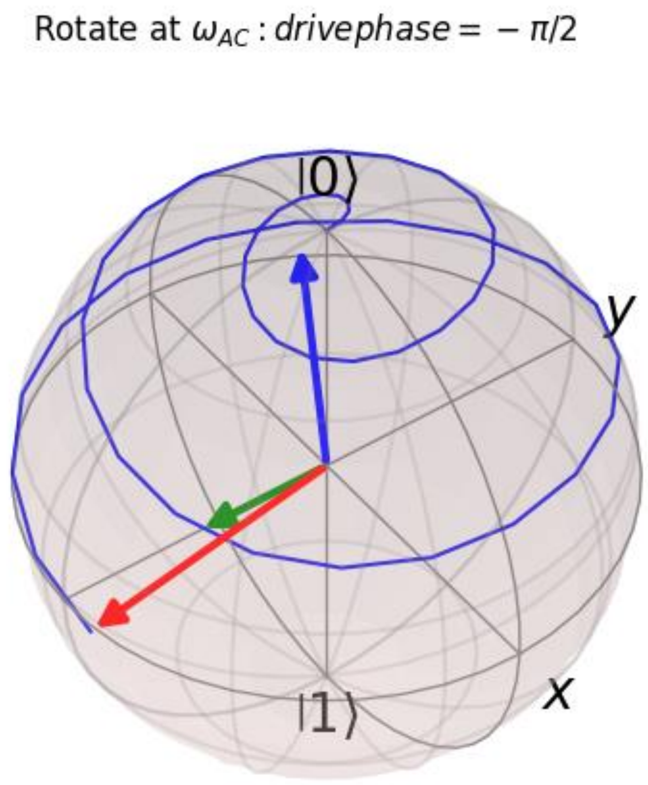
X –vs- Y – in a rotating frame???





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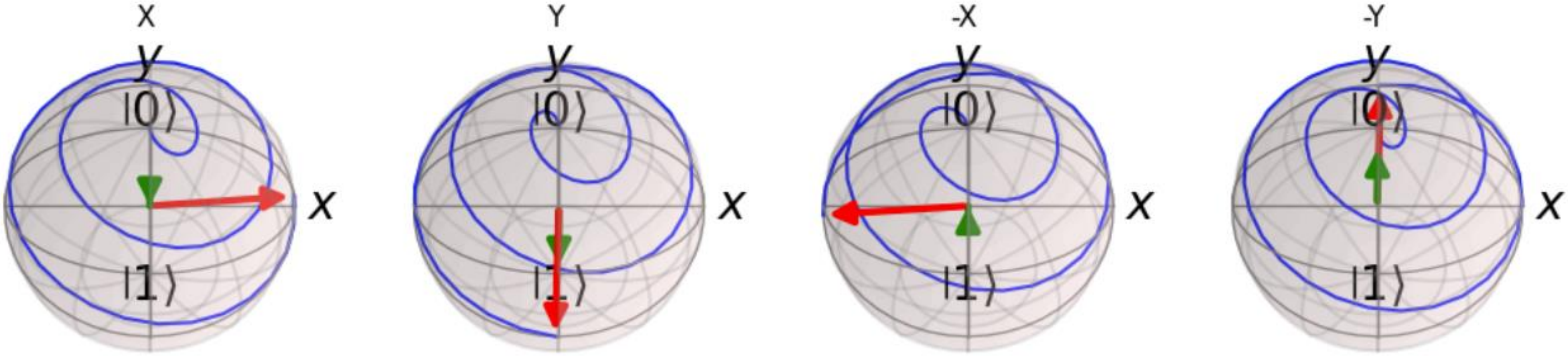
X , Y , -X , -Y : Rotation axis set by phase of drive



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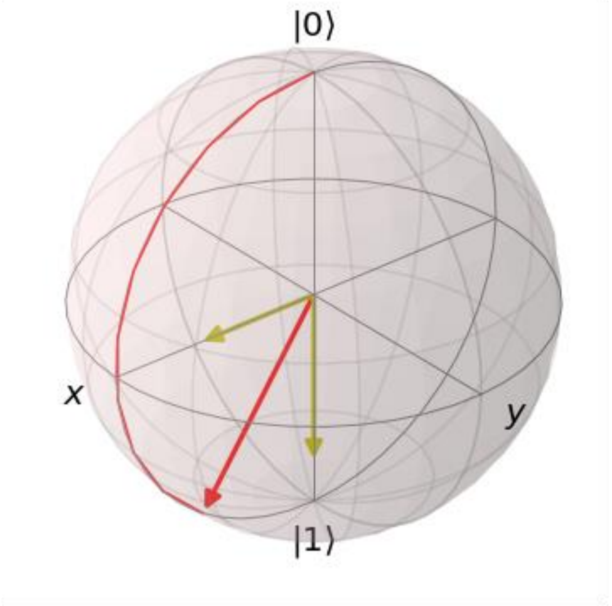
Short pulses (Amplitude Noise)

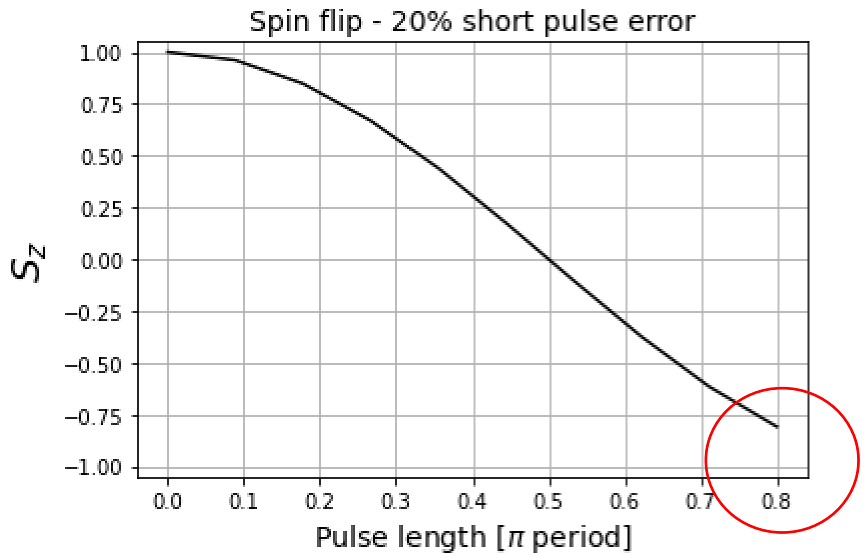
```
'''
Hamiltonian of the RY pulse
'''
HX = Omega/2*sigmay()

'''
Setup pulse timing

Add 20% Error to the amplitude of the field (or equivalently
to the timing of the pulse)

'''
percent_error = 0.20
pulse_error= 1-percent_error
times = np.linspace(0, pulse_error*(pi)/Omega, 10) # pi pulse
with error
```





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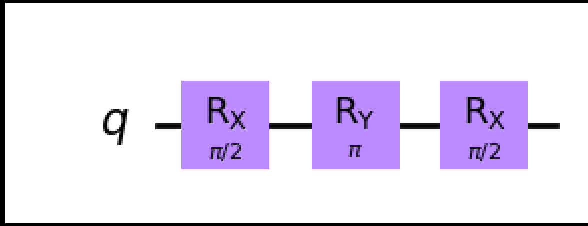
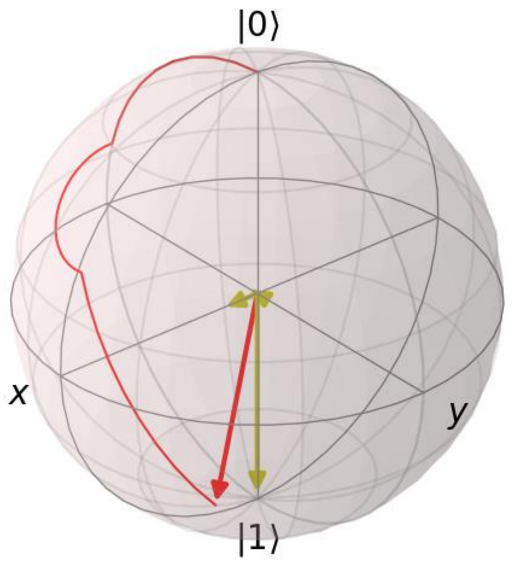
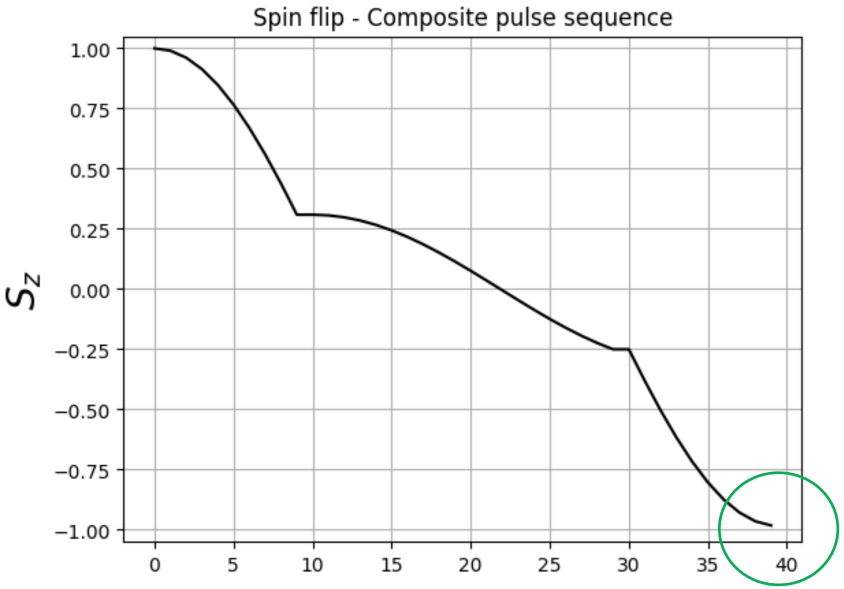
Spin Echo

```
'''
Circuit representation
'''
qc = QubitCircuit(1)

rotation = pi

qc.add_gate("RX", 0, arg_value=rotation/2)

qc.add_gate("RY", 0, arg_value=rotation)

qc.add_gate("RX", 0, arg_value=rotation/2)

qasmstr = circuit_to_qasm_str(qc) #Convert to QASM
qkqc = QuantumCircuit.from_qasm_str(qasmstr)#Import to Qisket
qkqc.draw('mpl')# Draw the circuit using QISKET
```







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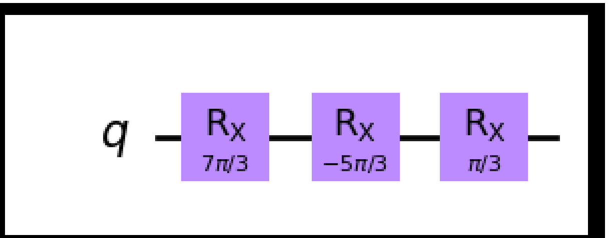
Compensation for Off-Resonance with a Pulse SEquence (CORPSE) - Frequency noise

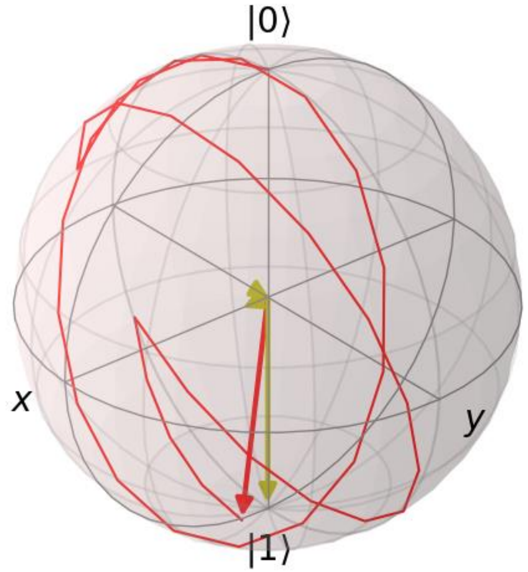
```
'''
Circuit representation
'''
qc = QubitCircuit(1)

qc.add_gate("RX", 0, arg_value=7*pi/3)

qc.add_gate("RX", 0, arg_value=-5*pi/3)

qc.add_gate("RX", 0, arg_value=pi/3)

qasmstr = circuit_to_qasm_str(qc) #Convert to QASM
qkqc = QuantumCircuit.from_qasm_str(qasmstr)#Import to Qisket
qkqc.draw('mpl')# Draw the circuit using QISKET
```

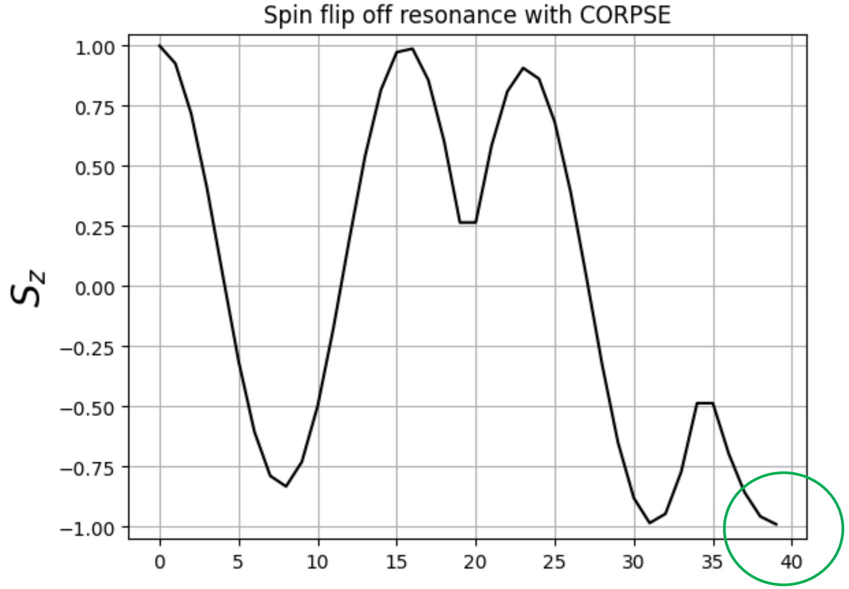


$\Omega = 100.0[kHz]$

Period= 10.0 [us]

$\delta = 30.0[kHz]$





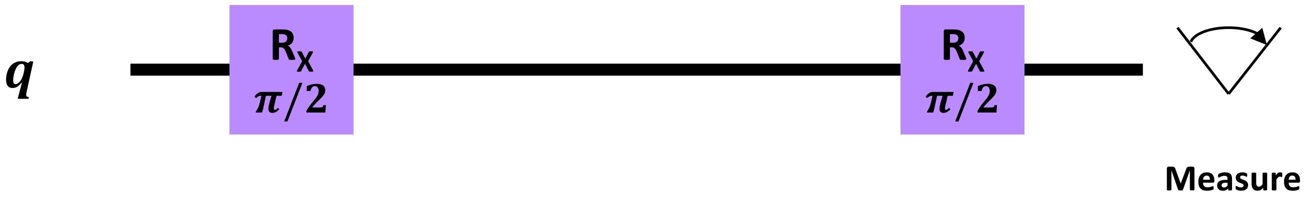
Common Composite Pulse Sequences

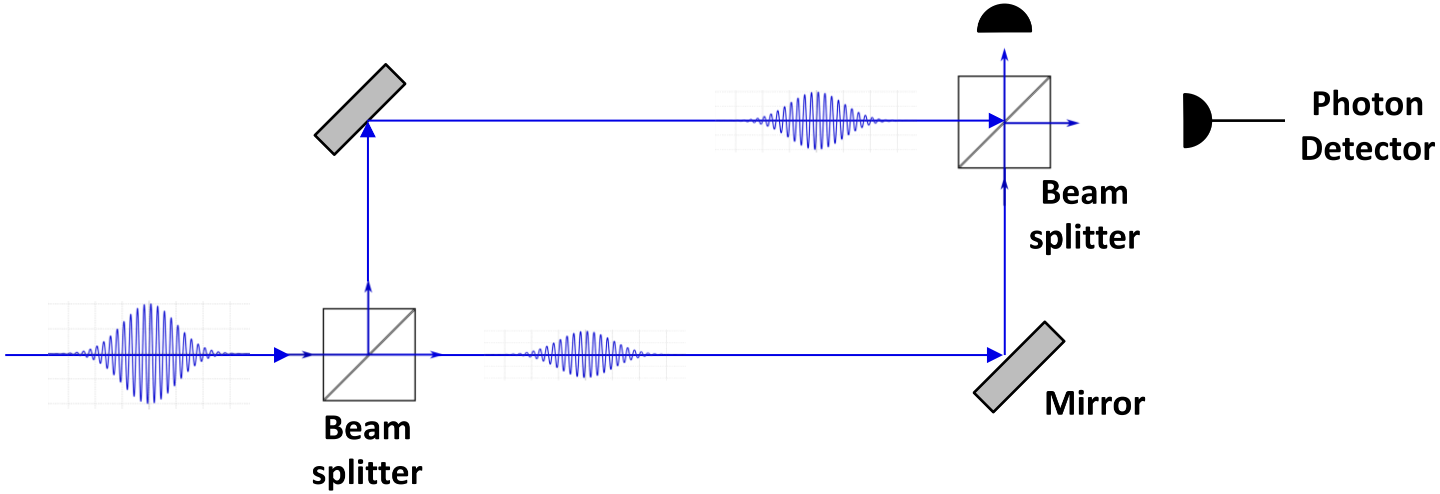
Composite Pulse	Type	Rotation Sequence $\theta_\phi \ldots$	Leading order		total angle	$\mathcal{F}(\sigma^+ - \sigma^+)$	$\mathcal{F}(\pi^+ - \pi^-)$
Rabi π-pulse	GR	180_0	ϵ^2	f^2	180°	0.47	0.73
CORPSE	GR	$60_0 300_{180} 420_0$	ϵ^2	f^4	780°	0.61	0.79
KNILL	GR	$180_{240} 180_{210} 180_{300} 180_{210} 180_{240}$	ϵ^4	f^4	900°	0.64	**0.89**
BB1	GR	$180_{104.5} 360_{313.4} 180_{104.5} 180_0$	ϵ^6	f^2	900°	0.56	0.80
90-360-90	PP	$90_0 360_{120} 90_0$	ϵ^6	f^2	540°	0.59	0.82
SCROFULOUS	GR	$180_{60} 180_{300} 180_{60}$	ϵ^6	f^2	540°	0.44	0.72
LEVITT	PP	$90_{90} 180_0 90_{90}$	ϵ^6	f^2	360°	0.70	0.86
90-240-90	GR	$90_{240} 240_{330} 90_{240}$	ϵ^2	f^2	420°	0.63	0.88
90-225-315	PP	$90_0 225_{180} 315_0$	ϵ^2	f^2	630°	0.71	**0.89**
WALTZ	PP	$90_0 180_{180} 270_0$	ϵ^2	f^2	540°	**0.77**	0.88

TABLE I. Common composite inversion pulses. The theoretical fidelity $\mathcal{F}$ depends upon the atom cloud temperature as shown in Figure 8, and is from simulations for typical parameters given in Table II. Bold values indicate best performance at $\delta = 0$, which reflects the leading-order terms in the fidelity and their coefficients. PP: point-to-point, GR: general rotor.

Lecture - 3/5

Mach Zehnder/Ramsey Interferometer





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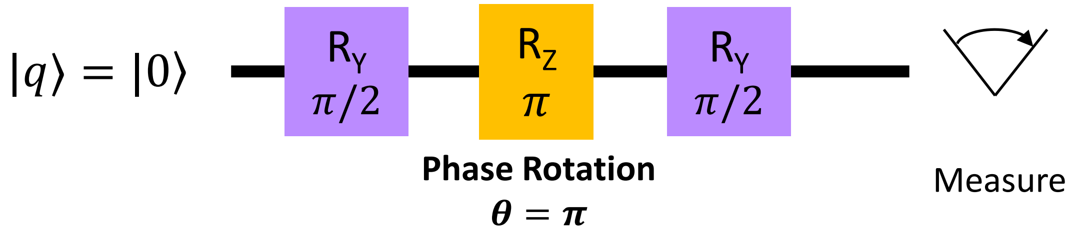
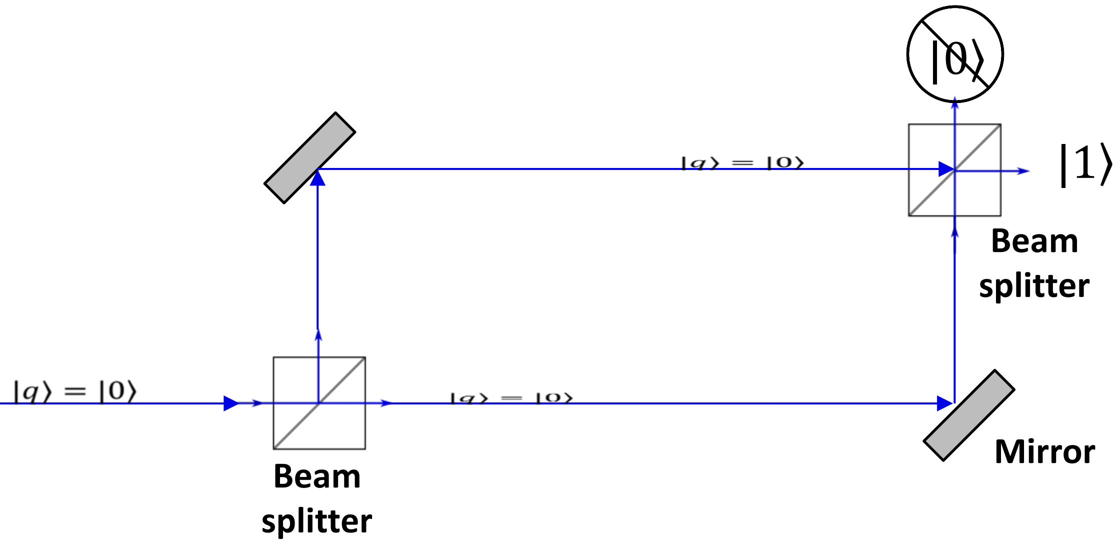
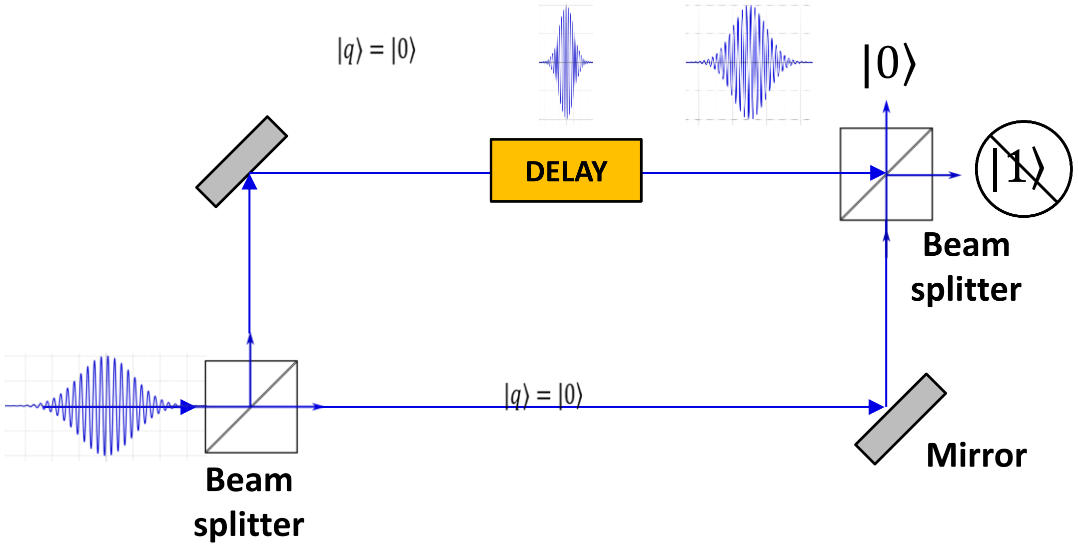
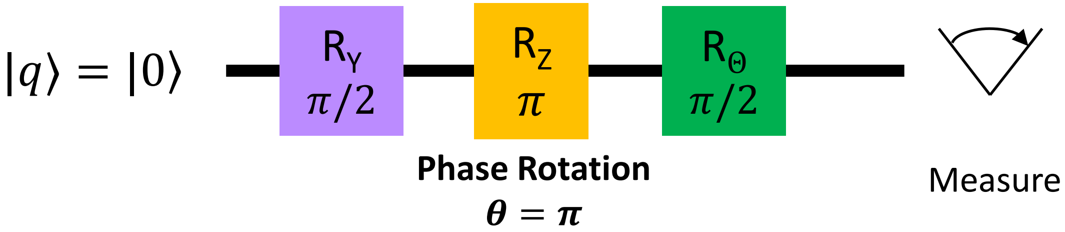
MZI = Ramsey Interferometer

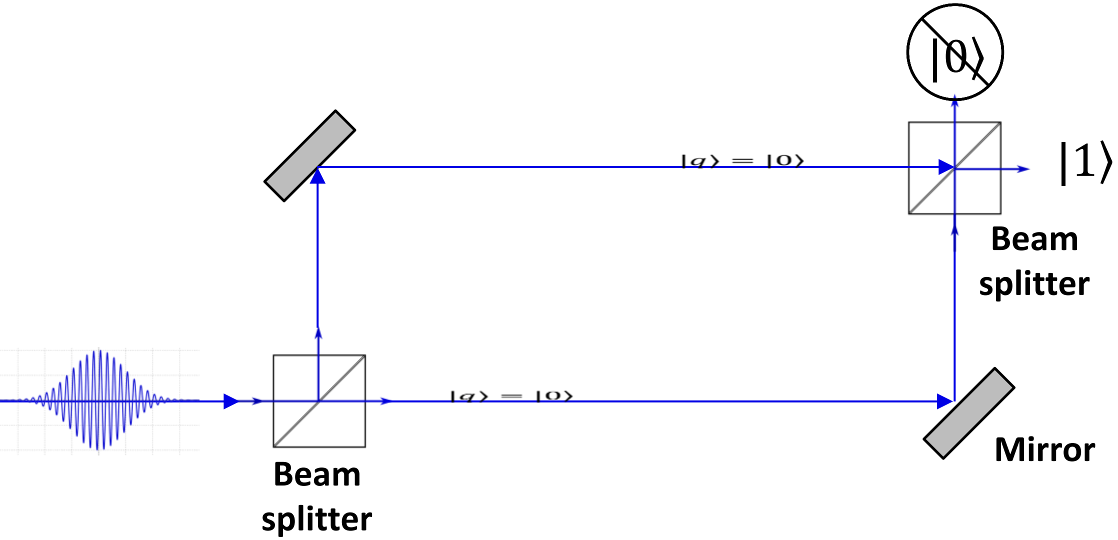


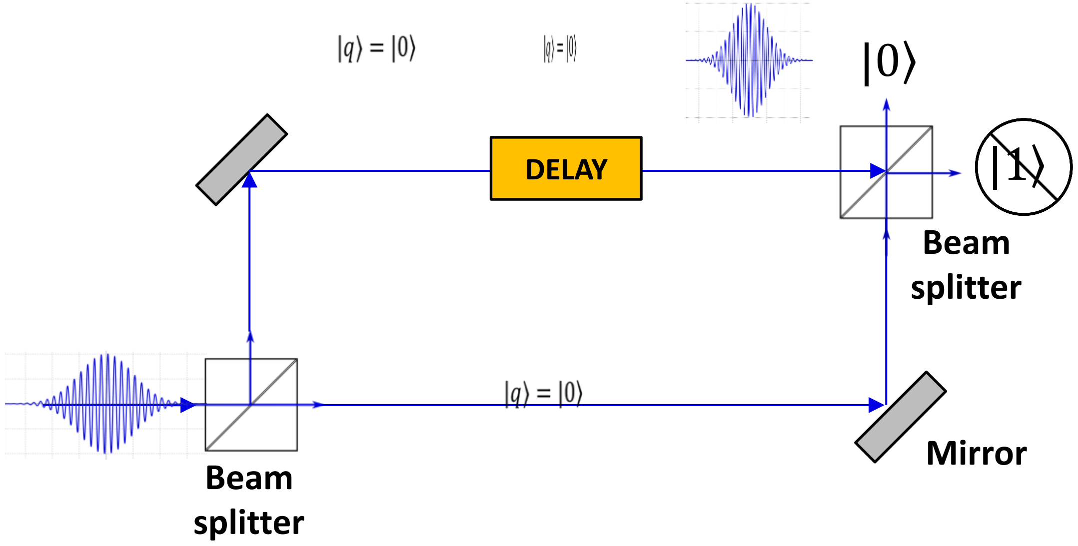




MZI = Ramsey







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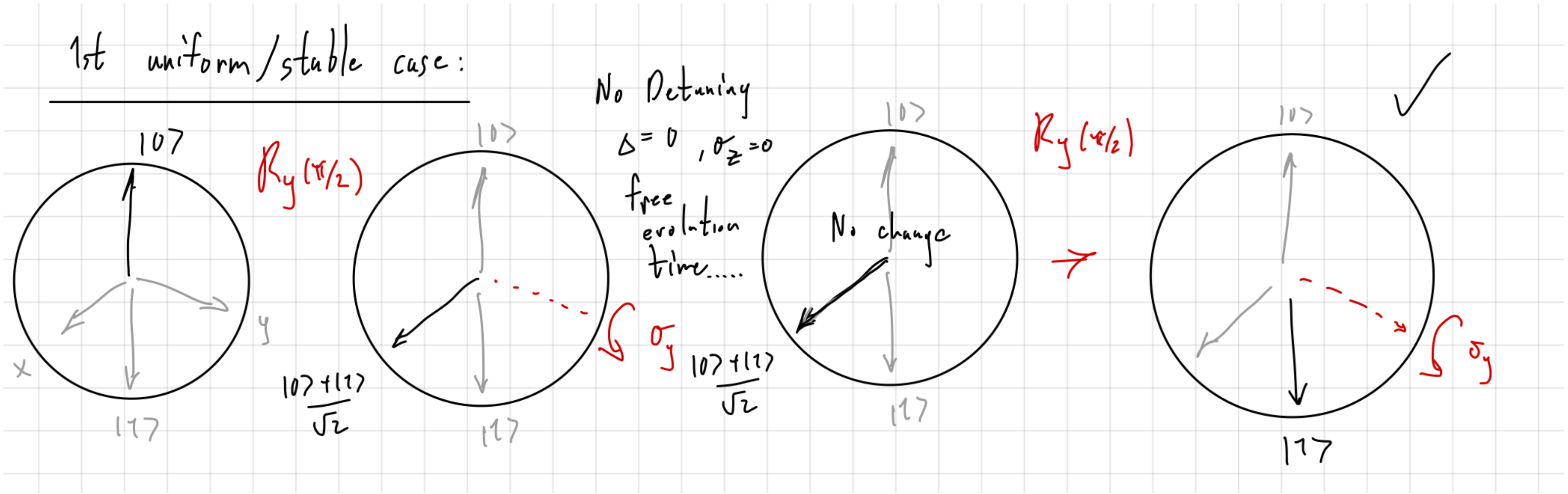
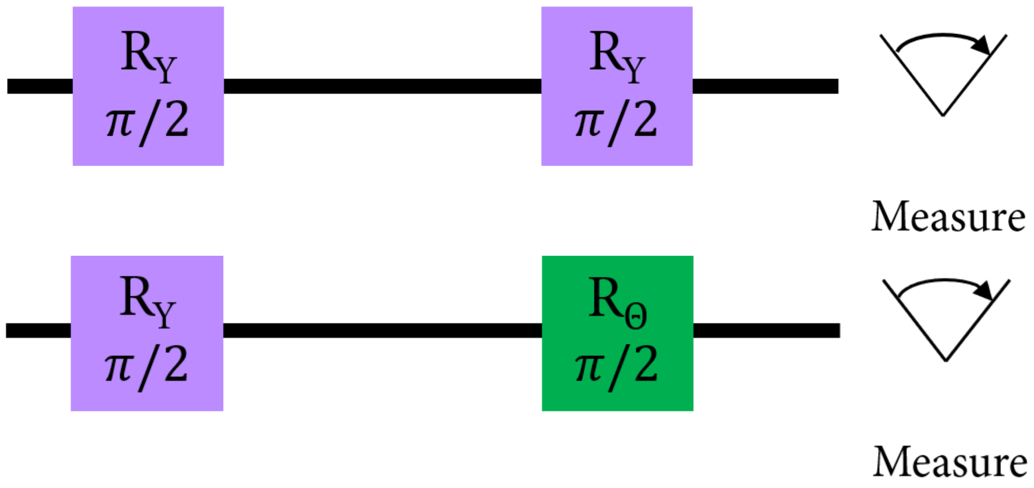
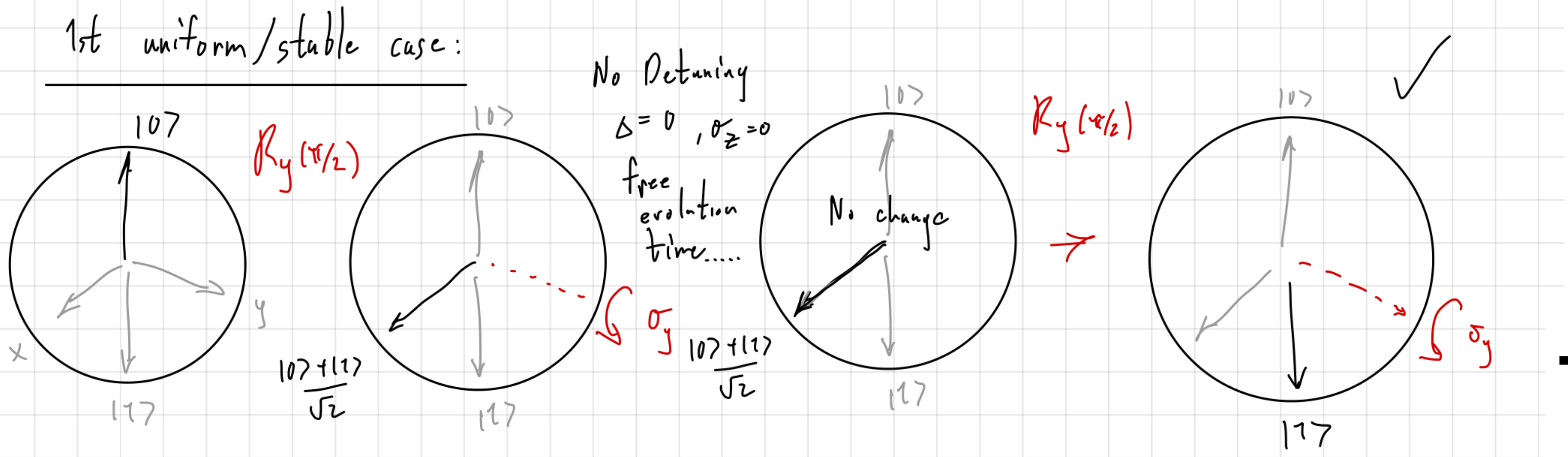
Ramsey Interference

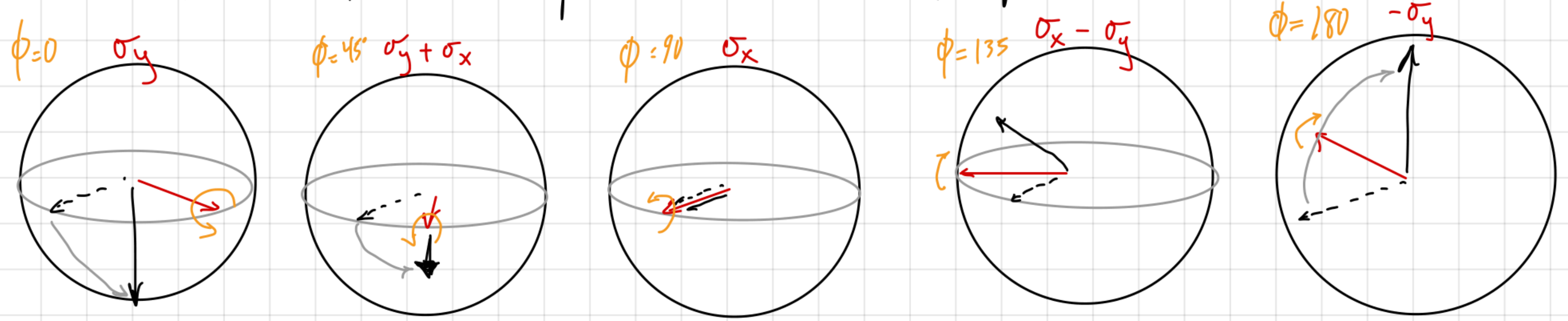


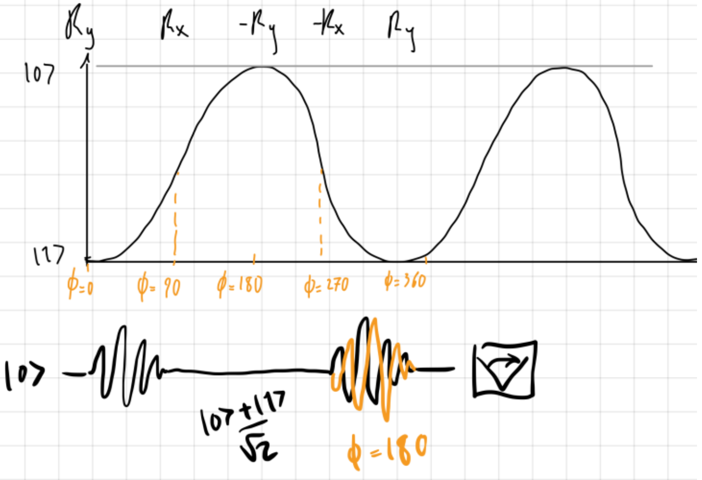


Ramsey Interference



However, if we rotate the phase of the final π/2 pulse we can also rotate about X





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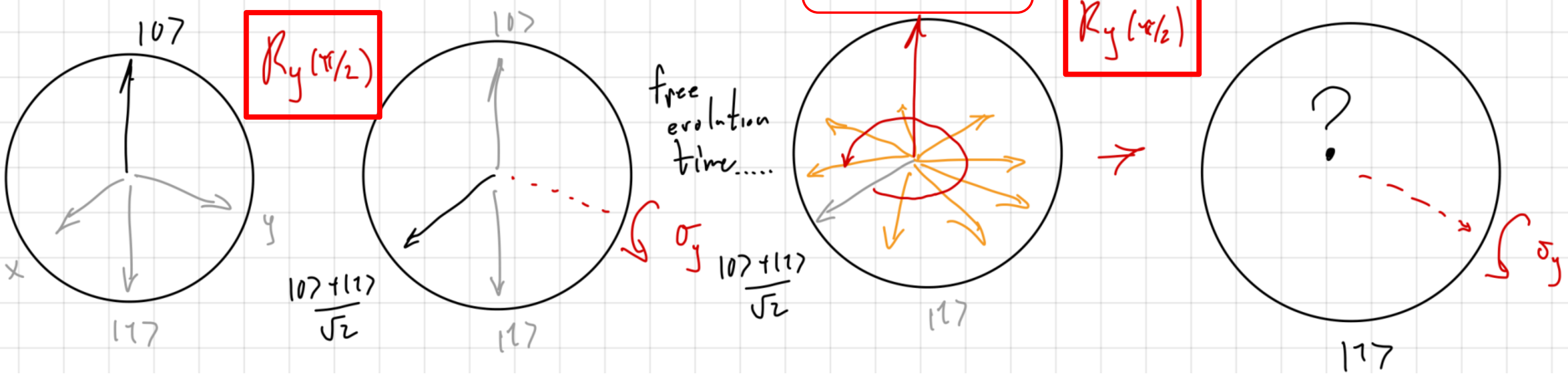
However, if $\Delta \neq 0$, detuning is not zero....?

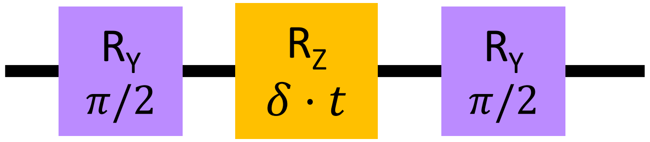
2nd, uniform detuned case:

$\Delta \neq 0$

$\boxed{R_z\left(\frac{\hbar\Delta}{2} \cdot t\right)}$

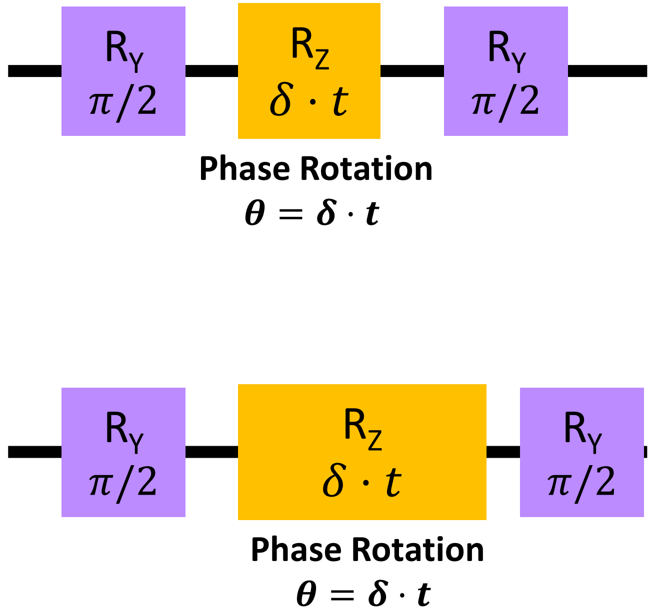
Time dependent!



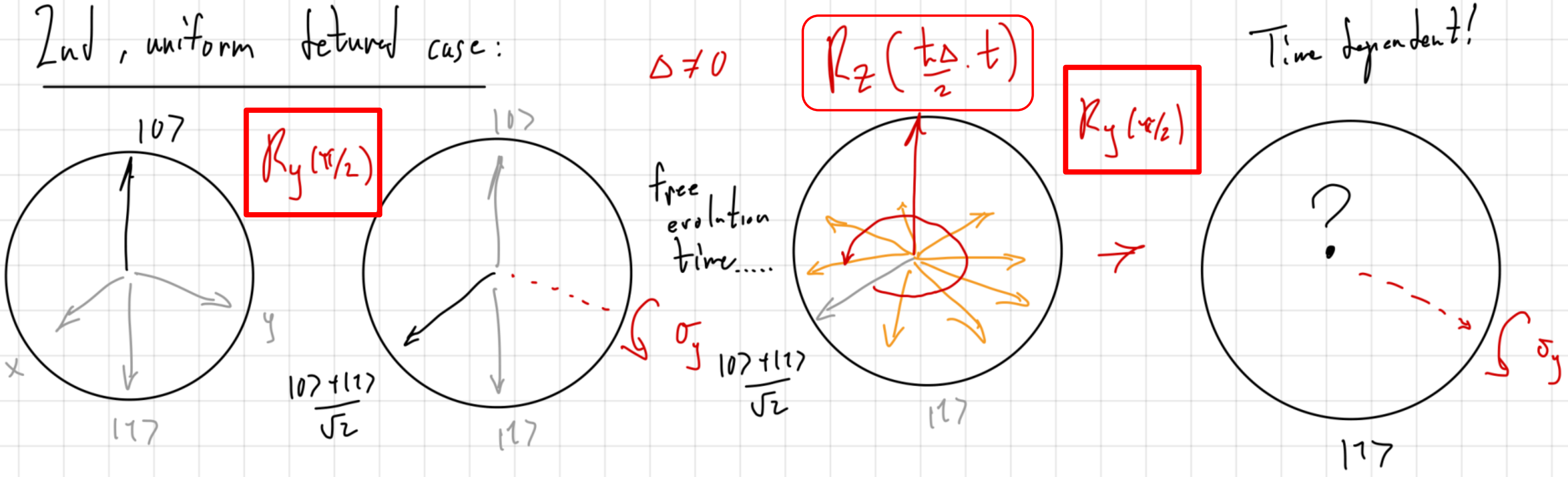


Phase Rotation
$\boldsymbol{\theta = \delta \cdot t}$

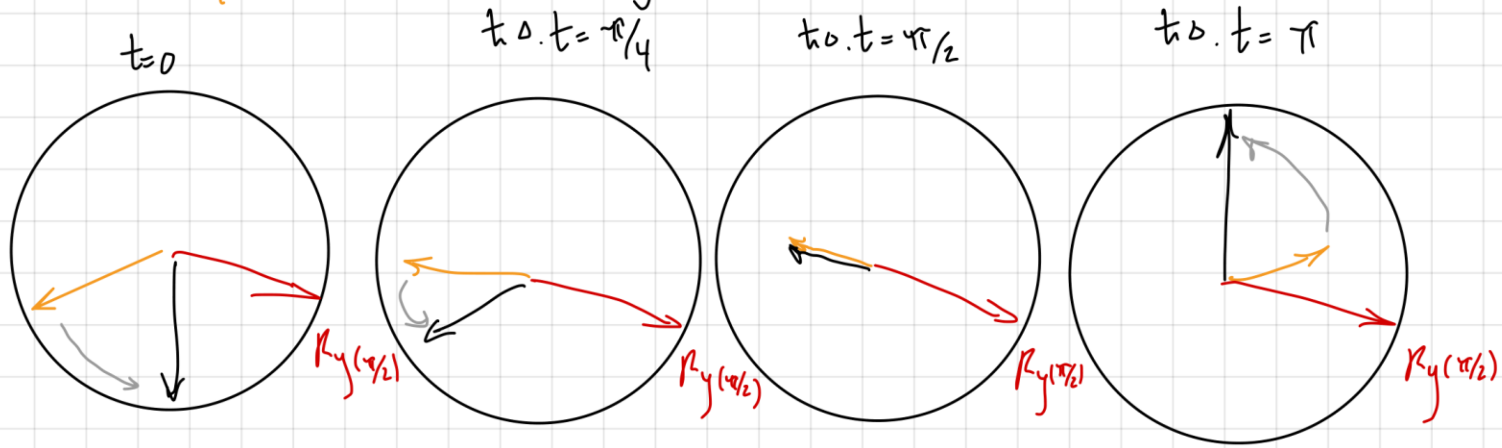
However, if $\Delta \neq 0$, detuning is not zero....?

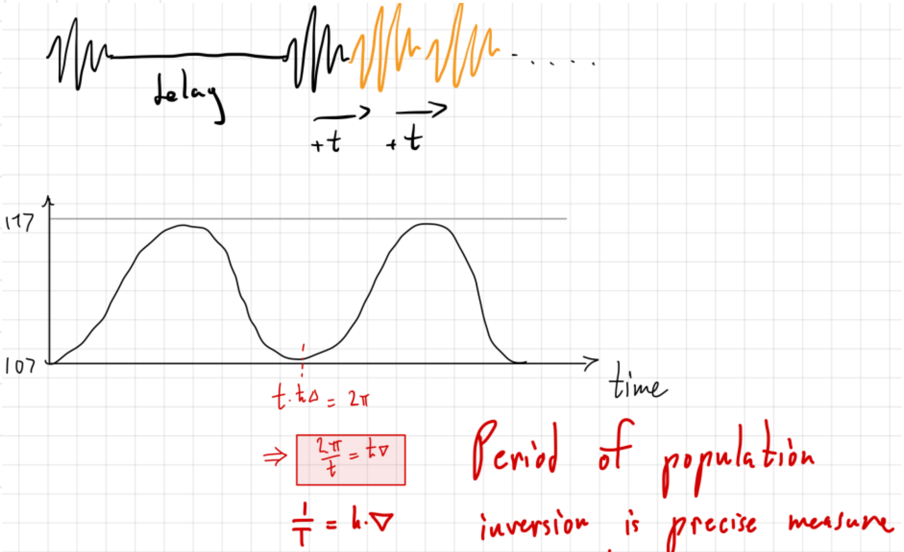


2nd, uniform detuned case:



Hold $\phi = 0$, so just $R_y(\pi/2)$:



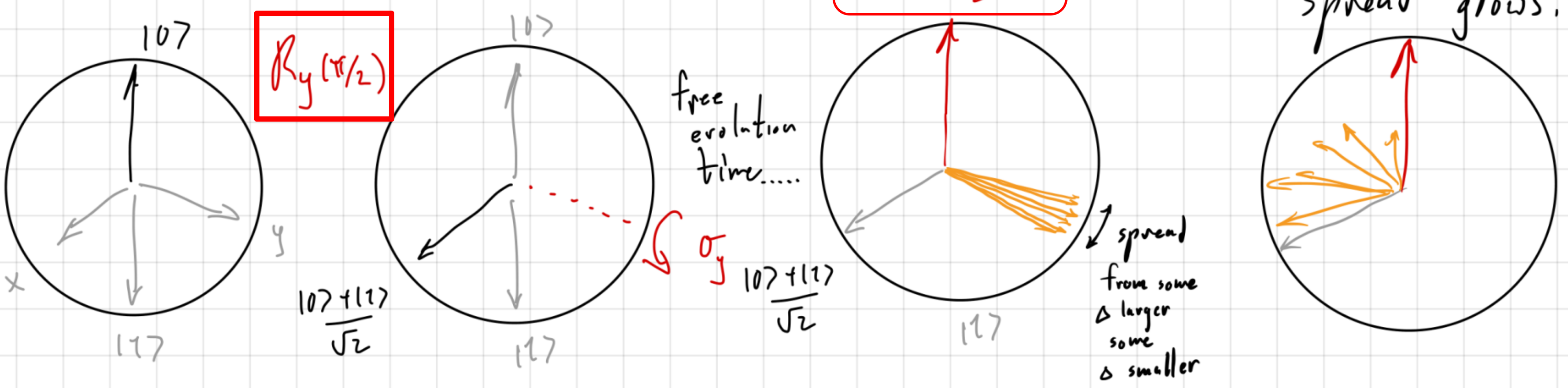


Period of population inversion is precise measure of Detuning!

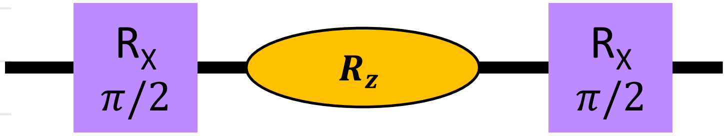
3rd, inhomogeneous, detuned case:

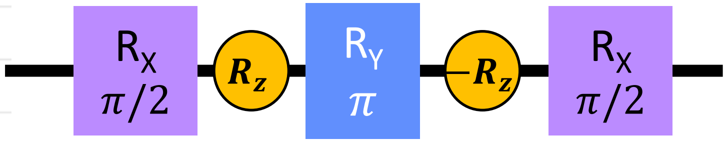
$\Delta \neq 0$

Over time spread grows!

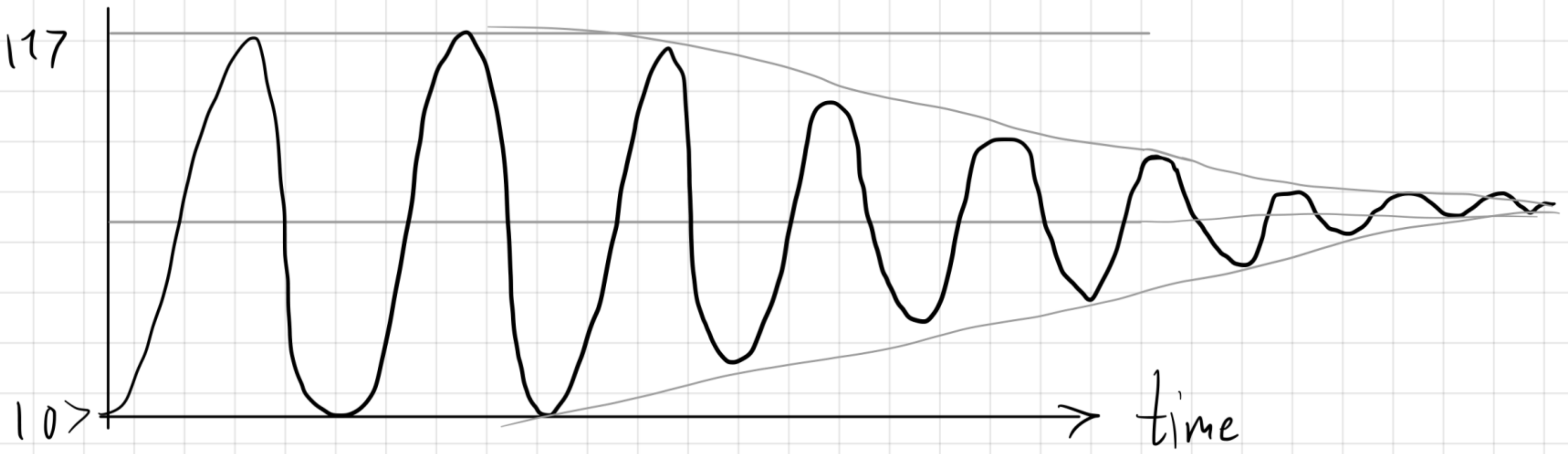


Detuning different each trial/shot





Spin Echo



For longer times, signal "washes" out and looks random ⇒ decoherent.

Inhomogeneous detuning is a main source of error!!