A FIRST SIMULATION OF TWO COUPLED QUBITS USING QUTIP

Joint Qub-IT PNRR February meeting – 27/02/2024

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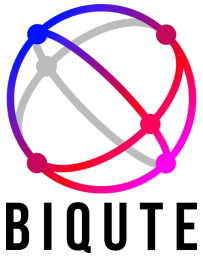
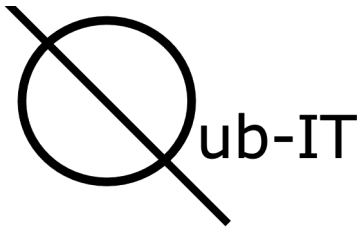
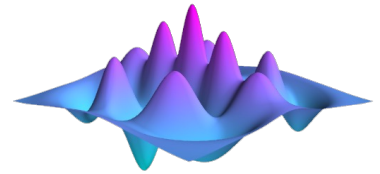




A PRELIMINARY STUDY

OBJECTIVE: Study the effects of non-computational levels on two coupled qubits using **QuTiP**.



https://arxiv.org/abs/1110.0573

Free Hamiltonians

Two level system (computational base)

$$H = \frac{\omega_q}{2}\sigma_z$$

Anharmonic oscillator (second quantization)

Numerically unstable! (from C. Gatti, L. Banchi notes)

Levels $= 10$

$$H = \omega_q a^\dagger a + \frac{\alpha}{2} a^\dagger a^\dagger a a$$

Transmon (charge base)

Levels $= 10$, $n_g = 5$

$$H = \sum_n 4E_C \left(n_g - n\right)^2 |n\rangle\langle n| - \frac{1}{2} E_J \sum_n \left(|n+1\rangle\langle n| + |n\rangle\langle n+1|\right)$$

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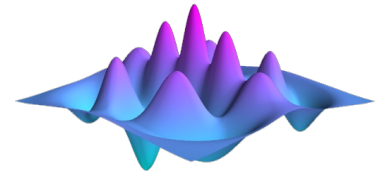

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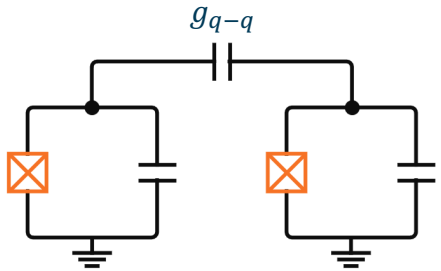
Interacting Hamiltonian

$$H_{\text{int}} = g\sigma_{y1} \otimes \sigma_{y2} = -g([\sigma^+ - \sigma^-] \otimes [\sigma^+ - \sigma^-])$$

Capacitance as a coupler (current simulations)

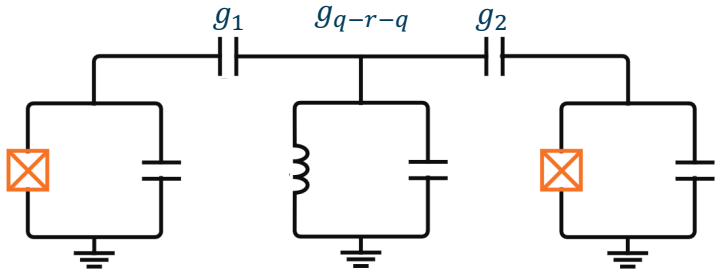
$$g \to g_{\text{q-q}} = \frac{1}{2}\sqrt{\omega_{q1}\omega_{q2}}\,\frac{C_{\text{q-q}}}{\sqrt{C_{\text{q-q}} + C_1}\sqrt{C_{q-q} + C_2}}$$



https://arxiv.org/abs/1904.06560

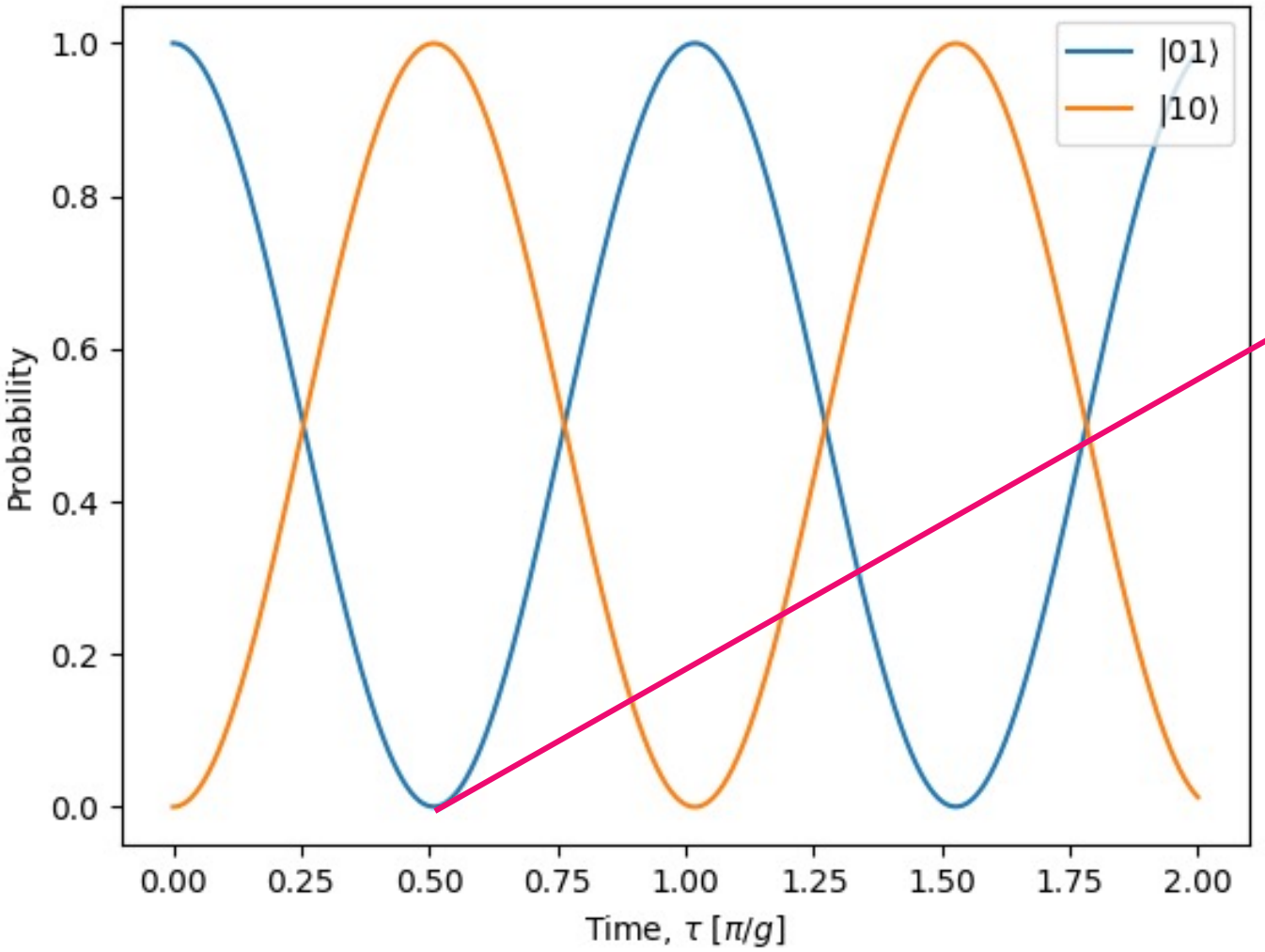
Resonator as a coupler (next simulations)

$$g \to g_{\text{q-r-q}} = \frac{g_1 g_2(\Delta_1 + \Delta_2)}{2\Delta_1\Delta_2} \qquad \Delta_i = \omega_{\text{qi}} - \omega_{\text{r}}$$



FIXED-FREQUENCY QUBITS

$$H_{q1} = 4E_C n^2 - E_J \cos(\phi) \qquad H_{q2} = 4E_C n^2 - E_J \cos(\phi)$$

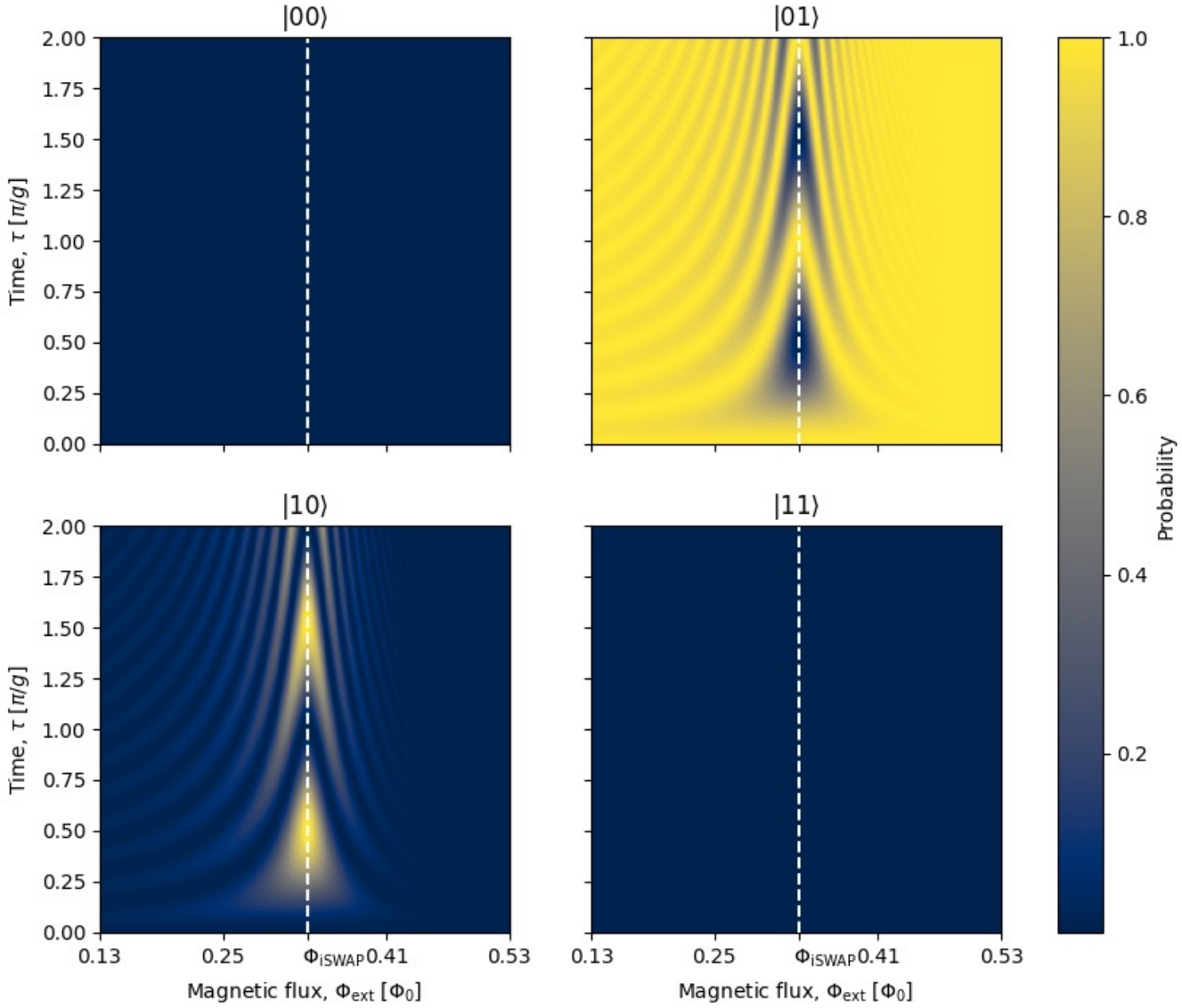


$$U_{qq} = \left(\frac{\pi}{2g}\right) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -i & 0 \\ 0 & -i & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \equiv iSWAP$$

Parameter	Value
E_J	16.34 GHz
E_C	230.84 MHz
C_s	83.92 fF
$C_{\mathrm{q-q}}$	5 fF
$g_{\mathrm{q-q}}$	0.147 GHz

from Alex's previous simulations

TUNABLE-FREQUENCY QUBIT



Two level system (computational base)

$$H_{q1} = 4E_C n^2 - E_J \cos(\phi)$$

$$H_{q2} = 4E_C n^2 - 2E_J |\cos(\varphi_e)| \cos(\phi)$$

Parameter	Value
E_J	16.34 GHz
E_{J2}	[0.017 , 32.68] GHz
E_C	230.84 MHz
C_s	83.92 fF
$C_{\mathrm{q-q}}$	5 fF
$g_{\mathrm{q-q}}$	[0.015 , 0.176] GHz

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No leakage in other levels!

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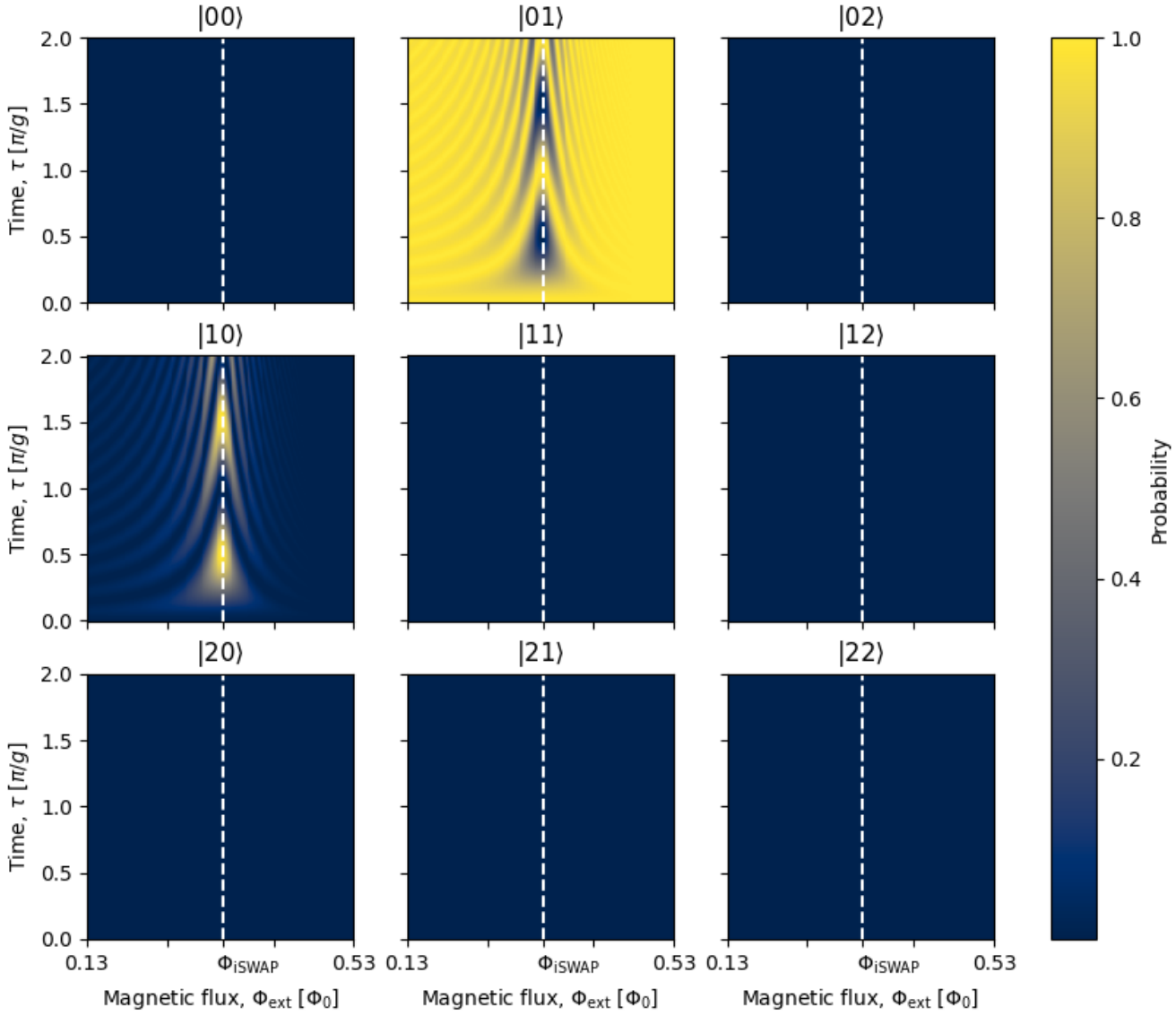

Anharmonic oscillator (second quantization)

Levels = 10

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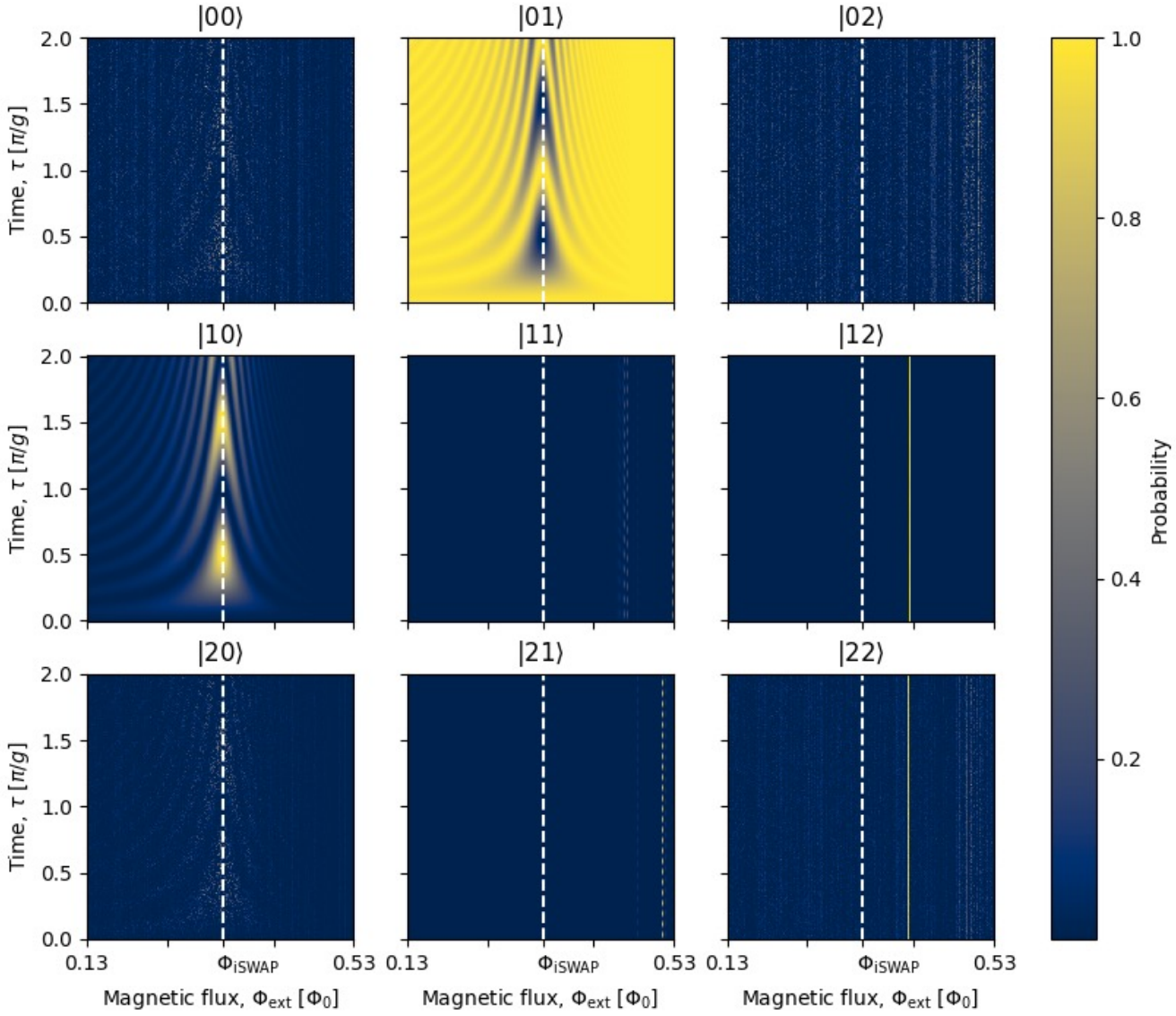

Transmon (charge base)

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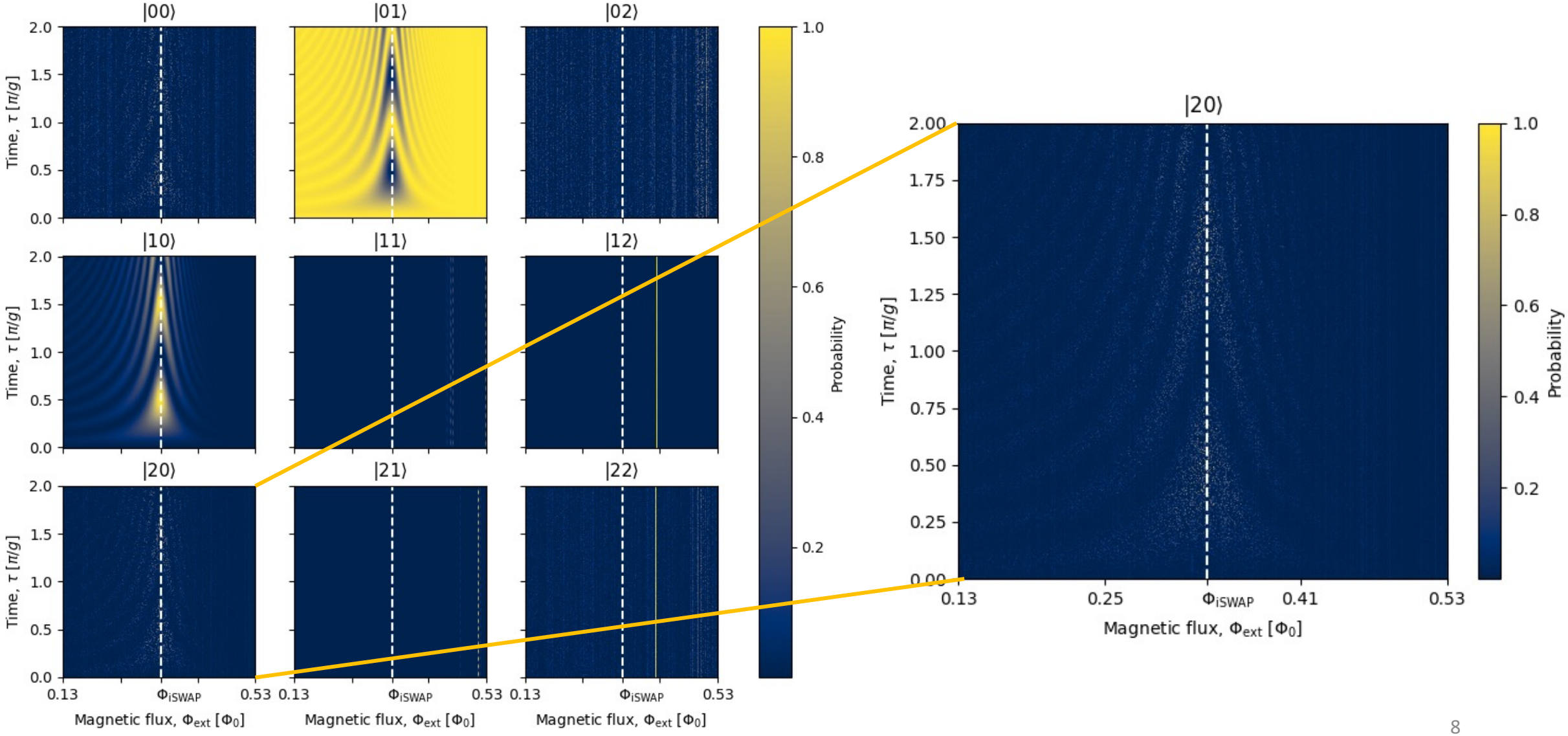

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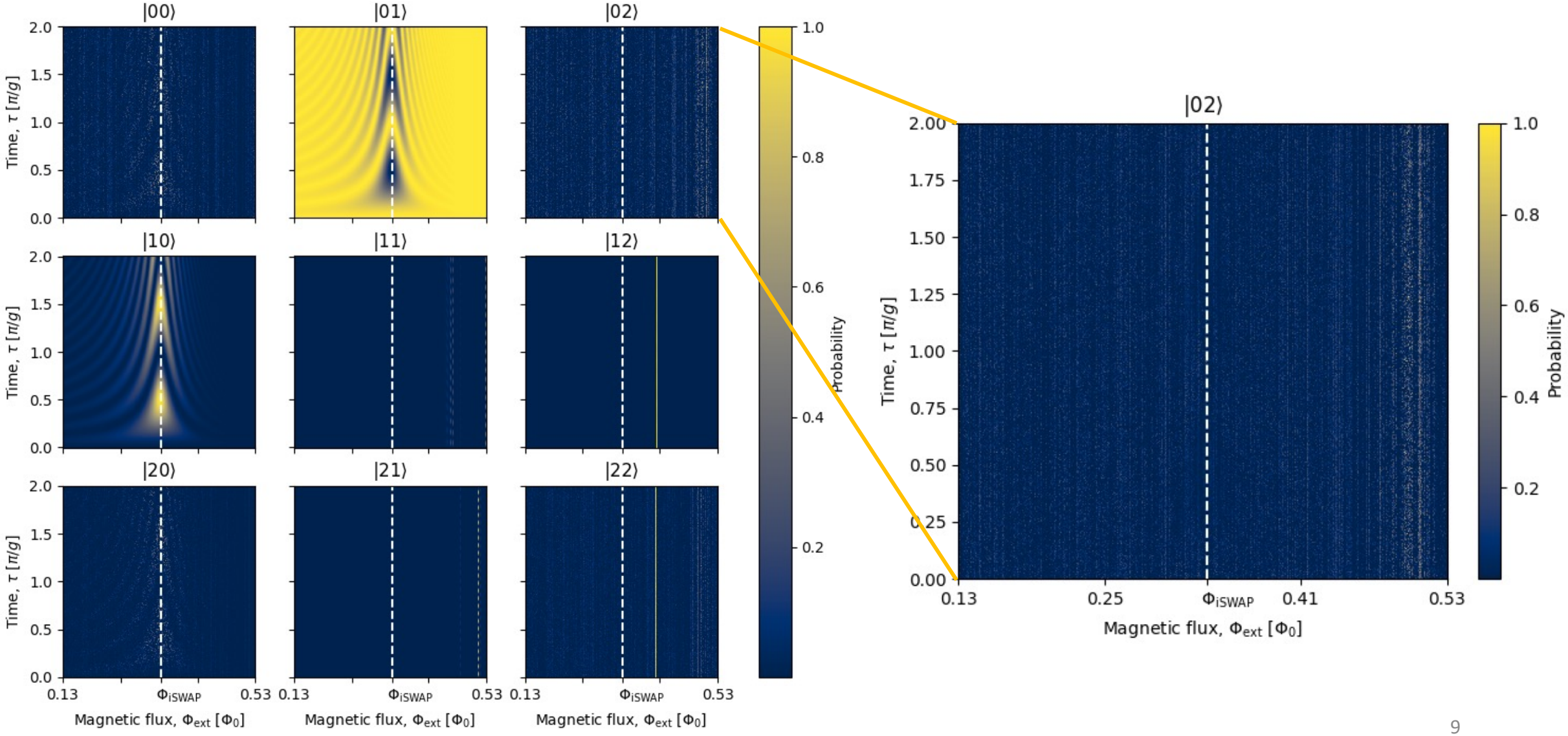

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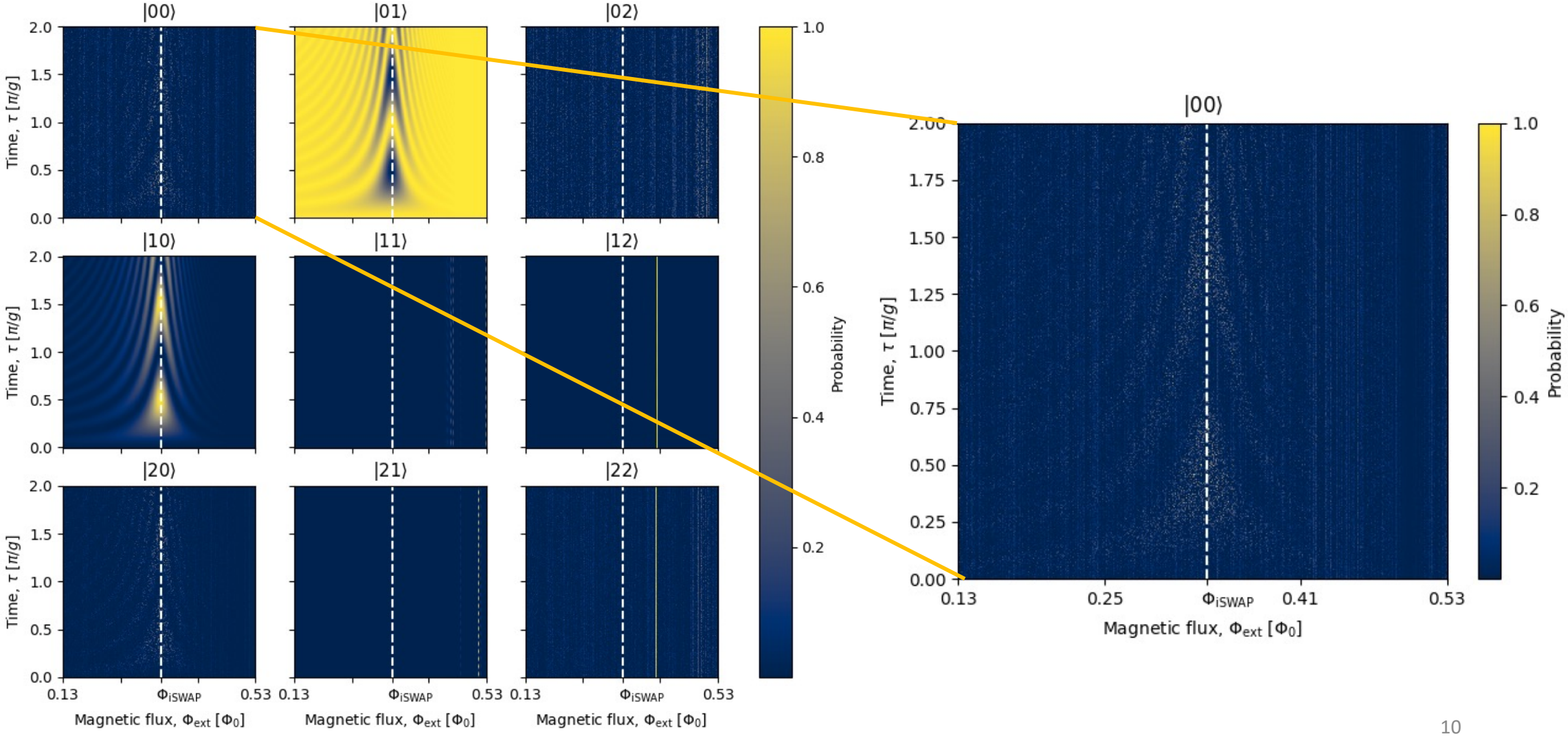

STILL A WORK IN PROGRESS

Preliminary conclusions

- Non-computational levels interacts with the computational ones
- Transmon Hamiltonian in the charge base can detect and model these effects

Roadmap

- Focus on the transmon case, varying anharmonicity
    1. Anharmonicity of the fixed-frequency qubit
    2. Anharmonicity of the tunable-frequency qubit
    3. Anharmonicities of the two coupled qubits
- More and more realistic simulations! Let’s open the system and introduce thermal noise!
- Study the resonator as a coupler