Using deep learning for digitally controlled STIRAP

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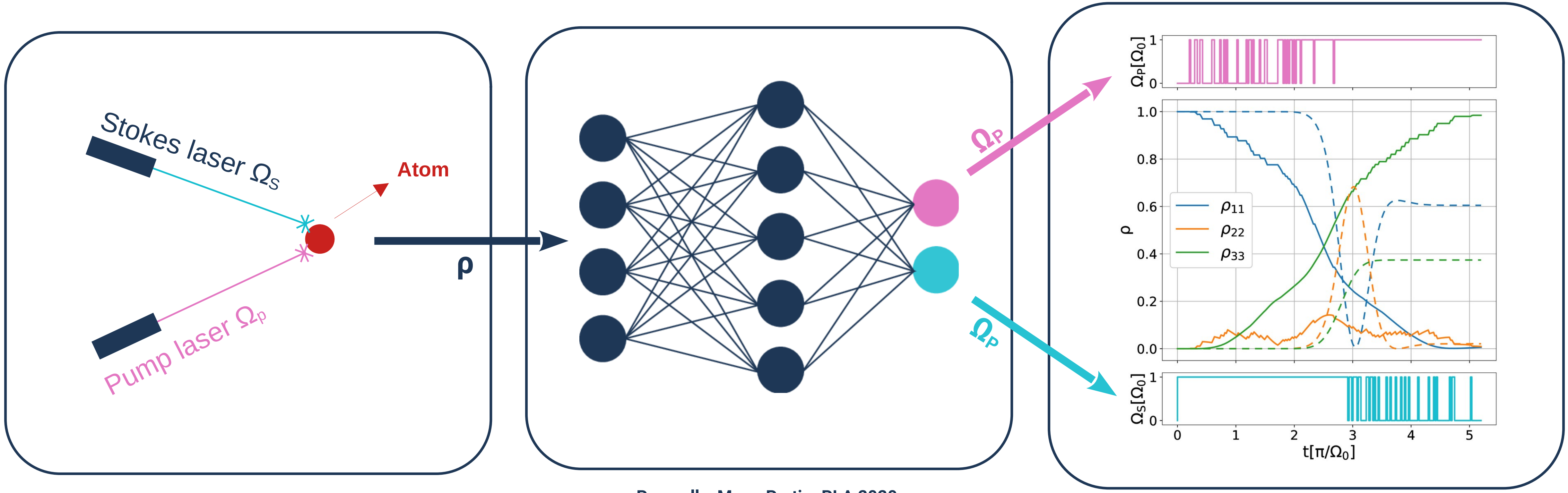

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(F)-STIRAP

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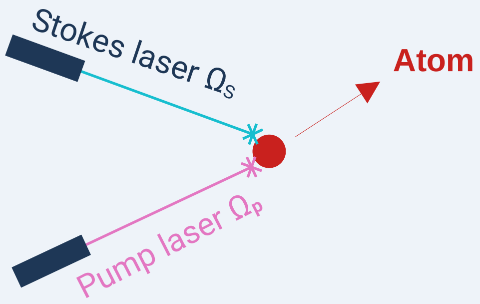


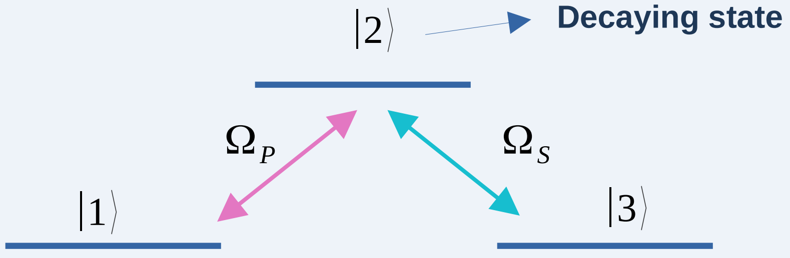
Physical system

(Fractional) Stimulated Raman Adiabaic Passage: methods for optical manipulation of atomic quantum states by laser pulses

|1> and |3> can be associated to the states of a qubit

|2> discarded because it's a decaying state

We want to control the state of the qubit by laser pulses



Three-level system

Δ: two-photon detuning

δ: one-photon detuning

Master equation

$$i\hbar\frac{d}{dt}\rho(t) = [H(t), \rho(t)] - iD(t)$$

$$H(t) = \hbar \begin{pmatrix} 0 & \frac{1}{2}\Omega_P(t) & 0 \\ \frac{1}{2}\Omega_P(t) & \Delta & \frac{1}{2}\Omega_S(t) \\ 0 & \frac{1}{2}\Omega_S(t) & \delta \end{pmatrix}$$

$$D(t) = \hbar \begin{pmatrix} 0 & \gamma_{12}\rho_{12}(t) & \gamma_{13}\rho_{13}(t) \\ \gamma_{12}\rho_{21}(t) & 0 & \gamma_{23}\rho_{23}(t) \\ \gamma_{13}\rho_{31}(t) & \gamma_{23}\rho_{32}(t) & 0 \end{pmatrix}$$

GOAL

2

The goal is to find the optimal lasers pulses in order to:

STIRAP	Flip the state of the qubit	$|1\rangle \longrightarrow |3\rangle$
f-STIRAP	Achieve superposition	$|1\rangle \longrightarrow \alpha|1\rangle + \beta|3\rangle$

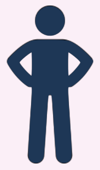
Some analytical solution to achieve STIRAP are known

We exploit a deep reinforcement learning agent to learn digiatal pulses to achieave faster STIRAP and f-STIRAP

Similar approach has been proven to be effective to control CTAP in

Porotti et Al. - Commun Phys 2, 61 (2019)
Coherent transport of quantum states by deep reinforcement learning

RL Agent



The agent interacts with the environment to learn suitable control pulses to achieve STIRAP and f-STIRAP

The agent can perform digital (ON-OFF) pulses only

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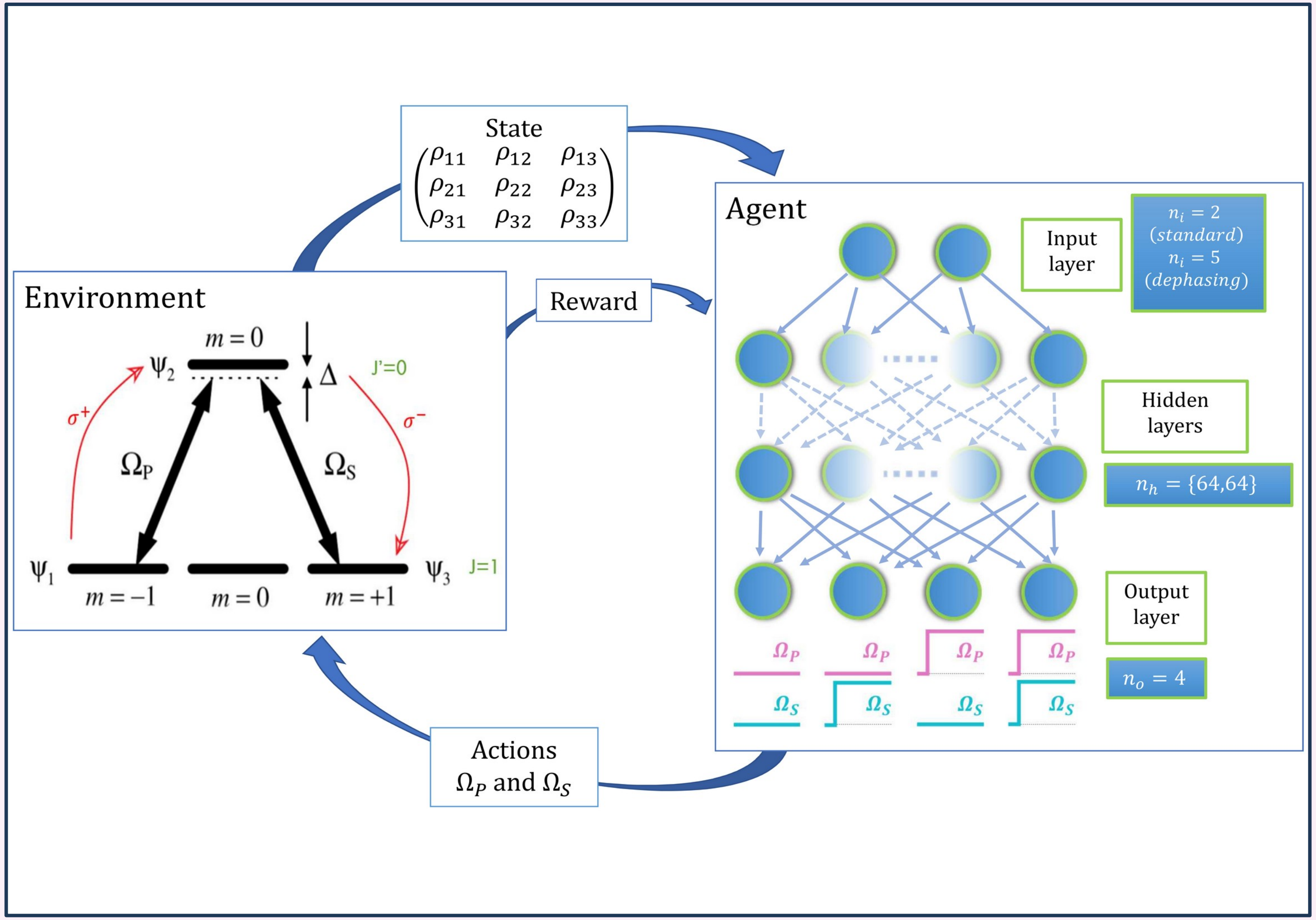

Environment

The environment corresponds to the physical system

Agent

The agent consists of a deep neural network with two hidden layers of 64 neurons each

Agent environment interaction

At each time-step the agent observes the current state of the environment and it determines an action to take. After the environment has evolved into a new state, the reward function is returned to the agent.

The agent goal of the agent is to maximize the reward (signal of pleasure/pain) over time

Training

We trained the agent exploiting Proximal Policy Optimization algorithm

ANALYTICAL SOLUTION STIRAP

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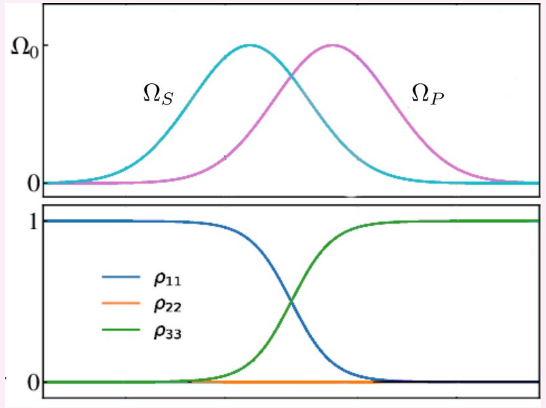

Gaussian pulses

Counterintuitive sequence: first stokes pulse then pump pulse

State |2> is never populated, i.e ρ_{22}=0

Transfer |1> --> |3> achieved after a time of $160/\Omega_0$

D-STIRaP

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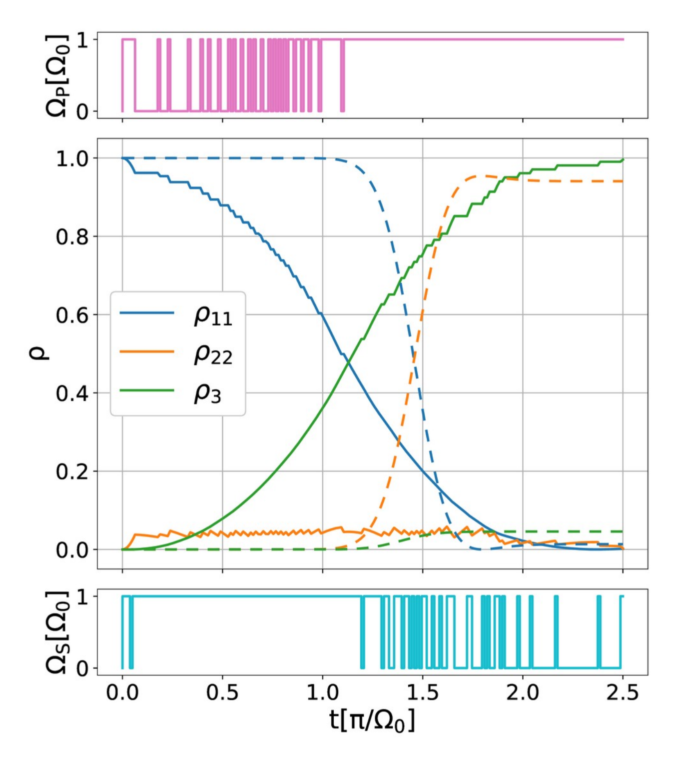
Actions	**Digital laser pulses (ON/OFF)**
Input	**Modulo of the elements of ρ at time-step n**

Reward

$$r(t) = -1 - \rho_{22}(t) + \rho_{33}(t) + A(t) + B(t) \quad \text{where} \quad \begin{cases} A(t) = 10 \cdot H(\rho_{33}(t) - 0.97) \\ B(t) = -e^{6\rho_{22}} \cdot H(\rho_{22}(t) - 0.05) \end{cases}$$



Pump digital pulses

Solid lines: Agent pulses
Dashed: Gaussian pulses

Counterintuitive sequence: first stokes pulse then pump pulse

State |2> is populated, i.e ρ_{22}= 0.05 but drops to 0

20x faster transfer than Gaussian pulses (time of ~ $8/\Omega_0$)

Gaussian pulses (dashed lines) fails to achieve STIRAP in such short time

Stokes digital pulses

Fractional D-STIRaP

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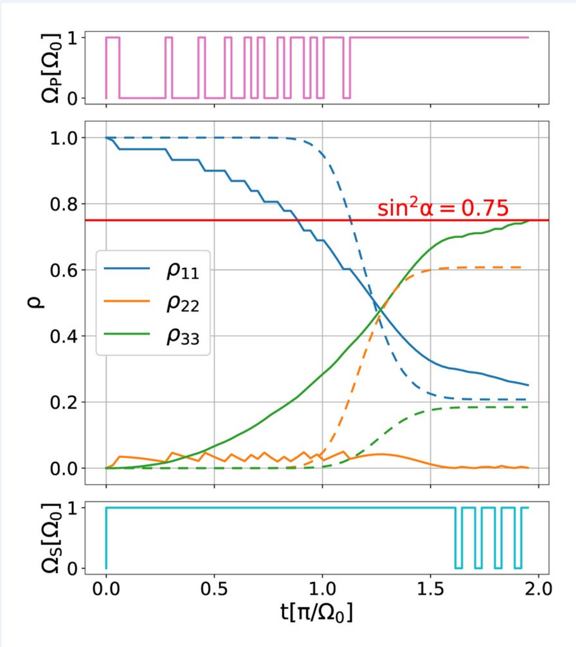
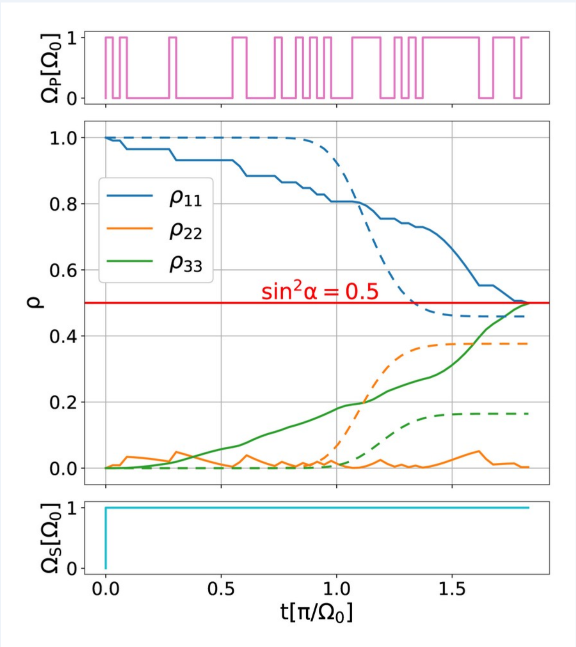




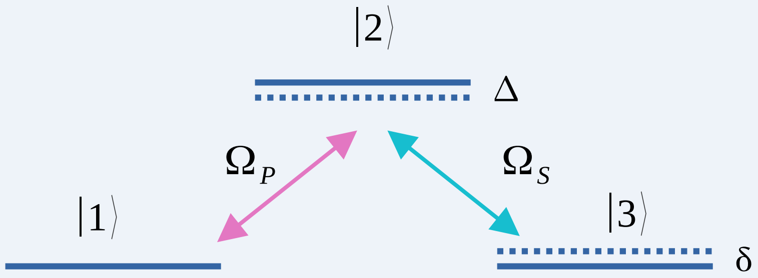
Actions — **Digital laser pulses (ON/OFF)**

Reward

$$r(t) = -1 - (\rho_1(t) + \cos^2(\alpha))^2 - (\rho_{33}(t) - \sin^2(\alpha))^2 + B(t)$$

Alghtough the condition of adiabaticity is violated digital laser pulses achieve faster STIRAP and f-STIRAP

DETUNING



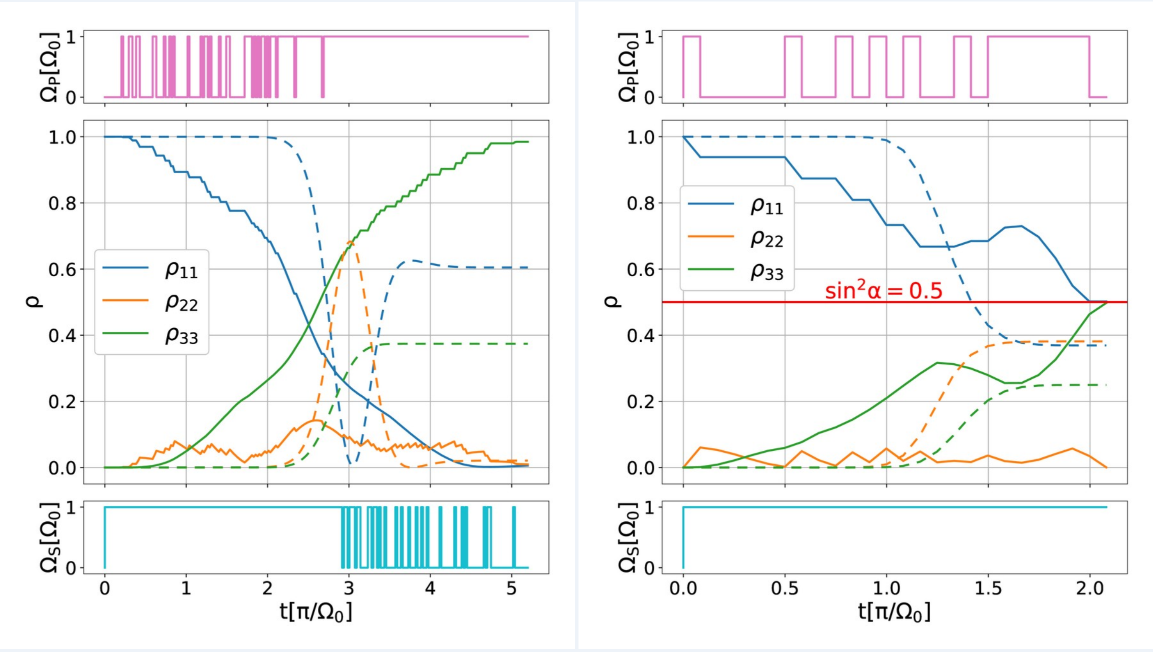
Δ: two-photon detuning

δ: one-photon detuning

$$\Delta = \delta = 0.15\cdot\Omega_0$$

The agent is able to find fast pulses even in the presence of detuning

D-STIRaP **Fractional D-STIRaP**



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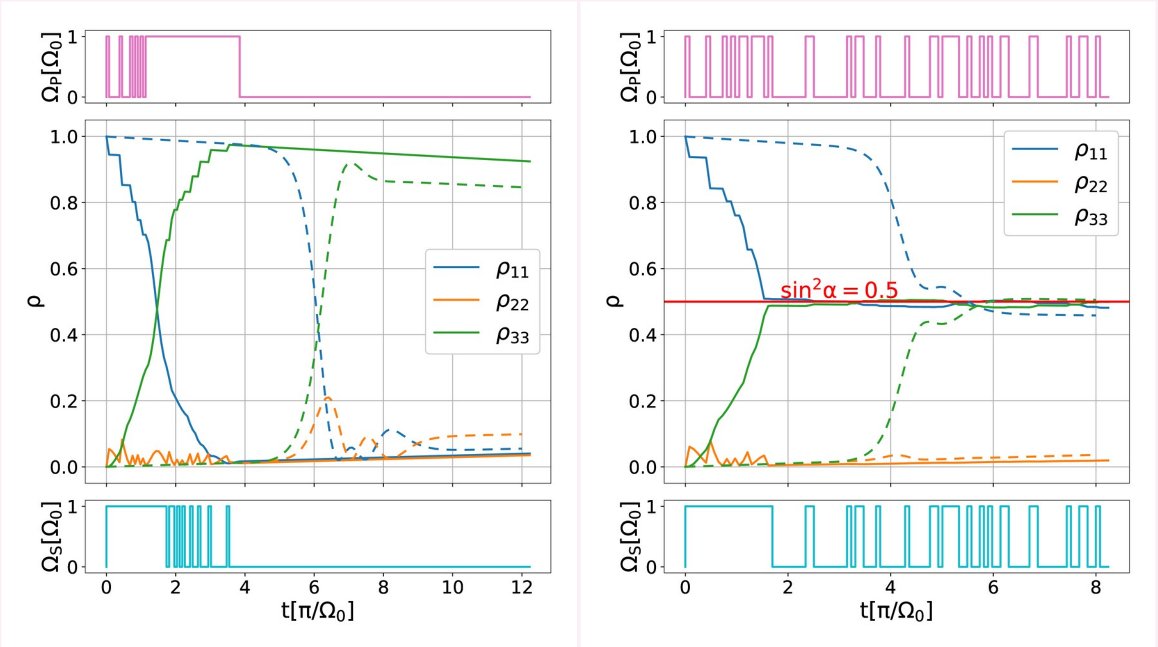
D-STIRaP **Fractional D-STIRaP**



DEPHASING

System coupled with environment

$$i\hbar\frac{d}{dt}\rho(t) = [H(t),\rho(t)] - iD(t)$$

$$\Upsilon_{nm} = \Upsilon\ \forall n,m$$

$$D(t) = \hbar\begin{pmatrix} 0 & \gamma_{12}\rho_{12}(t) & \gamma_{13}\rho_{13}(t) \\ \gamma_{12}\rho_{21}(t) & 0 & \gamma_{23}\rho_{23}(t) \\ \gamma_{13}\rho_{31}(t) & \gamma_{23}\rho_{32}(t) & 0 \end{pmatrix}$$

$$\Upsilon = 0.1\cdot\Omega_0$$

The agent is able to find fast pulses even in the presence of dephasing

CONCLUSION

Thanks to deep reinforcement learning it is possible to exploit digital laser pulses to manipulate the state of a qubit

Alghtough the condition of adiabaticity is violated digital laser pulses achieve STIRAP and f-STIRAP

Such transfer is faster than continuous amplitude mudulated pulses

DRL allows to learn laser sequences even in the presence of disturbances such as dephasing and detuning

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