Simphony

our python package to simulate point defect dynamics

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Funding acknowledgment

Qutility

FAULHORN LABS

AI4QT

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innovation beyond borders

AI4QT partners (Hungary, Germany)

FAULHORN LABS

Fraunhofer IAF

HUN REN Wigner

XEEQ

Simphony

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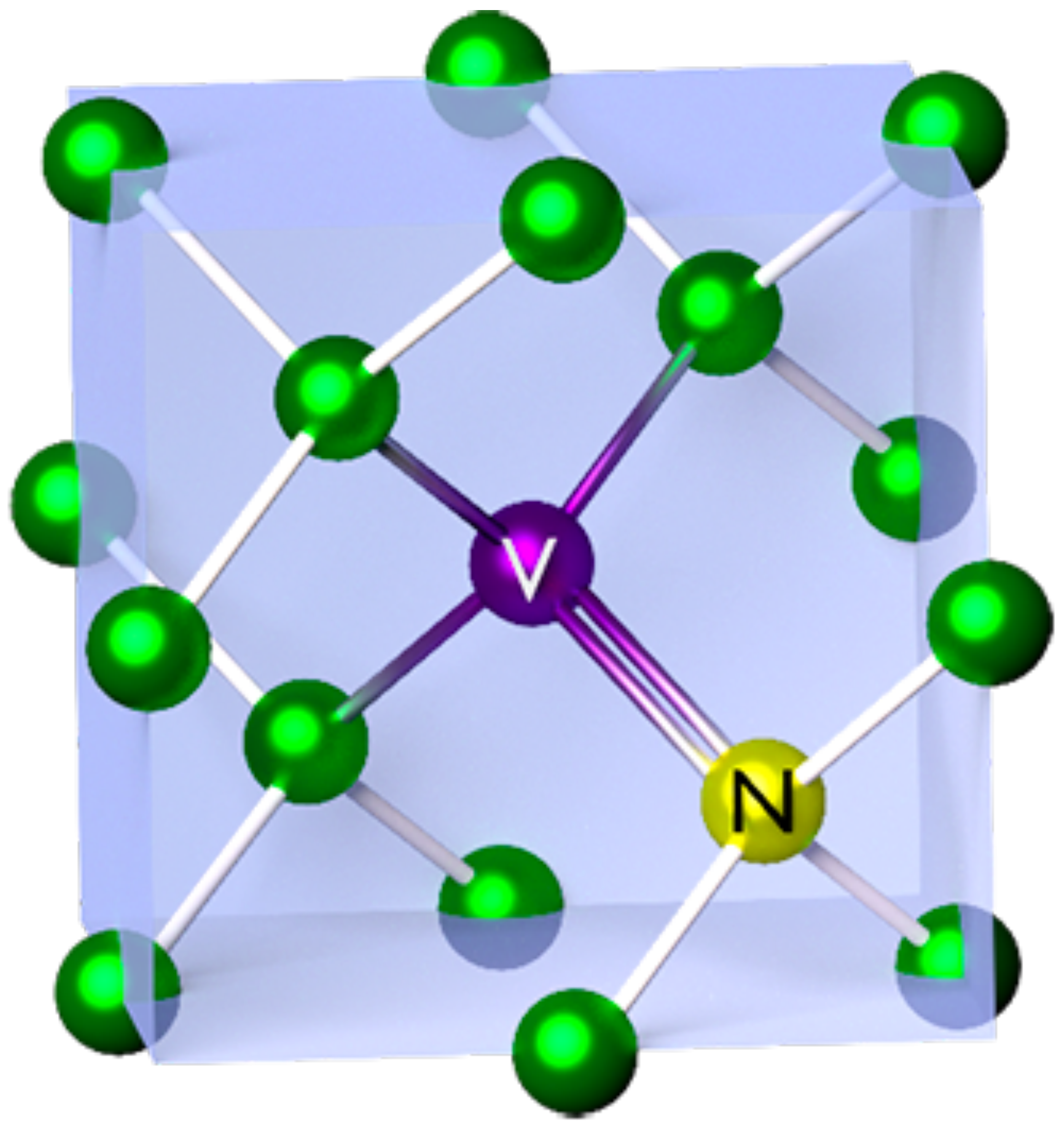
Our python package to simulate point defect quantum dynamics
for quantum technology applications

Quantum Computing

Universal high-fidelity quantum gates
for spin-qubits in diamond
https://arxiv.org/abs/2403.10633
Taminiau group, Delft

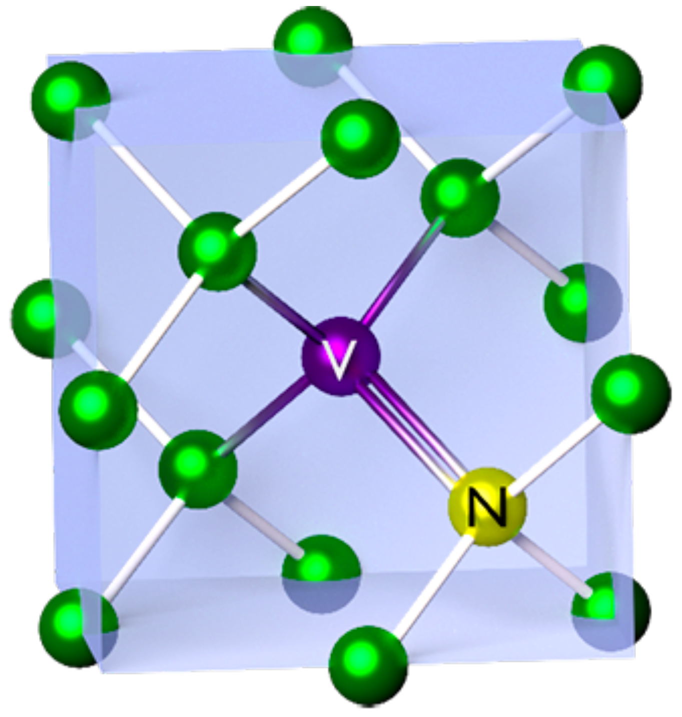
High-Fidelity Electron Spin Gates
in a Scalable Diamond Quantum Register
https://arxiv.org/abs/2406.04199
Jelezko group, Ulm



Quantum Sensing

Nanoscale magnetism and magnetic
phase transitions in atomically thin CrSBr
https://arxiv.org/abs/2312.09279
Maletinsky group, Basel

Simphony



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- Simphony is our python package to simulate point defect quantum dynamics for quantum technology applications
- Simphony is our “Minimal Viable Product” => **We are looking for collaborators!**

Input-output structure of Simphony

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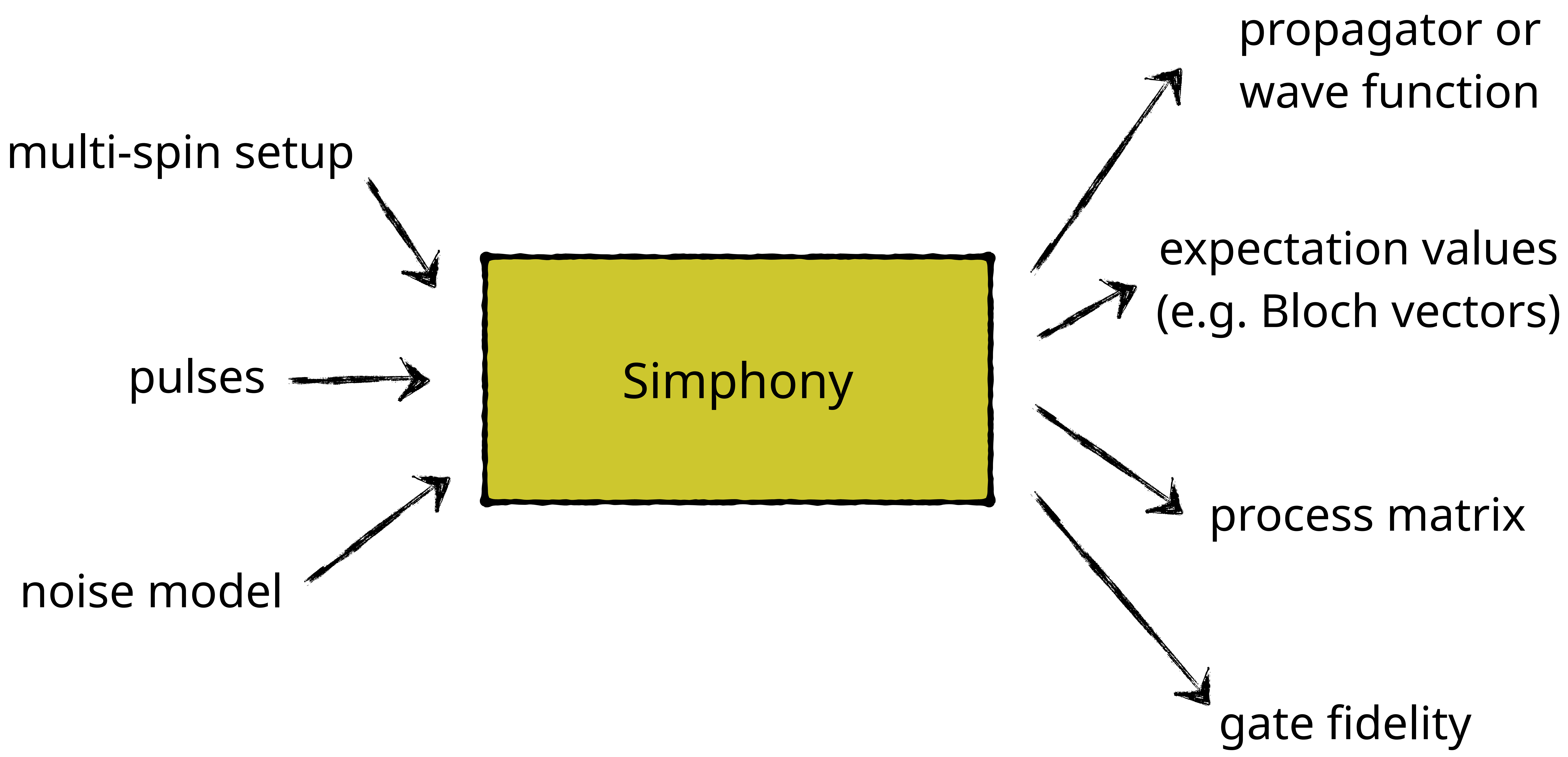

Dependency diagram of Simphony

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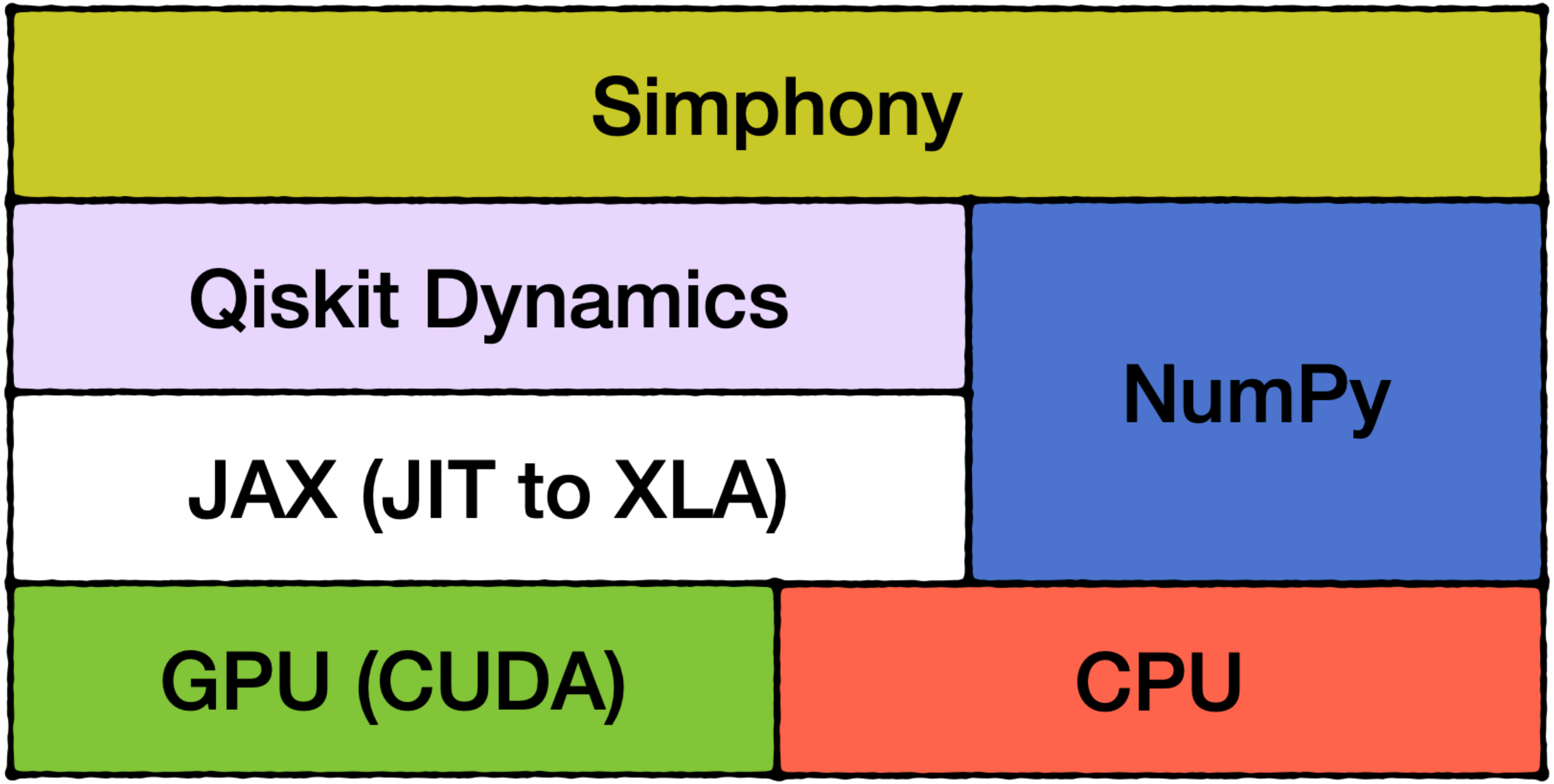
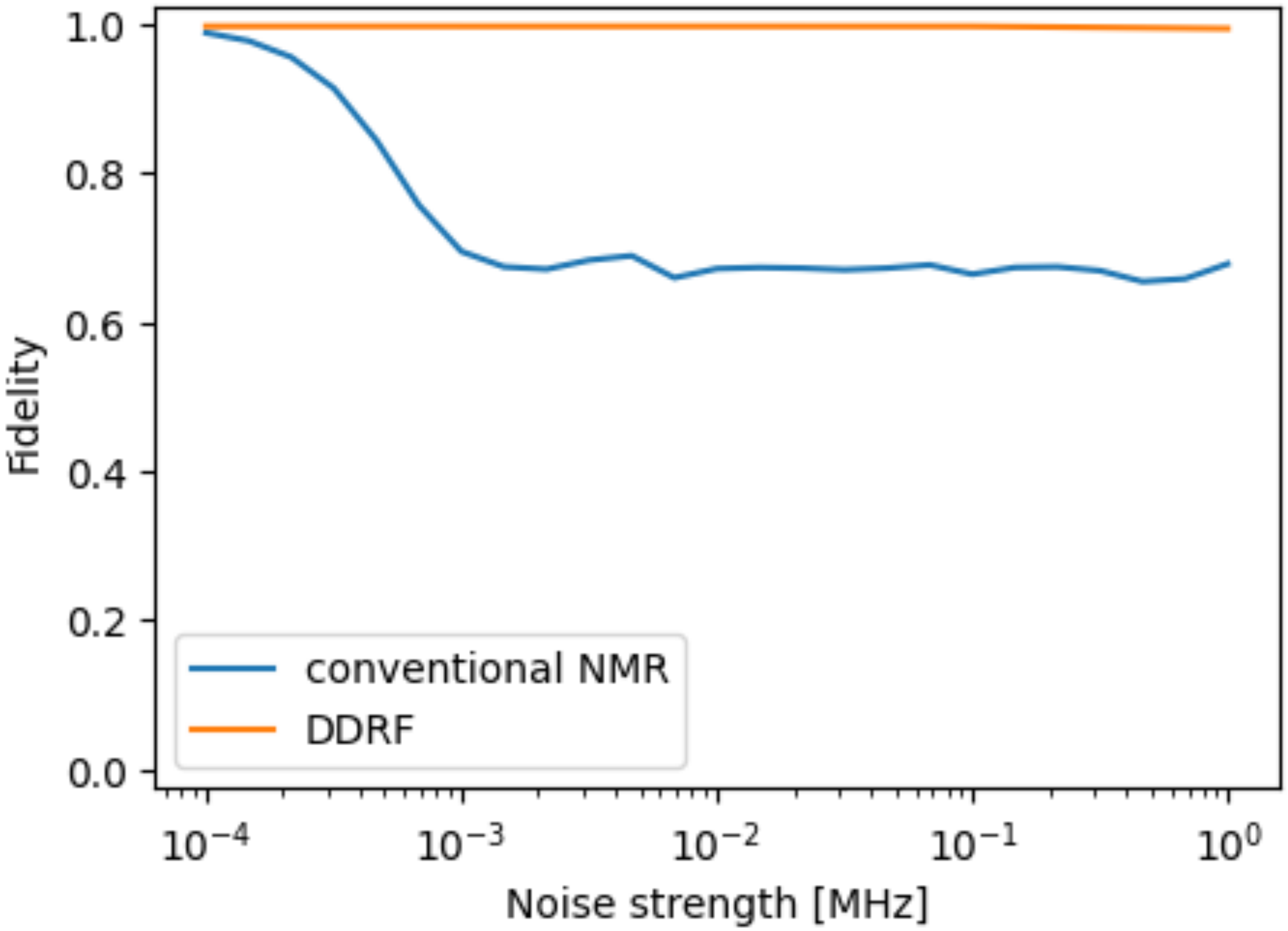
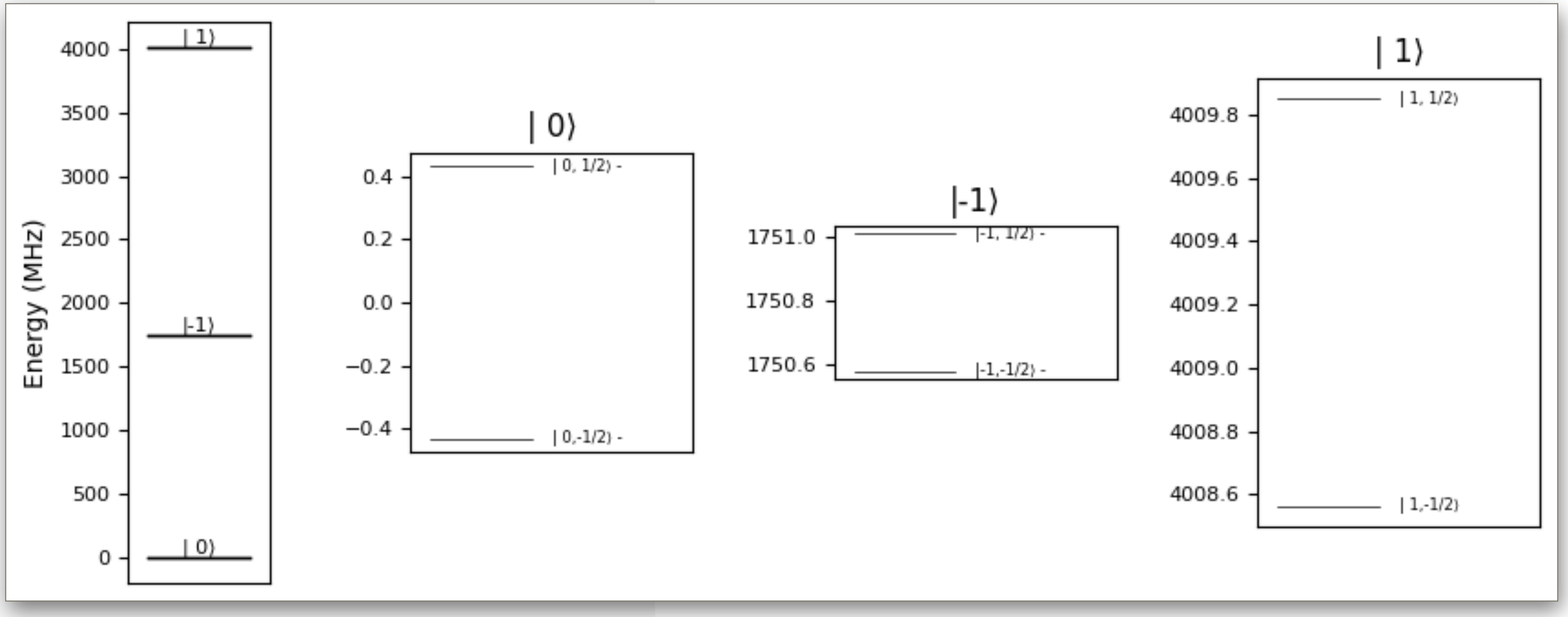


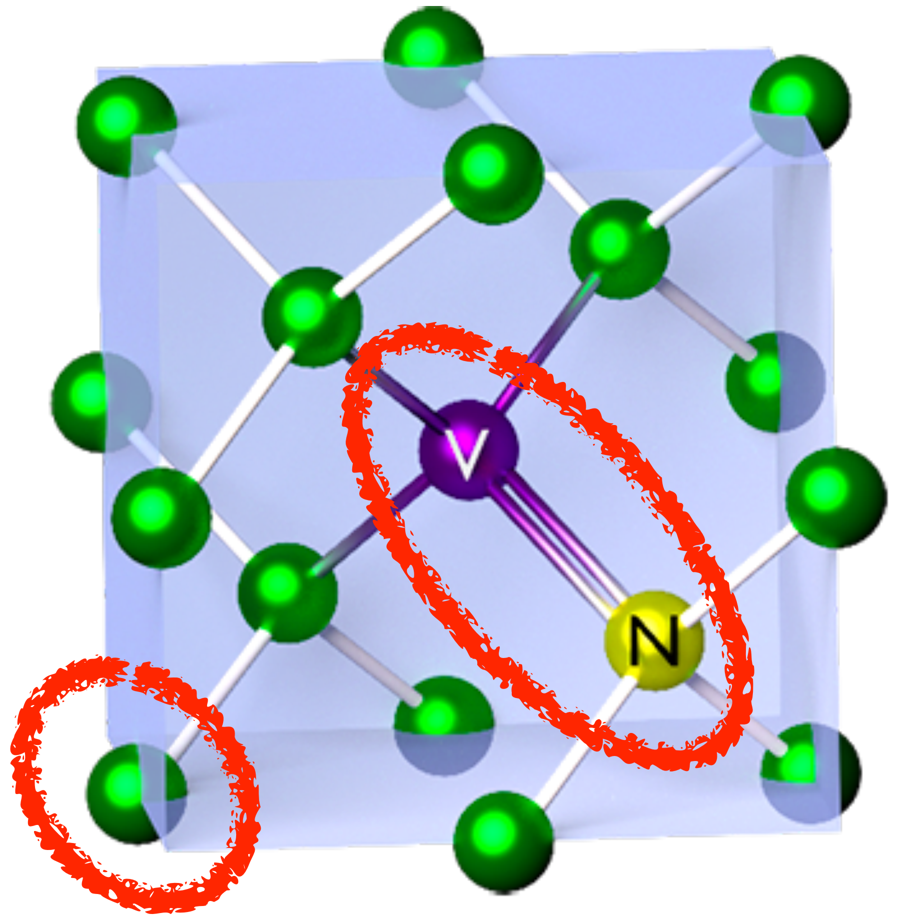
Example: noise-resistant controlled rotation



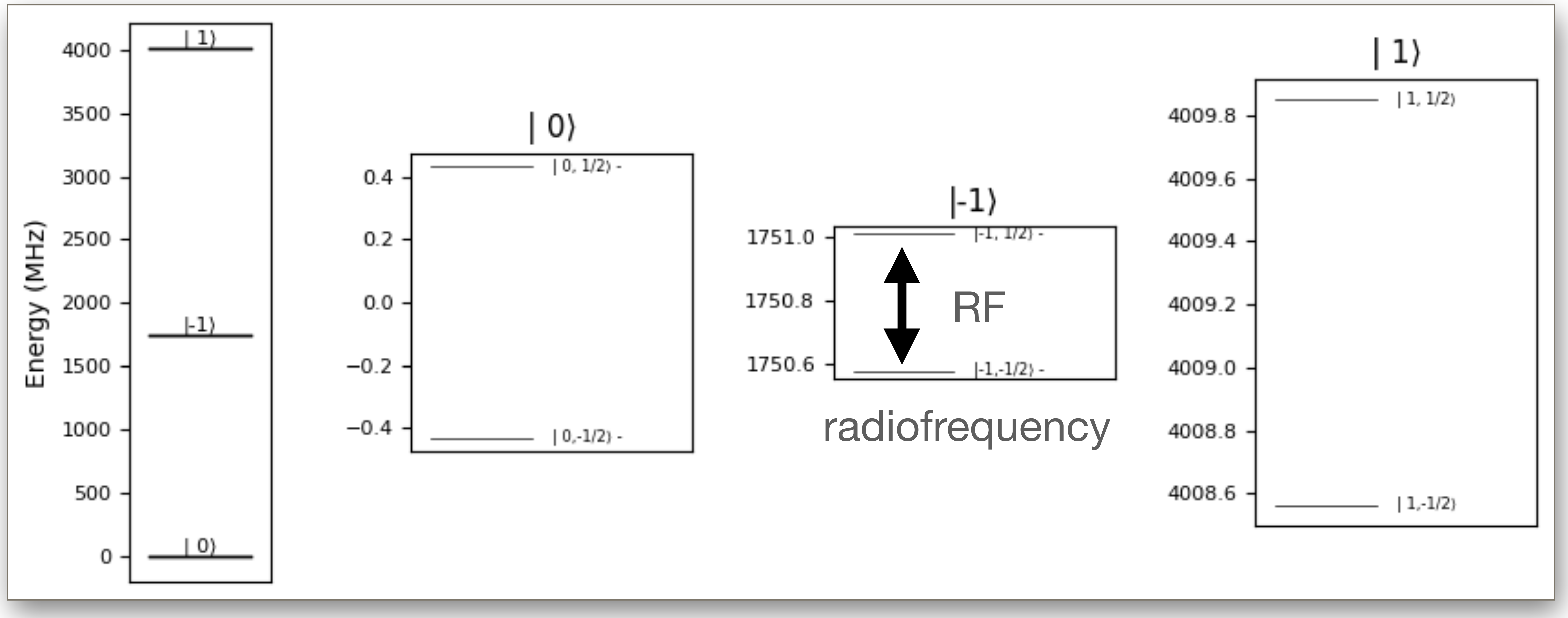
Multi-spin setup

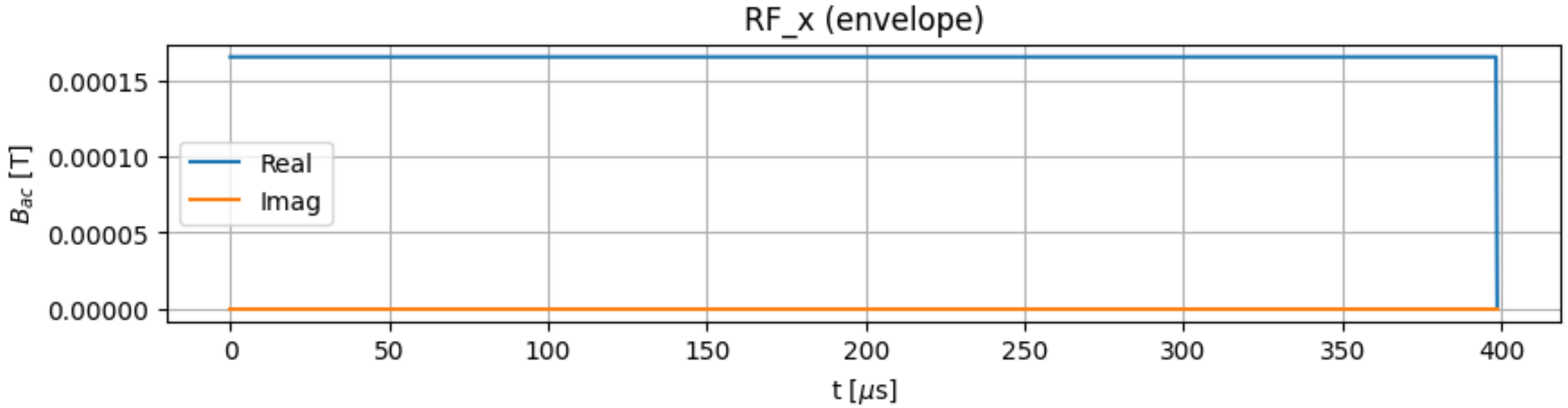
```python
spin_e = simphony.Spin(
    dimension = 3,
    name = 'NV-e',
    gyromagnetic_ratio = 28020, # MHz/T
    qubit_subspace = (0, -1),
    zero_field_splitting = 2880 # MHz
)

spin_C = simphony.Spin(
    dimension = 2,
    name = '13C',
    gyromagnetic_ratio = 10.71, # MHz/T
    qubit_subspace = (-1/2, 1/2),
    zero_field_splitting = 0
)

hyperfine = simphony.Interaction(spin_e, spin_C)
hyperfine.zz = 0.213154 # MHz
hyperfine.xz = 0.003 # MHz
hyperfine.zx = 0.003 # MHz

static_field = simphony.StaticField()
static_field.z = 0.0403 # T

driving_field_MW = simphony.DrivingField(direction = [1, 0, 0], name = 'MW_x')
driving_field_RF = simphony.DrivingField(direction = [1, 0, 0], name = 'RF_x')
```

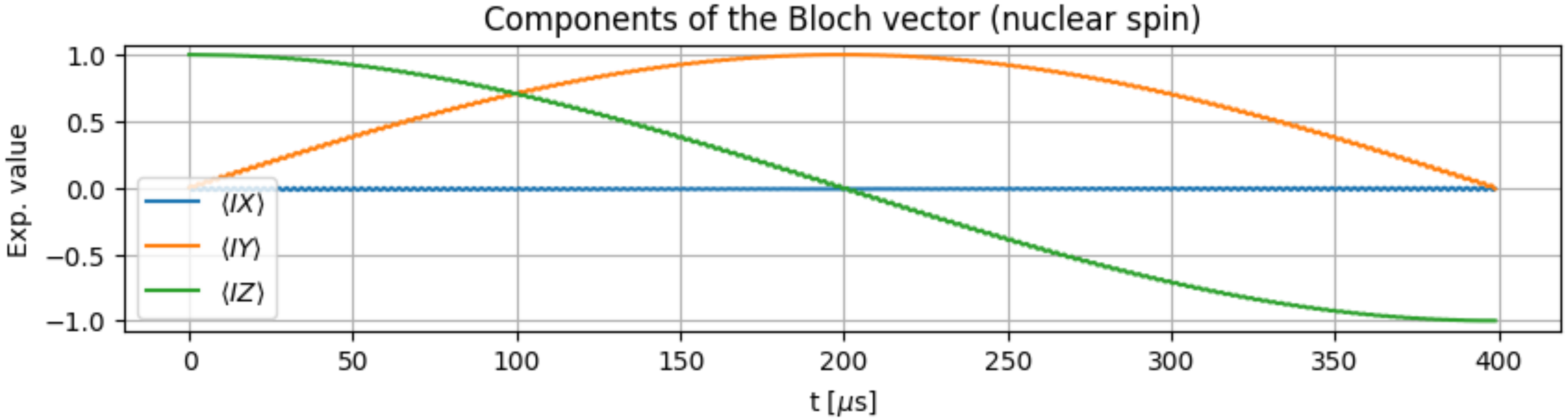




Conventional
nuclear magnetic resonance

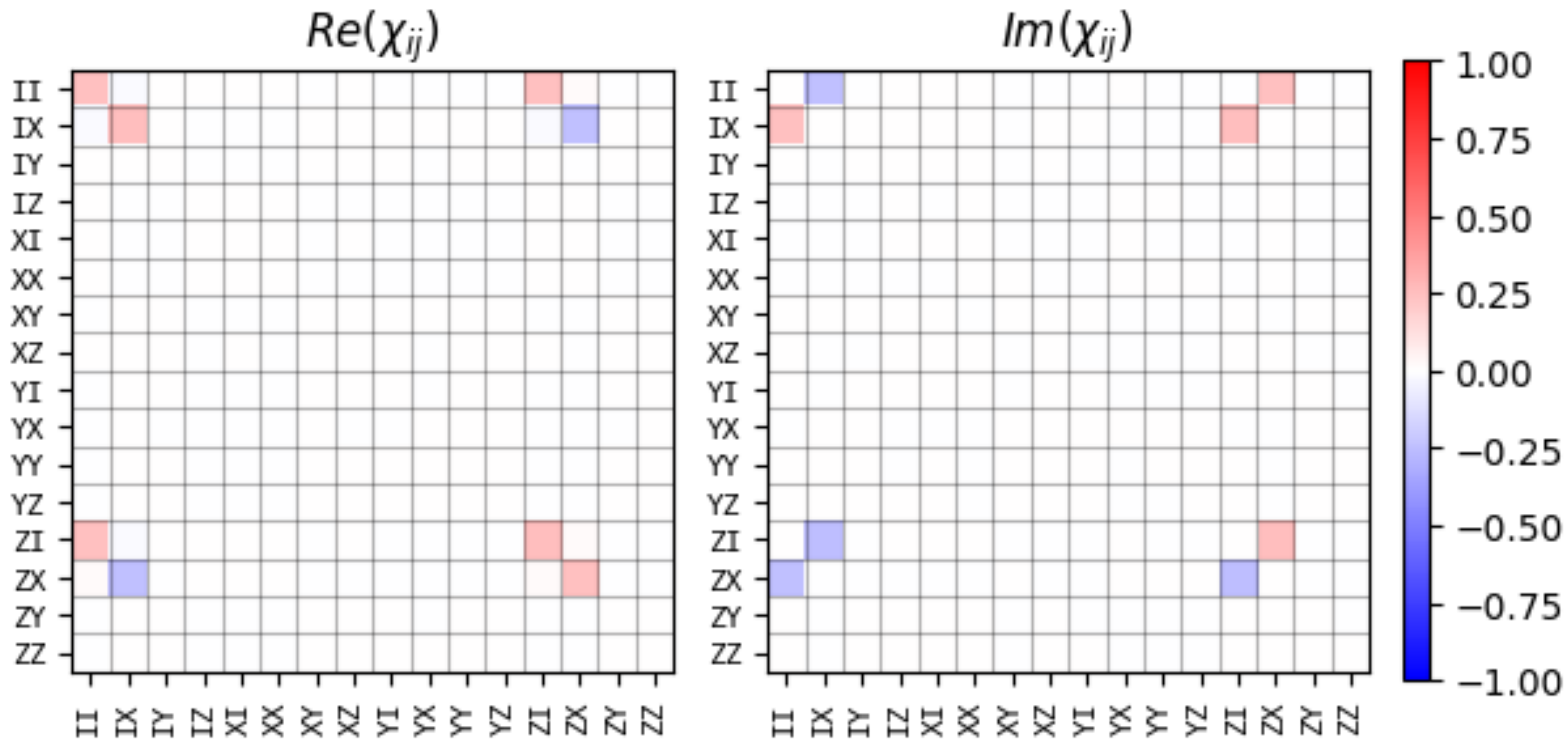






Conventional nuclear magnetic resonance

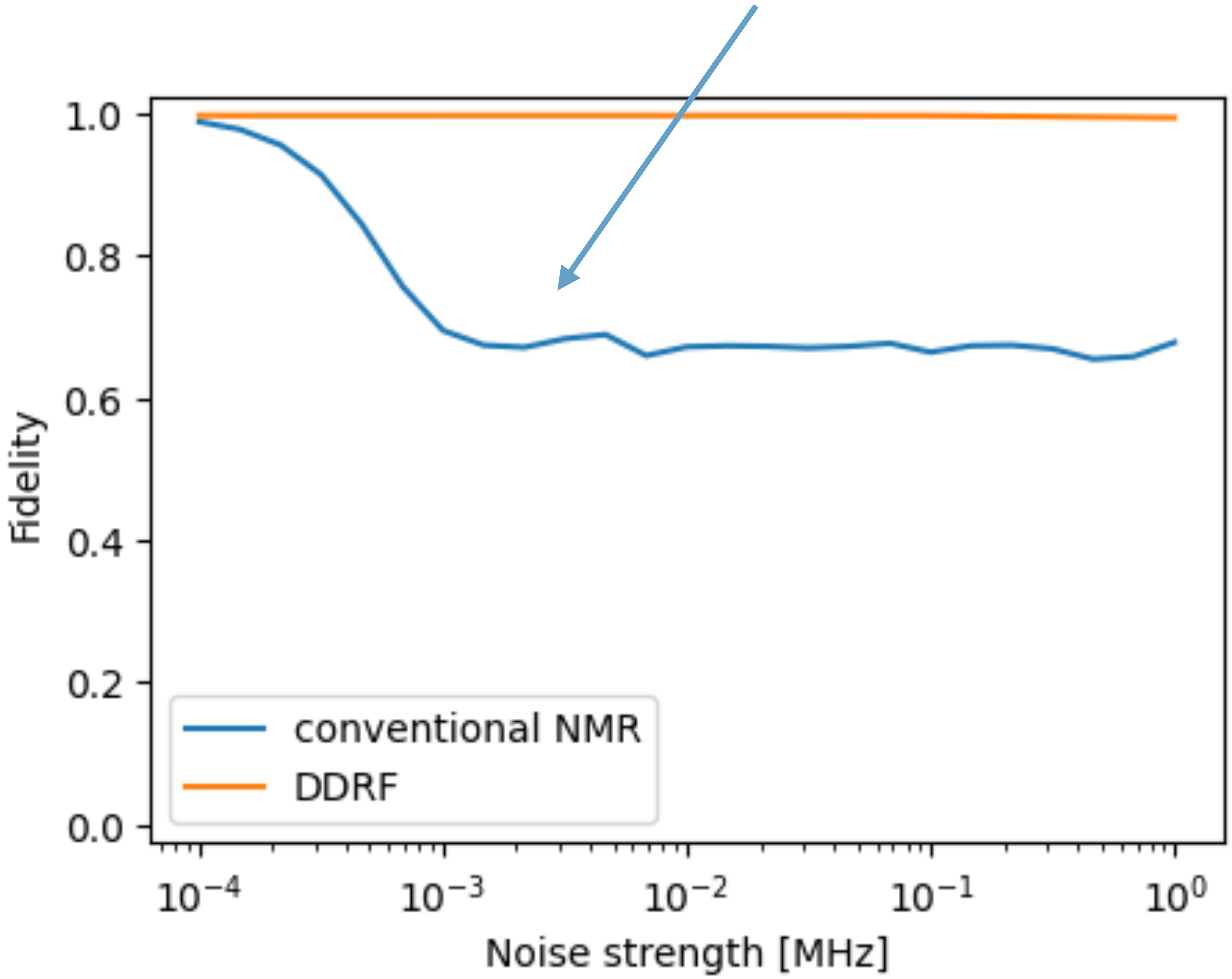
Process matrix



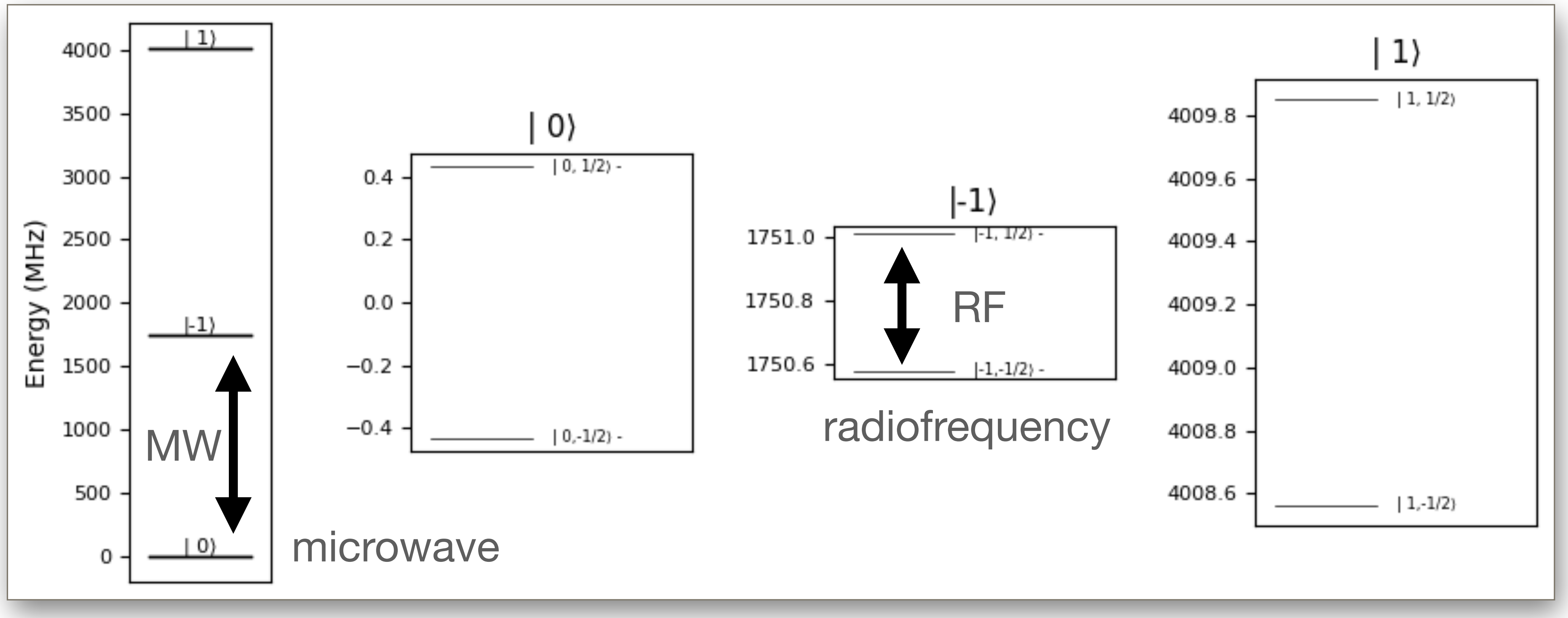
Ideal gate:
$RX(\pi)$ controlled on $m_S = -1$

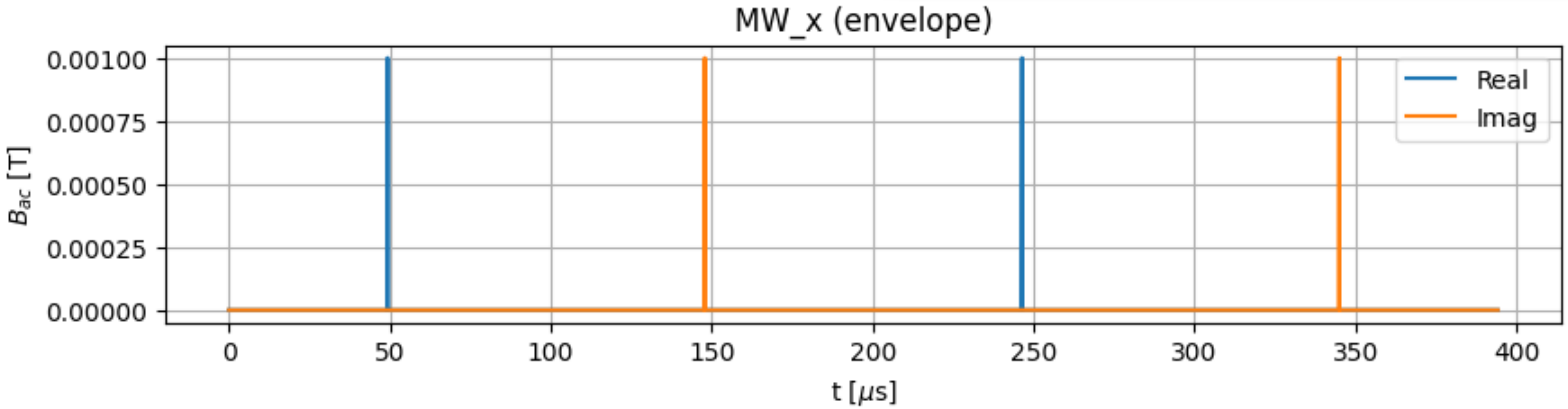
Average gate fidelity:
99.87%

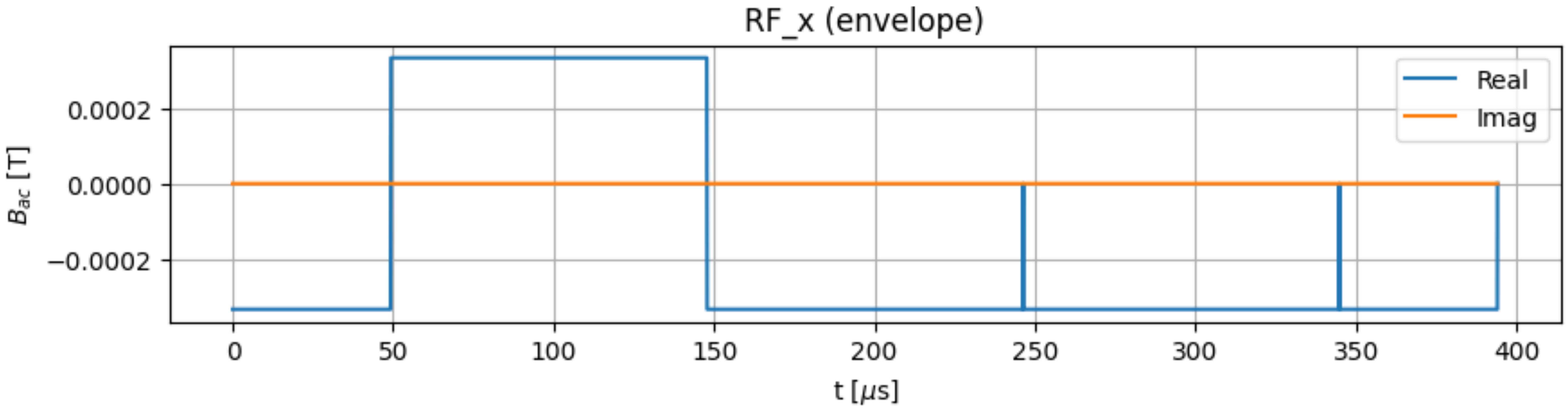
Conventional NMR: vulnerable to noise



DDRF pulse sequence

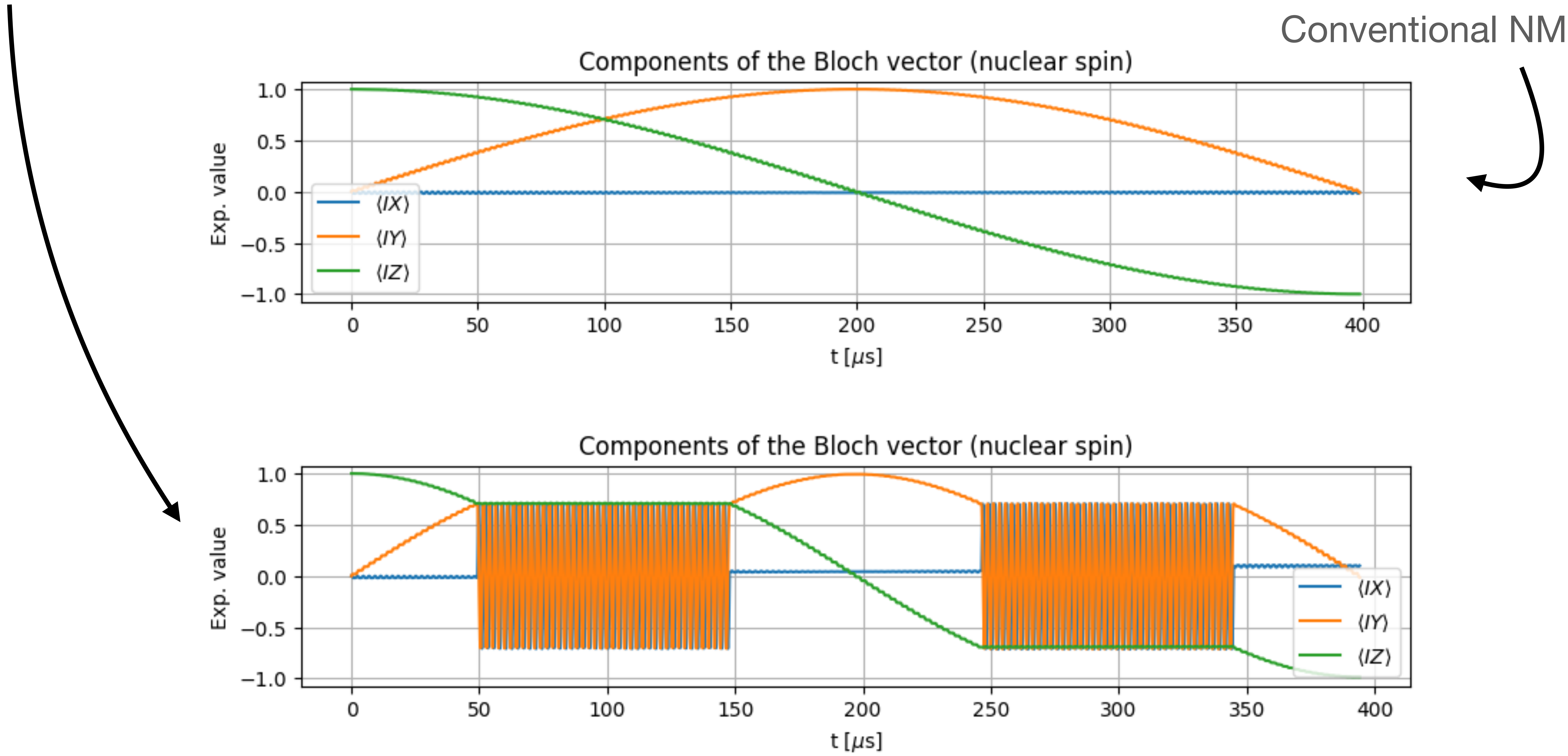




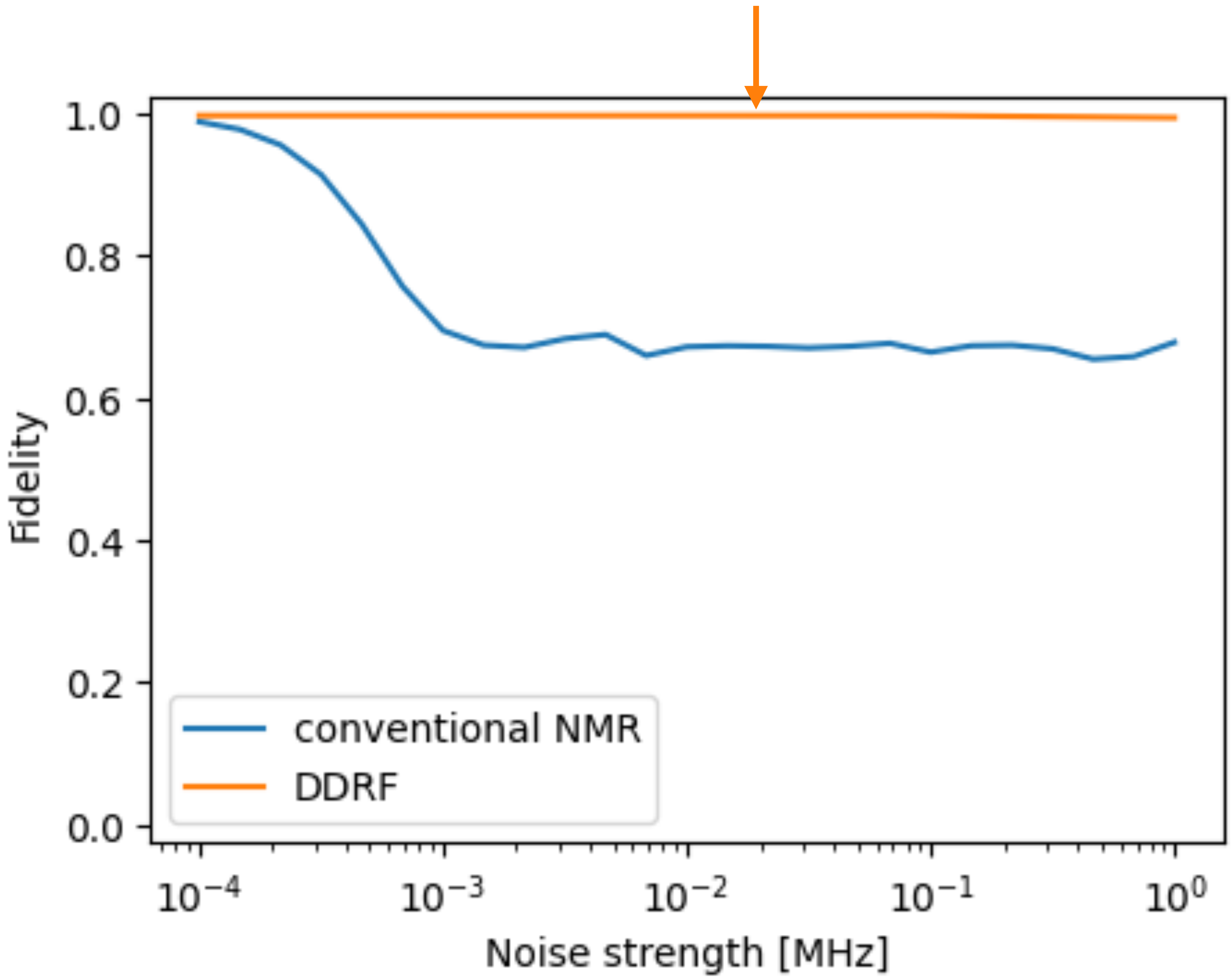


Spin dynamics due to DDRF pulse sequence

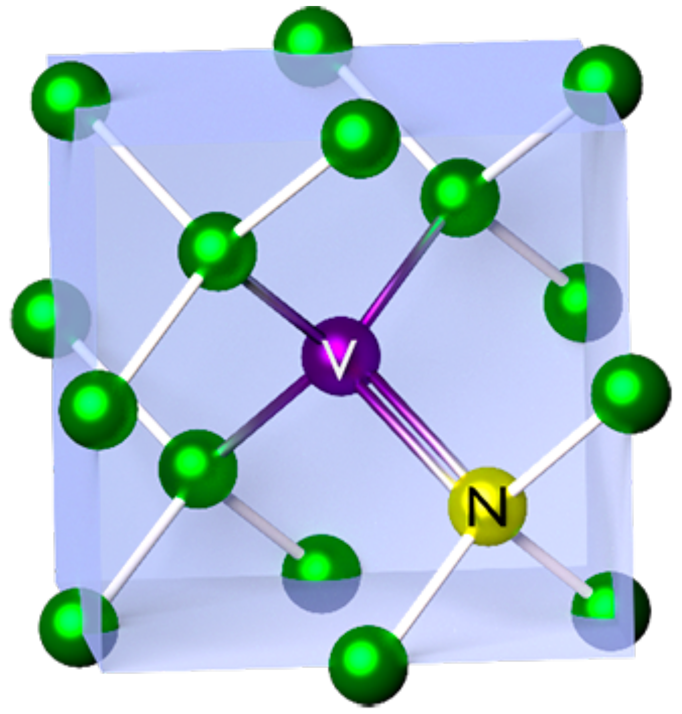
Conventional NMR



DDRF pulse sequence: robust against noise



Simphony



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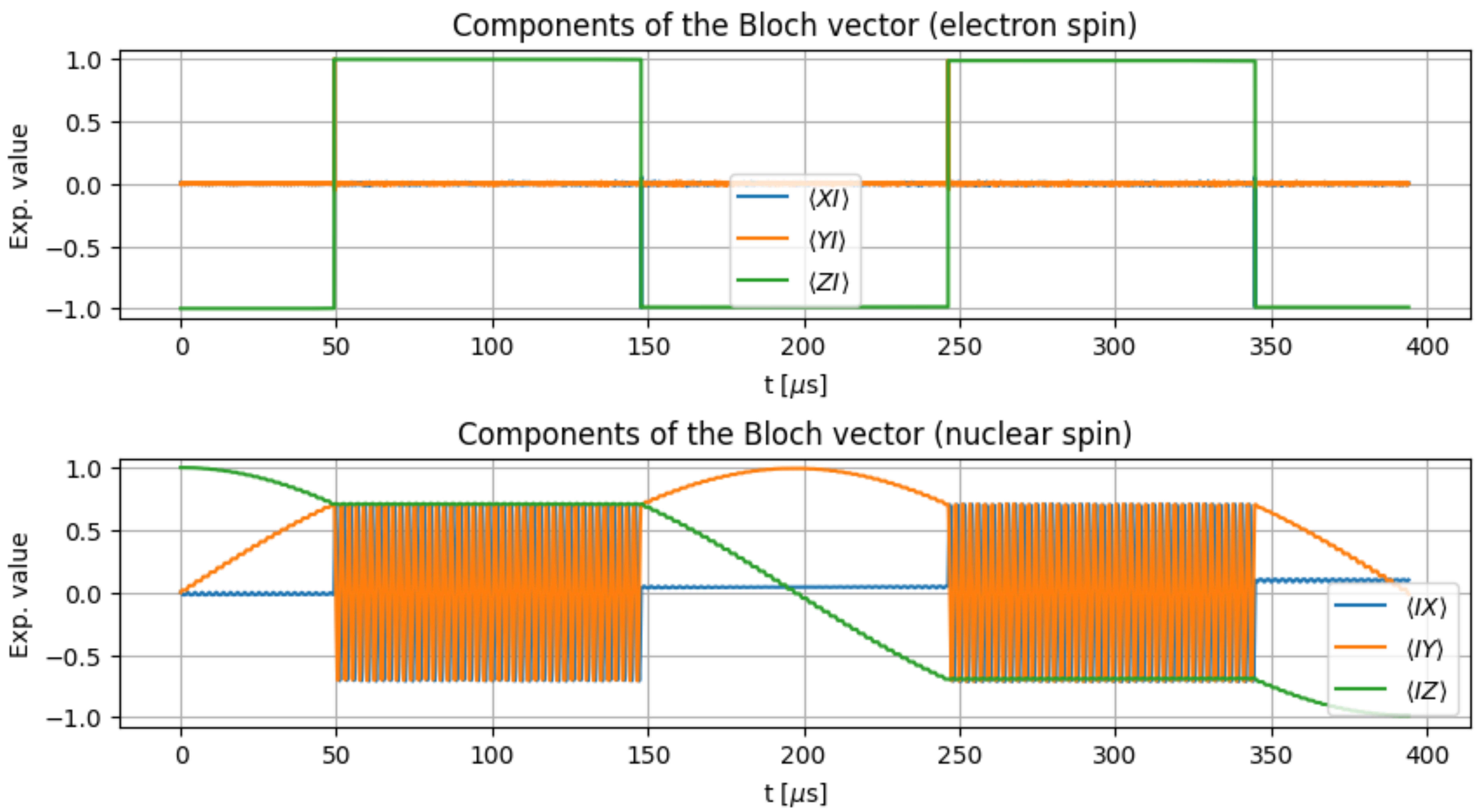
Roadmap

- Integration of ^{13}C hyperfine database.
- Integration of point-defect Hamiltonians beyond NV centers.
- Scalable registers of coupled NV centers.
- Lindblad-type noise models.
- Non-Markovian system-bath interaction.
- Photophysics dynamics: initialisation and readout.

Summary

- Simphony is our python package to simulate point defect spin dynamics for quantum technology applications.
- Simphony is our “Minimal Viable Product” => **We are looking for collaborators!**

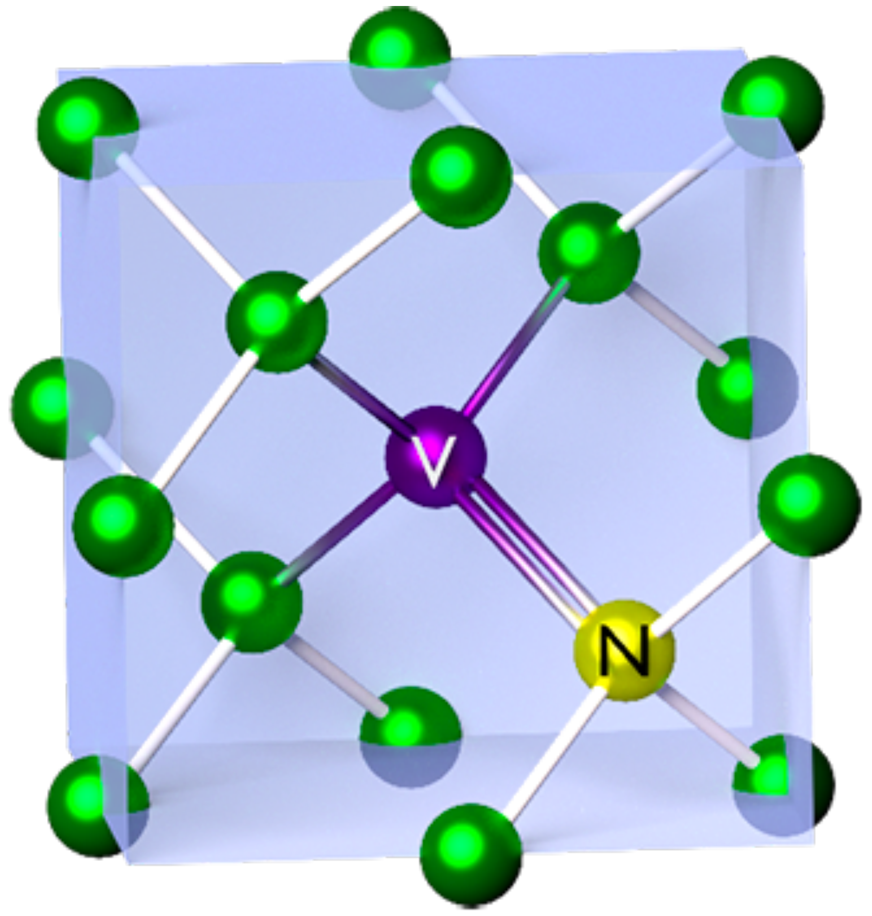
DDRF pulse sequence

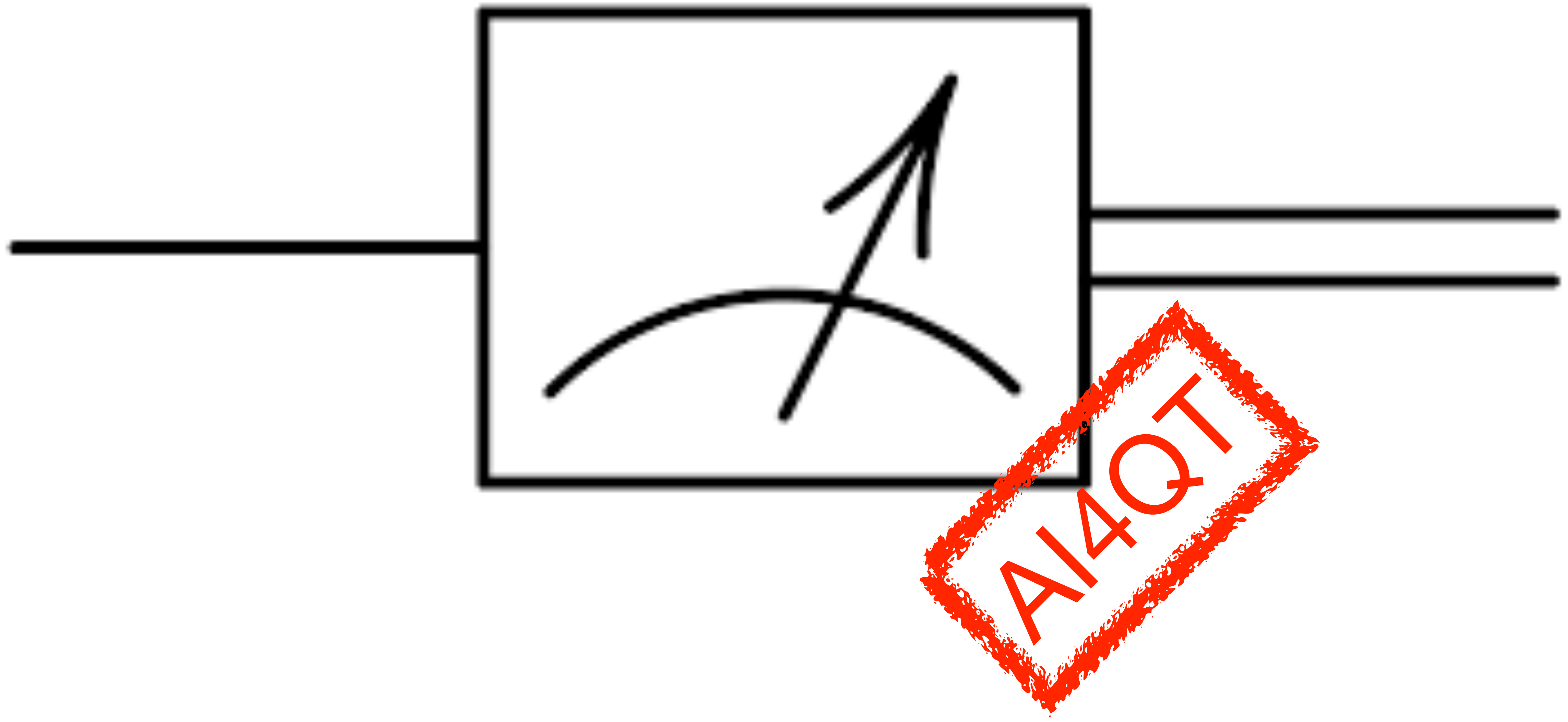


Towards an AI tool to enhance qubit readout in NV-based registers

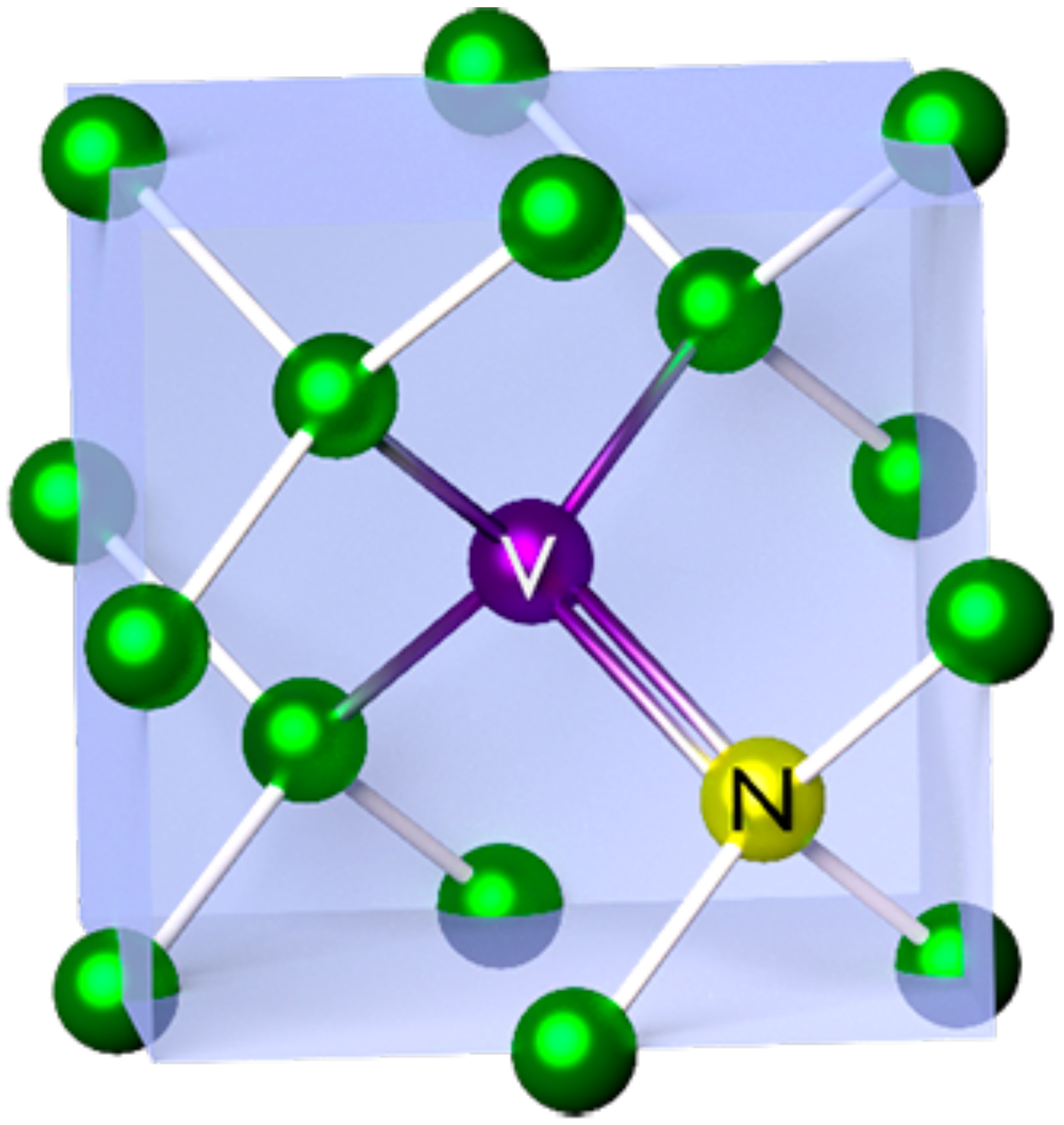
How could this tool improve readout?

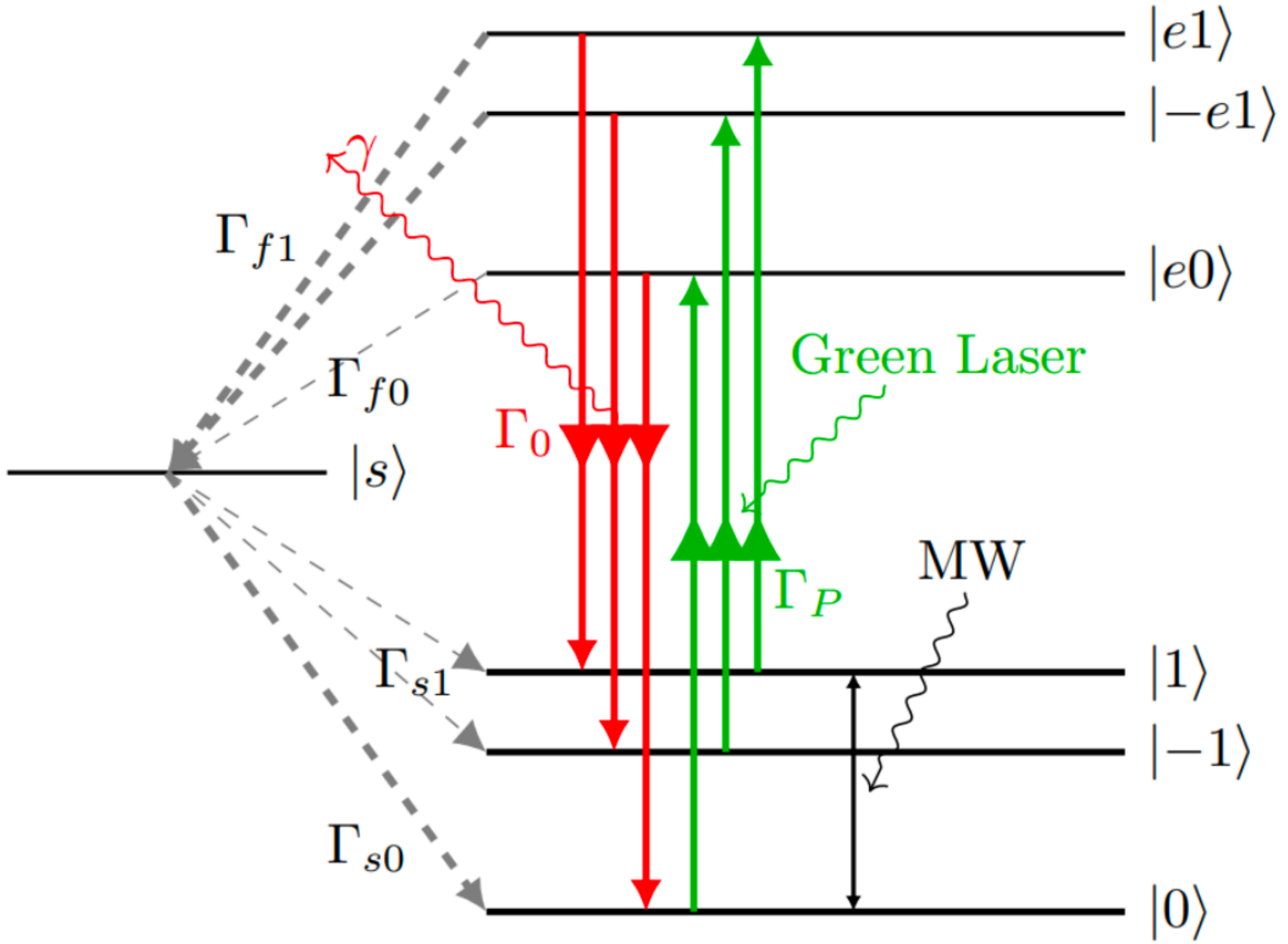
- Single-shot readout at elevated temperatures.
- In multi-shot readout (standard for room temperature): reduce the number of shots needed for a given precision.





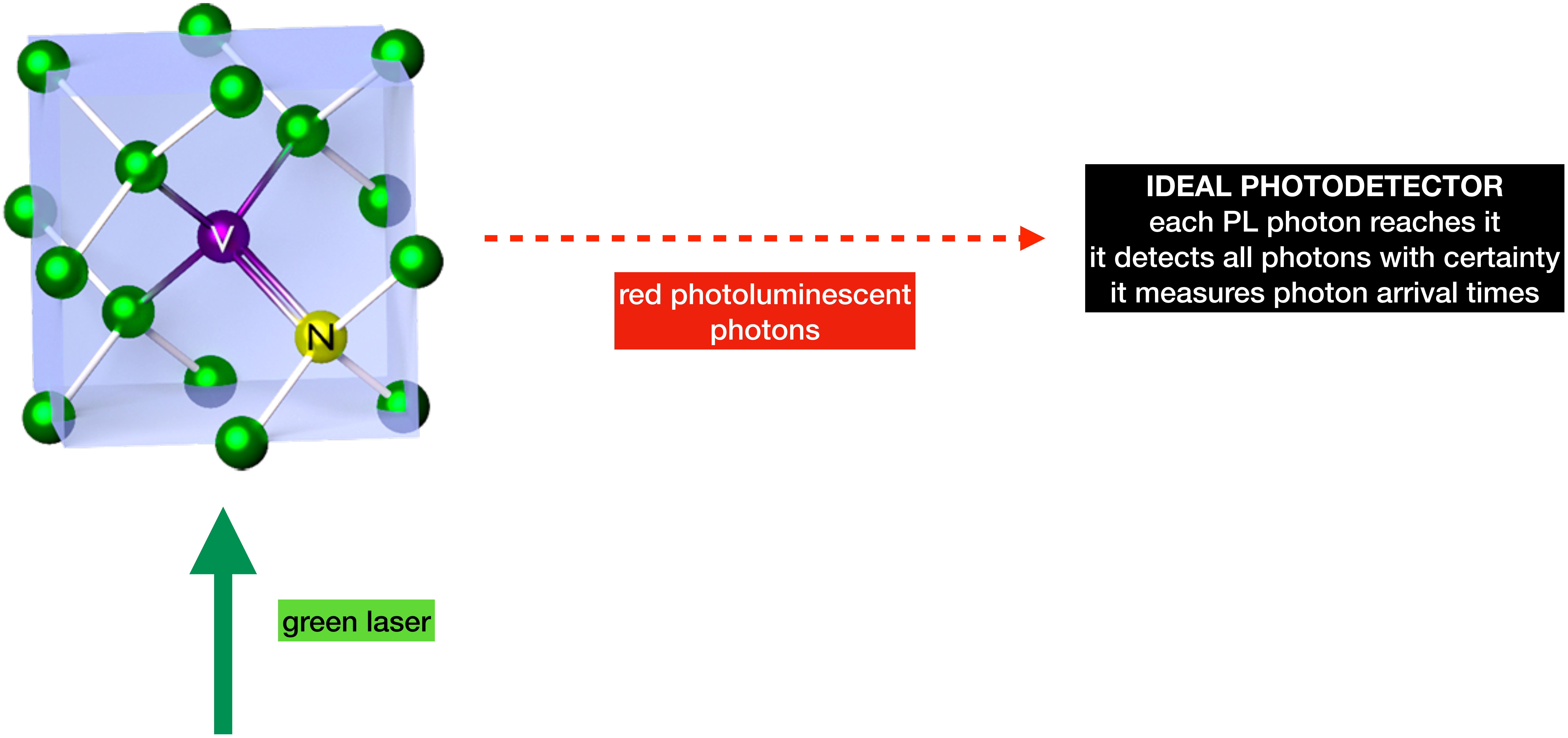
Towards an AI tool to enhance qubit readout in NV-based registers





ical values of the decay rates are $\Gamma_0 \simeq 63$ MHz, $\Gamma_{f0} \simeq 12$ MHz, $\Gamma_{f1} \simeq 80$ MHz, $\Gamma_{s1} \simeq 2.4$ MHz and $\Gamma_{s0} \simeq 3.3$ MHz

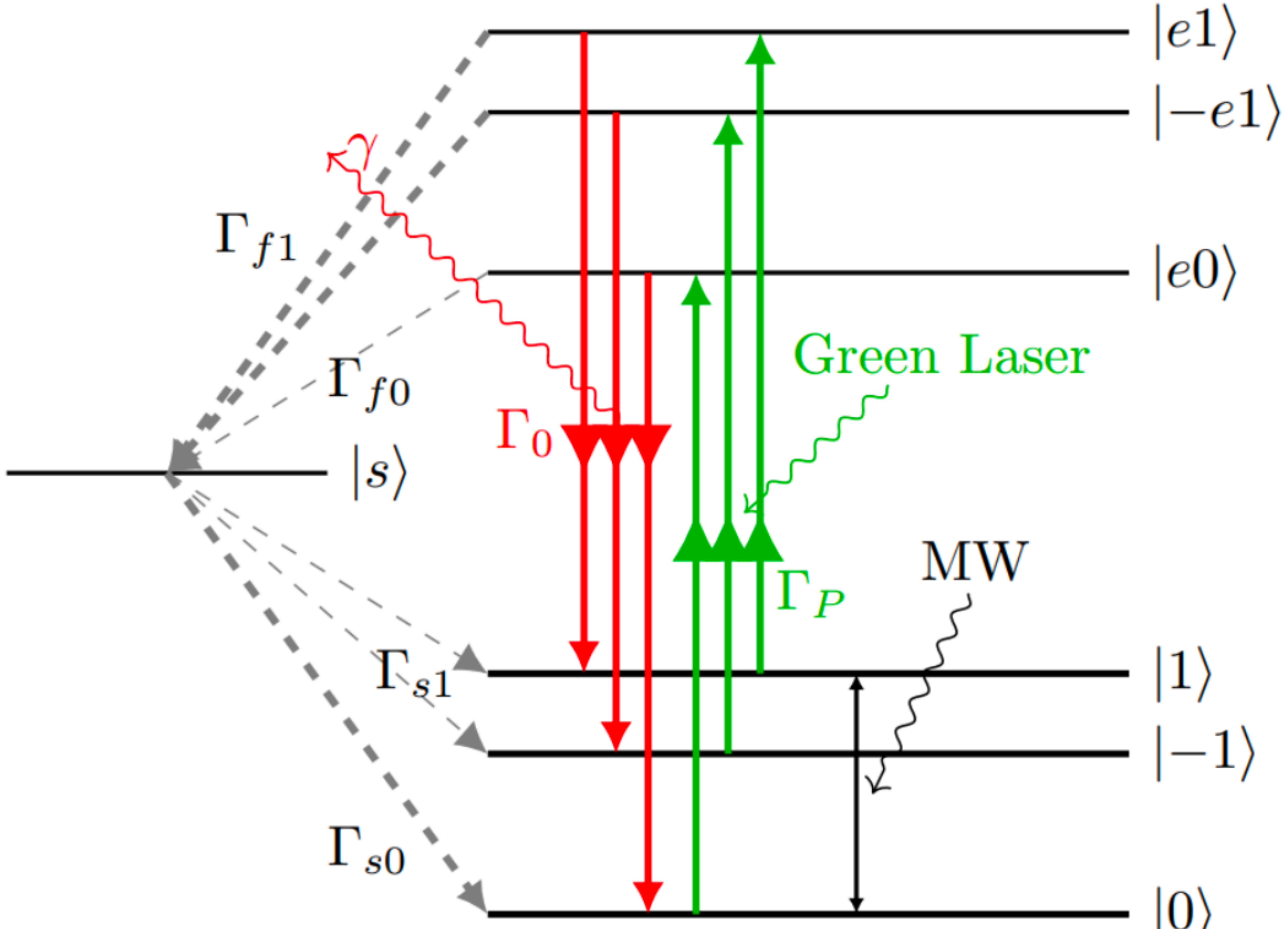
Minimal model to understand fundamental limitations of readout



Model: photon-number-resolved master equation

$$\dot\rho_0^n = -i\frac{\Omega}{2}(\rho_{01}^n - \rho_{10}^n) - \frac{\gamma_1}{2}(\rho_0^n - \rho_1^n) - \frac{\gamma_1}{2}(\rho_0^n - \rho_{-1}^n)$$
$$- \Gamma_P\rho_0^n + \Gamma_0\rho_{e0}^{n-1} + \Gamma_{s0}\rho_s^n,$$
$$\dot\rho_1^n = i\frac{\Omega}{2}(\rho_{01}^n - \rho_{10}^n) + \frac{\gamma_1}{2}(\rho_0^n - \rho_1^n)$$
$$- \Gamma_P\rho_1^n + \Gamma_0\rho_{e1}^{n-1} + \Gamma_{s1}\rho_s^n,$$
$$\dot\rho_{-1}^n = \frac{\gamma_1}{2}(\rho_0^n - \rho_{-1}^n) - \Gamma_P\rho_1^n + \Gamma_0\rho_{-e1}^{n-1} + \Gamma_{s1}\rho_s^n,$$

$$\dot\rho_{e0}^n = \Gamma_P\rho_0^n - \Gamma_0\rho_{e0}^n - \Gamma_{f0}\rho_{e0}^n,$$
$$\dot\rho_{e1}^n = \Gamma_P\rho_1^n - \Gamma_0\rho_{e1}^n - \Gamma_{f1}\rho_{e1}^n,$$
$$\dot\rho_{-e1}^n = \Gamma_P\rho_{-1}^n - \Gamma_0\rho_{-e1}^n - \Gamma_{f1}\rho_{-e1}^n,$$
$$\dot\rho_s^n = \Gamma_{f1}\rho_{e1}^n + \Gamma_{f1}\rho_{-e1}^n + \Gamma_{f0}\rho_{e0}^n - (\Gamma_{s0} + \Gamma_{s1})\rho_s^n.$$



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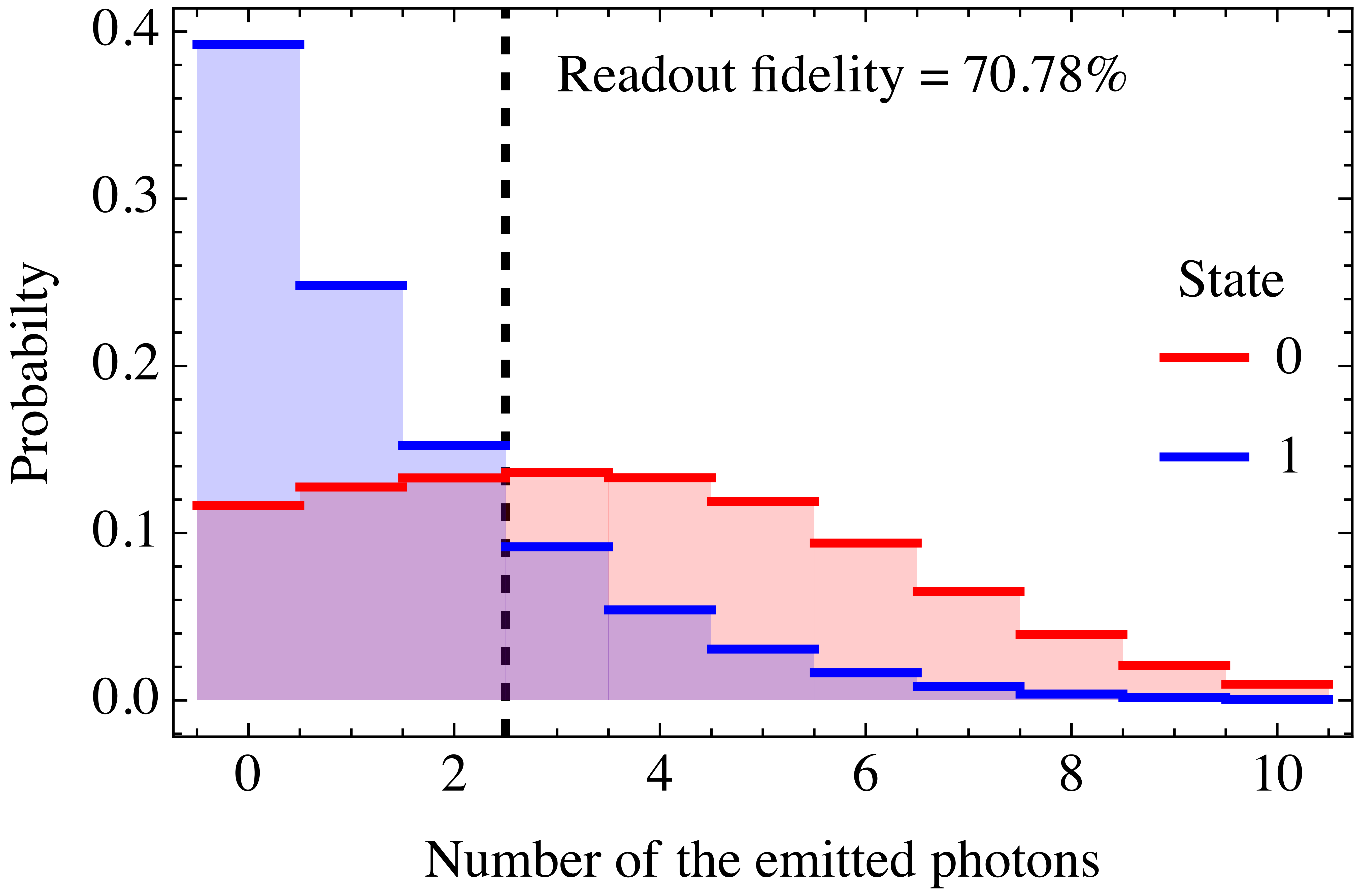
Panadero et al., https://arxiv.org/abs/2307.02854

Photon count reveals partial information about qubit state

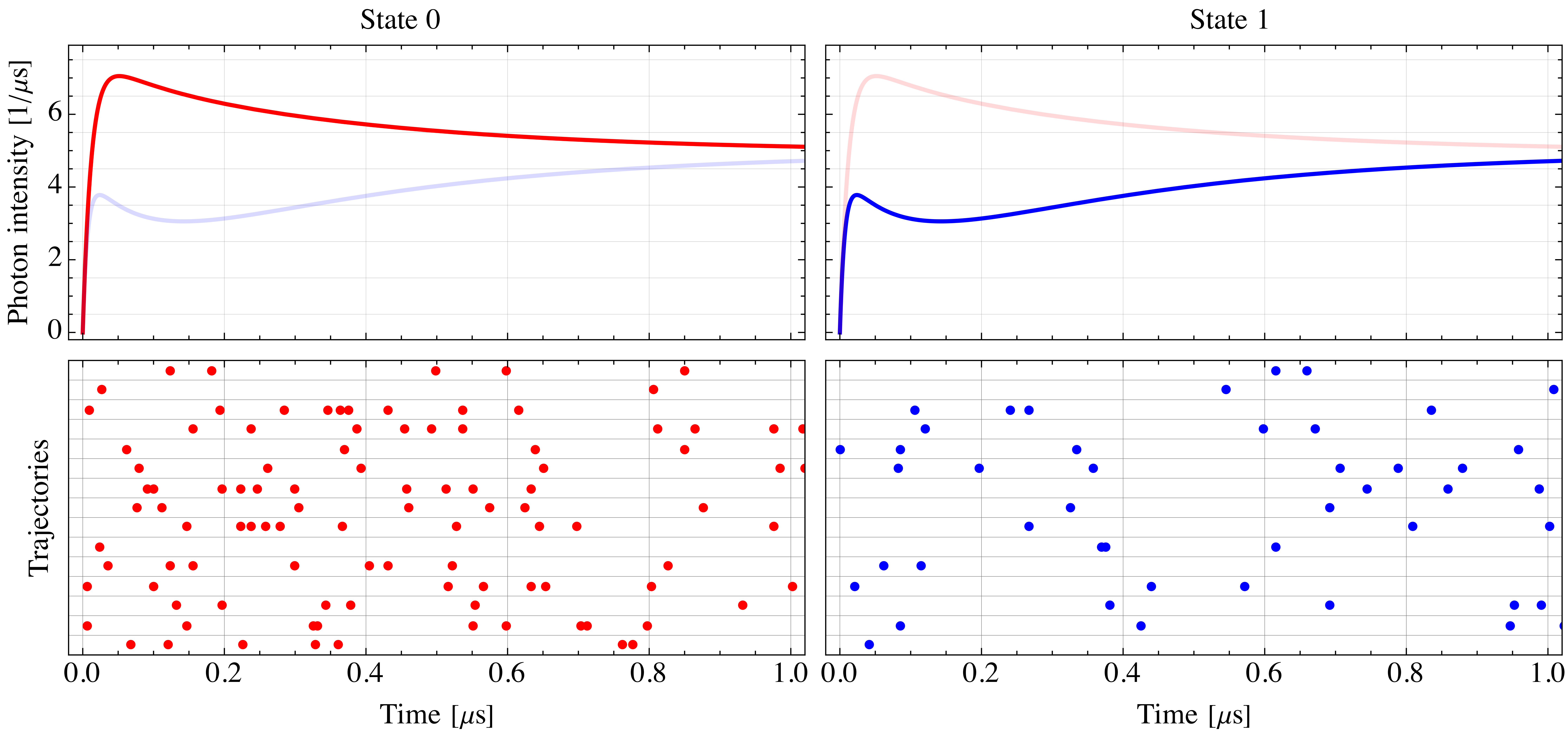
(1) fixed laser intensity
(2) fixed `integration time'

red/blue:
photon-count histograms for 0/1 qubit basis states



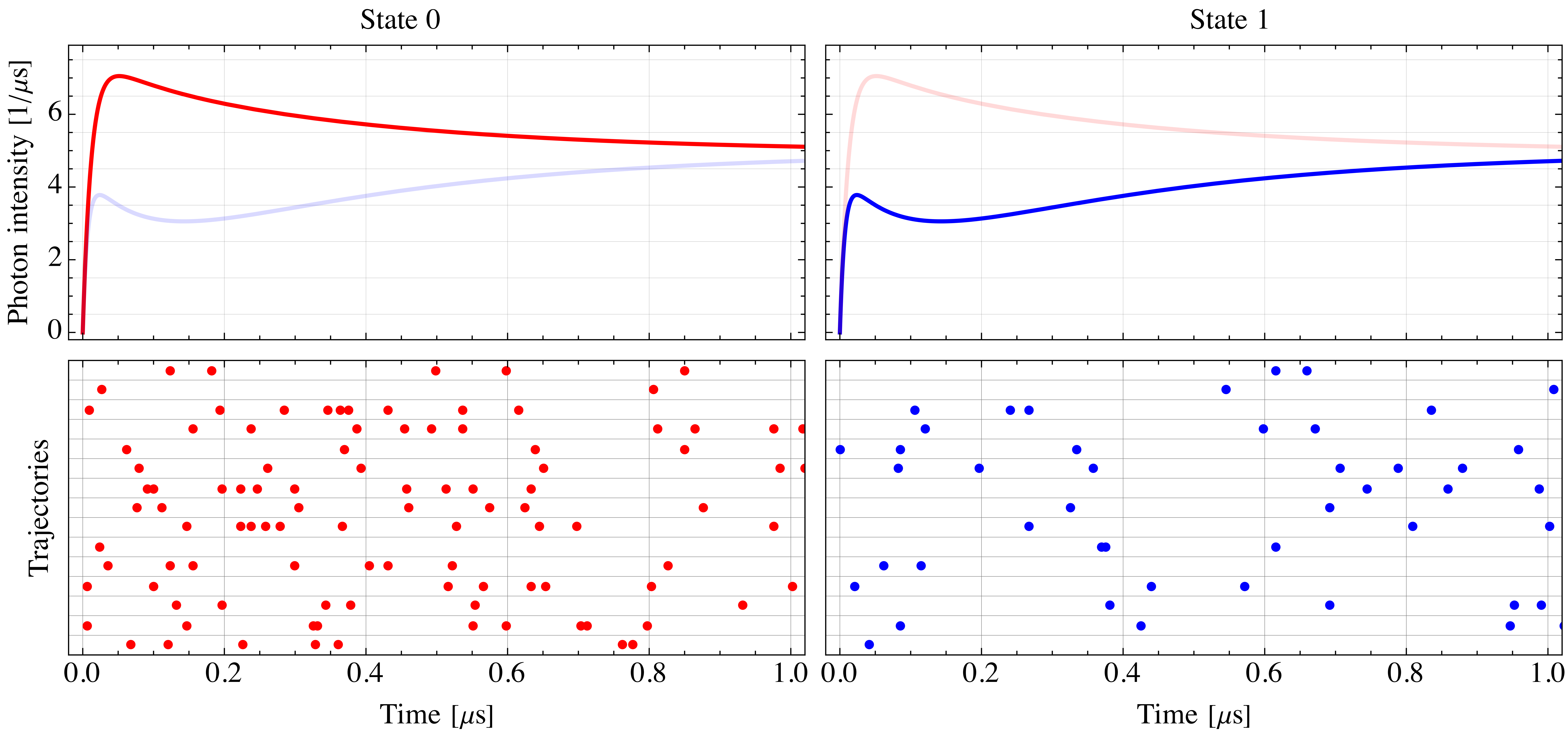
Laser intensity = 10 x PL decay rate.
Integration time = 0.1 us

Photon detection trajectories from the master equation



Laser intensity = 0.16 x PL decay rate.

There is more information in the trajectory than in the photon count!



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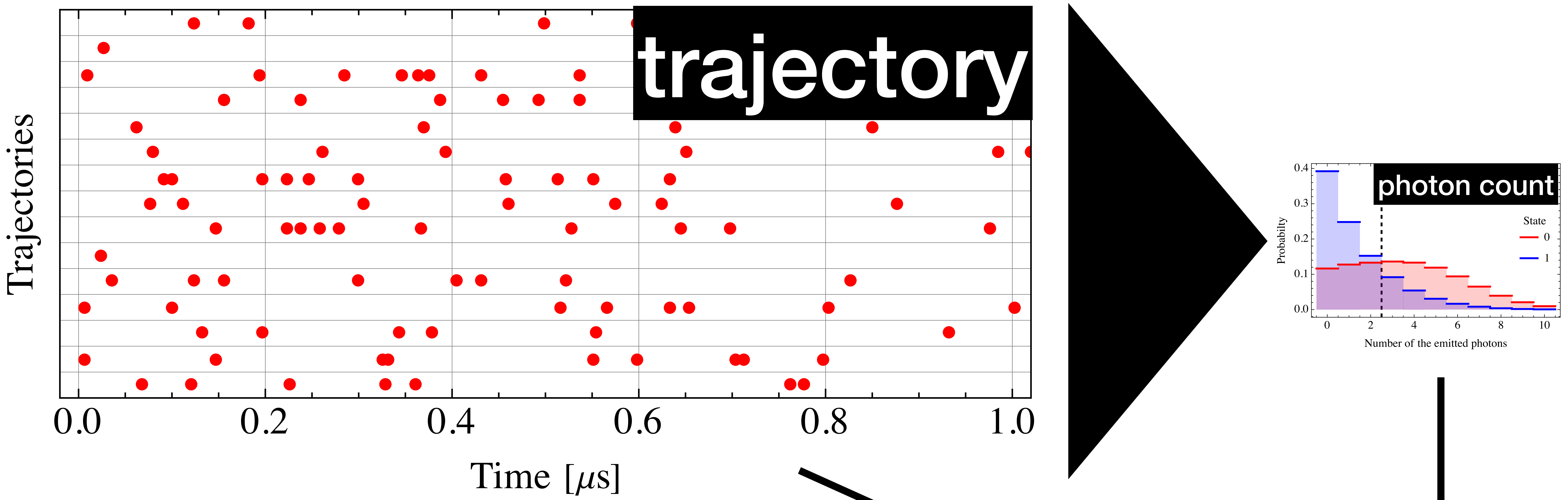

We try to squeeze out a more precise qubit readout
from the more complete information present in the trajectories.

inferred bit, 0 or 1

Photon count trajectories from master equation

$$
\begin{aligned}
\dot{\rho}_0^n &= -i\frac{\Omega}{2}(\rho_{01}^n - \rho_{10}^n) - \frac{\gamma_1}{2}(\rho_0^n - \rho_1^n) - \frac{\gamma_1}{2}(\rho_0^n - \rho_{-1}^n) \\
&\quad - \Gamma_P \rho_0^n + \Gamma_0 \rho_{e0}^{n-1} + \Gamma_{s0}\rho_s^n, \\
\dot{\rho}_1^n &= i\frac{\Omega}{2}(\rho_{01}^n - \rho_{10}^n) + \frac{\gamma_1}{2}(\rho_0^n - \rho_1^n) \\
&\quad - \Gamma_P \rho_1^n + \Gamma_0 \rho_{e1}^{n-1} + \Gamma_{s1}\rho_s^n, \\
\dot{\rho}_{-1}^n &= \frac{\gamma_1}{2}(\rho_0^n - \rho_{-1}^n) - \Gamma_P \rho_1^n + \Gamma_0 \rho_{-e1}^{n-1} + \Gamma_{s1}\rho_s^n,
\end{aligned}
$$

(1) Given transition rates $W_{i\leftarrow j}$ and initial time $t = 0$
(2) Given state j
(3) Random realization of the jump times $\tau_i \sim \mathrm{Exp}(1/W_{i\leftarrow j})$ $(\forall i)$
(4) $j \leftarrow \mathrm{argmin}_i \tau_i$ is the new state and $t \leftarrow t + \min \tau_i$
(5) if $t > t_{\max}$ break else goto (2)

$$
\begin{aligned}
\dot{\rho}_{e0}^n &= \Gamma_P \rho_0^n - \Gamma_0 \rho_{e0}^n - \Gamma_{f0}\rho_{e0}^n, \\
\dot{\rho}_{e1}^n &= \Gamma_P \rho_1^n - \Gamma_0 \rho_{e1}^n - \Gamma_{f1}\rho_{e1}^n, \\
\dot{\rho}_{-e1}^n &= \Gamma_P \rho_{-1}^n - \Gamma_0 \rho_{-e1}^n - \Gamma_{f1}\rho_{-e1}^n, \\
\dot{\rho}_s^n &= \Gamma_{f1}\rho_{e1}^n + \Gamma_{f1}\rho_{-e1}^n + \Gamma_{f0}\rho_{e0}^n - (\Gamma_{s0} + \Gamma_{s1})\rho_s^n.
\end{aligned}
$$


Laser intensity (excitation rate) = 0.01 (in the unit of direct decay rate from excited state to ground state)
Readout fidelity
Optimal = 6.25 μs
Integration time [μs]
Probabilty
Readout fidelity = 61.5%
State
0
1
Number of the emitted photons
Laser intensity (excitation rate) = 0.1 (in the unit of direct decay rate from excited state to ground state)
Readout fidelity
Optimal = 0.756 μs
Integration time [μs]
Probabilty
Readout fidelity = 64.98%
State
0
1
Number of the emitted photons
Laser intensity (excitation rate) = 1 (in the unit of direct decay rate from excited state to ground state)
Readout fidelity
Optimal = 0.1575 μs
Integration time [μs]
Probabilty
Readout fidelity = 70.49%
State
0
1
Number of the emitted photons
Laser intensity (excitation rate) = 10 (in the unit of direct decay rate from excited state to ground state)
Readout fidelity
Optimal = 0.096 μs
Integration time [μs]
Probabilty
Readout fidelity = 70.78%
State
0
1
Number of the emitted photons
Laser intensity (excitation rate) = 100 (in the unit of direct decay rate from excited state to ground state)
Readout fidelity
Optimal = 0.0912 μs
Integration time [μs]
Probabilty
Readout fidelity = 70.69%
State
0
1
Number of the emitted photons