# Supervise learning of time-independent Hamiltonians for gate design

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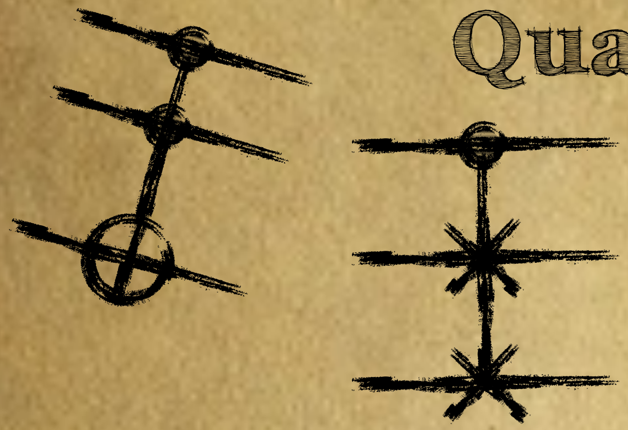
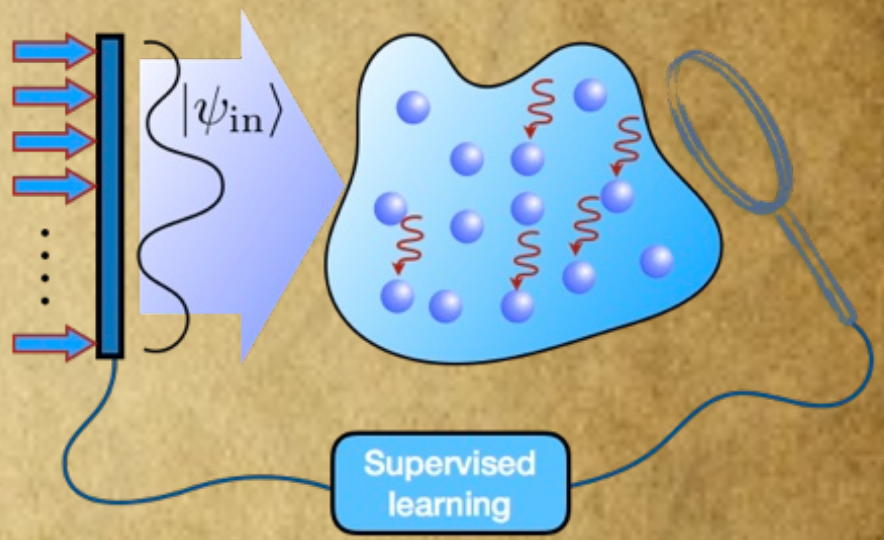
QTEQ QUANTUM TECHNOLOGY at QUEEN'S

# PLAN OF THE TALK

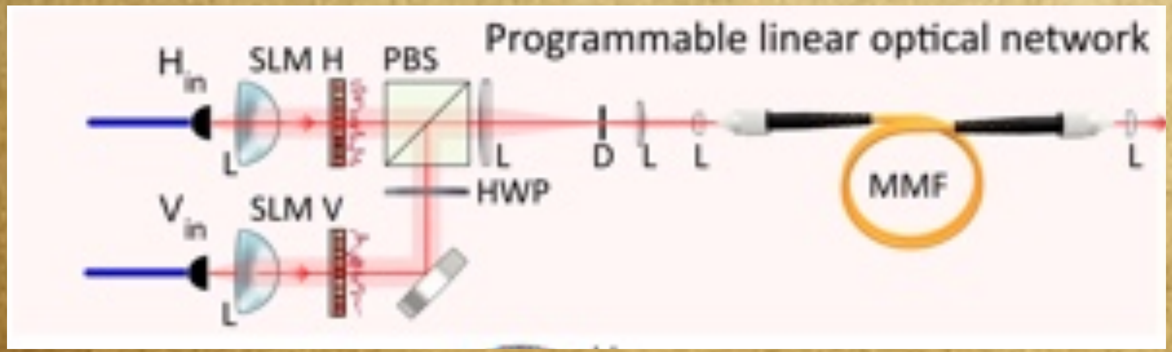
## 1 Quantum gate synthesis and design



## 2 Machine learning for quantum state engineering




## 3 Programming linear networks with a fiber



# PART

# 1

# QUANTUM GATE SYNTHESIS AND DESIGN

# DUE CREDIT

Luca Innocenti (QUB)

Alessandro Ferraro (QUB)

Leonardo Banchi (Florence)

Sougato Bose (UCL)

L. Innocenti, L. Banchi, A. Ferraro, S. Bose, and M. Paternostro, arXiv: 1803.07119

# MOTIVATIONS

(CLASSICAL)

Sammy, 3 years old:

typical learner

What Sammy wants

What Sammy has!

(15 of them)

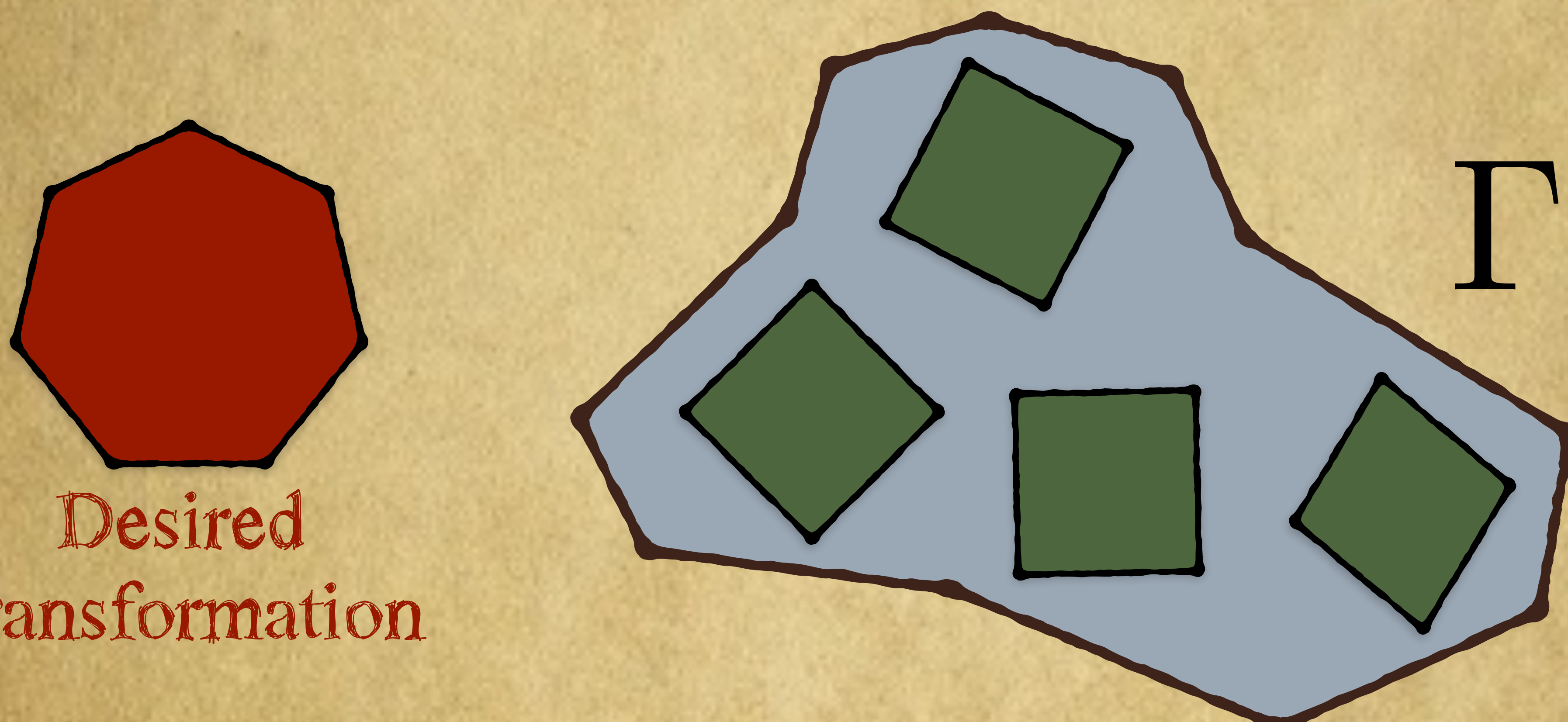
# A simple question

Is it possible to synthesise exactly a gate $\mathcal{G}$ from a generator $\mathcal{H}_{\mathcal{G}}$ comprising operations drawn only from an assigned $\Gamma$?


L. Innocenti, L. Banchi, A. Ferraro, S. Bose, and M. Paternostro, arXiv: 1803.07119

# A simple question

Is it possible to synthesise exactly a gate $\mathcal{G}$ from a generator $\mathcal{H}_{\mathcal{G}}$ comprising operations drawn only from an assigned $\Gamma$?




Desired transformation

The gates that a given experimental platform implements naturally

L. Innocenti, L. Banchi, A. Ferraro, S. Bose, and M. Paternostro, arXiv: 1803.07119

# What to take home?

Is it possible to synthesise exactly a gate $\mathcal{G}$ from a generator $\mathcal{H}_{\mathcal{G}}$ comprising operations drawn only from an assigned $\Gamma$?

## Take - home messages from this talk

-3 conditions to produce a $\tilde{\mathcal{H}}$ comprising only operations drawn from $\pi$ such that

$$\mathcal{G} = \exp(i\tilde{\mathcal{H}})$$

-Present a supervised-learning optimisation technique to train qubit networks & achieve the desired synthesis

- Discuss & demonstrate algorithm-training instances of multi-qubit gates

L. Innocenti, L. Banchi, A. Ferraro, S. Bose, and M. Paternostro, arXiv: 1803.07119

# General methodology

$$\mathcal{G} = e^{i\mathcal{H}_\mathcal{G}} = U\Lambda U^\dagger \Rightarrow \boxed{\mathcal{H}_\mathcal{G}} = -iU\,\mathrm{Log}(\Lambda)U^\dagger$$

Will contain both feasible and unfeasible interactions

The goal: Construct $\tilde{\mathcal{H}}_\mathcal{G}$ built using $\Gamma$ only, such that $\mathcal{G} = \exp(i\tilde{\mathcal{H}}_\mathcal{G})$

What we do NOT want:

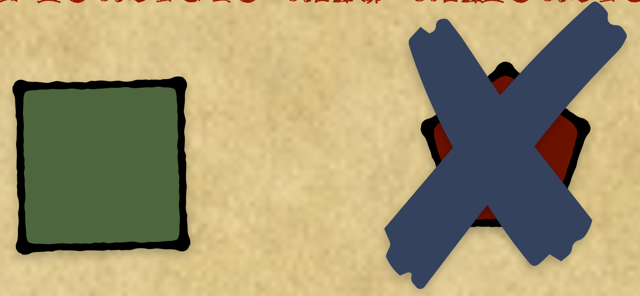
1) Time-dependent Hamiltonians
2) Ancillary systems
3) Complicated quantum control

L. Innocenti, L. Banchi, A. Ferraro, S. Bose, and M. Paternostro, arXiv: 1803.07119

# General methodology

$$\mathcal{G} = e^{i\mathcal{H}_\mathcal{G}} = U\Lambda U^\dagger \Rightarrow \boxed{\mathcal{H}_\mathcal{G}} = -iU\,\mathrm{Log}(\Lambda)U^\dagger$$

Will contain both feasible and unfeasible interactions



The goal: Construct $\tilde{\mathcal{H}}_\mathcal{G}$ built using $\Gamma$ only, such that $\mathcal{G} = \exp(i\tilde{\mathcal{H}}_\mathcal{G})$

What we DO want:

1) $\tilde{\mathcal{H}}_\mathcal{G}$ contains only feasible interactions
2) $[\tilde{\mathcal{H}}_\mathcal{G}, \mathcal{H}_\mathcal{G}] = 0$
3) $\mathrm{Eig}(\tilde{\mathcal{H}}_\mathcal{G} - \mathcal{H}_\mathcal{G}) = \{2\pi n_i \text{ with } n_i \in \mathbb{Z}\}$

L. Innocenti, L. Banchi, A. Ferraro, S. Bose, and M. Paternostro, arXiv: 1803.07119

# General methodology

1) $\tilde{\mathcal{H}}_{\mathcal{G}}$ contains only feasible interactions ✓

2) $[\tilde{\mathcal{H}}_{\mathcal{G}}, \mathcal{H}_{\mathcal{G}}] = 0$ 3) $\mathrm{Eig}(\tilde{\mathcal{H}}_{\mathcal{G}} - \mathcal{H}_{\mathcal{G}}) = \{2\pi n_i \text{ with } n_i \in \mathbb{Z}\}$

$$\Downarrow$$

$$\begin{aligned} \mathcal{G} &= \exp(i\tilde{\mathcal{H}}_{\mathcal{G}} - i\mathcal{H}_{\mathcal{G}}) \exp(i\mathcal{H}_{\mathcal{G}}) \\ \exp(i\tilde{\mathcal{H}}_{\mathcal{G}} - i\mathcal{H}_{\mathcal{G}}) &= \mathbb{1} \end{aligned}$$

The gist of it: given $\mathcal{G}$ look for $\tilde{\mathcal{H}}_{\mathcal{G}} = \mathcal{H}_{\mathcal{G}}$ + something else satisfying 1), 2), and 3)

L. Innocenti, L. Banchi, A. Ferraro, S. Bose, and M. Paternostro, arXiv: 1803.07119

# General methodology

$\tilde{\mathcal{H}}_{\mathcal{G}}$ contains only physical interactions ✔

2) $[\tilde{\mathcal{H}}_{\mathcal{G}}, \mathcal{H}_{\mathcal{G}}] = 0$ 3) $\mathrm{Eig}(\tilde{\mathcal{H}}_{\mathcal{G}} - \mathcal{H}_{\mathcal{G}}) = \{2\pi n_i \text{ with } n_i \in \mathbb{Z}\}$

$\Downarrow$

A) Analytically solved in at least some situations of physical interest

B) Help to identify efficient starting points for numeric optimizations

L. Innocenti, L. Banchi, A. Ferraro, S. Bose, and M. Paternostro, arXiv: 1803.07119

# General methodology

B) Help to identify efficient starting points for numeric optimizations

Choose $\tilde{\mathcal{H}}_G(\lambda)$ drawn from $\Gamma$

Use condition 2) to reduce set of possible interactions & to constrain parameters

Non-trivial step: enforce 3) $\Longrightarrow$ Inverse eigenvalue problem

Supervised learning approach

L. Innocenti, L. Banchi, A. Ferraro, S. Bose, and M. Paternostro, arXiv: 1803.07119

# General methodology

**Supervised learning approach**

Strategy

Decompose $\mathcal{H}(\lambda) = \sum_i \lambda_i O_i$

Consider $\mathcal{F}(\lambda, \psi) \equiv \langle\psi|\mathcal{G}^\dagger \exp(i\mathcal{H}(\lambda))|\psi\rangle$

Look for $\lambda_0$ such that $\mathcal{F}(\lambda_0, \psi) = 1$ for all $|\psi\rangle$

L. Innocenti, L. Banchi, A. Ferraro, S. Bose, and M. Paternostro, arXiv: 1803.07119

# General methodology

Supervised learning approach

Algorithm

a. Make an initial choice for $\boldsymbol{\lambda}$

b. Generate a random set of input states $|\psi_k\rangle$, $k = 1, ..., N_b$

c. For each k compute $\nabla_{\lambda}\mathcal{F}(\boldsymbol{\lambda}, \psi_k)$

Automatic Derivative with error backpropagation: Theano,PyTorch, TensorFlow

d. Update the choice of $\boldsymbol{\lambda}$ using momentum gradient

$$\boldsymbol{v} \to \gamma \boldsymbol{v} + \eta \nabla_{\lambda}\mathcal{F}(\boldsymbol{\lambda}, \psi_k)$$
$$\boldsymbol{\lambda} \to \boldsymbol{\lambda} + \boldsymbol{v}$$

momentum term learning rate

e. Repeat till a satisfactory value of fidelity is found

L. Innocenti, L. Banchi, A. Ferraro, S. Bose, and M. Paternostro, arXiv: 1803.07119

# Results: Toffoli

$$\mathcal{H}_{\text{Toff}} = \frac{\pi}{8}(1 - \sigma_1^z)(1 - \sigma_2^z)(1 - \sigma_3^x)$$

$\Gamma$: only 2-qubit terms!

$$\tilde{\mathcal{H}}_{\text{Toff}} = h_0 \mathbb{1} + \sum h_{i,\alpha}\sigma_i^\alpha + \sum J_{i,j}^{\alpha,\beta}\sigma_i^\alpha\sigma_j^\beta$$

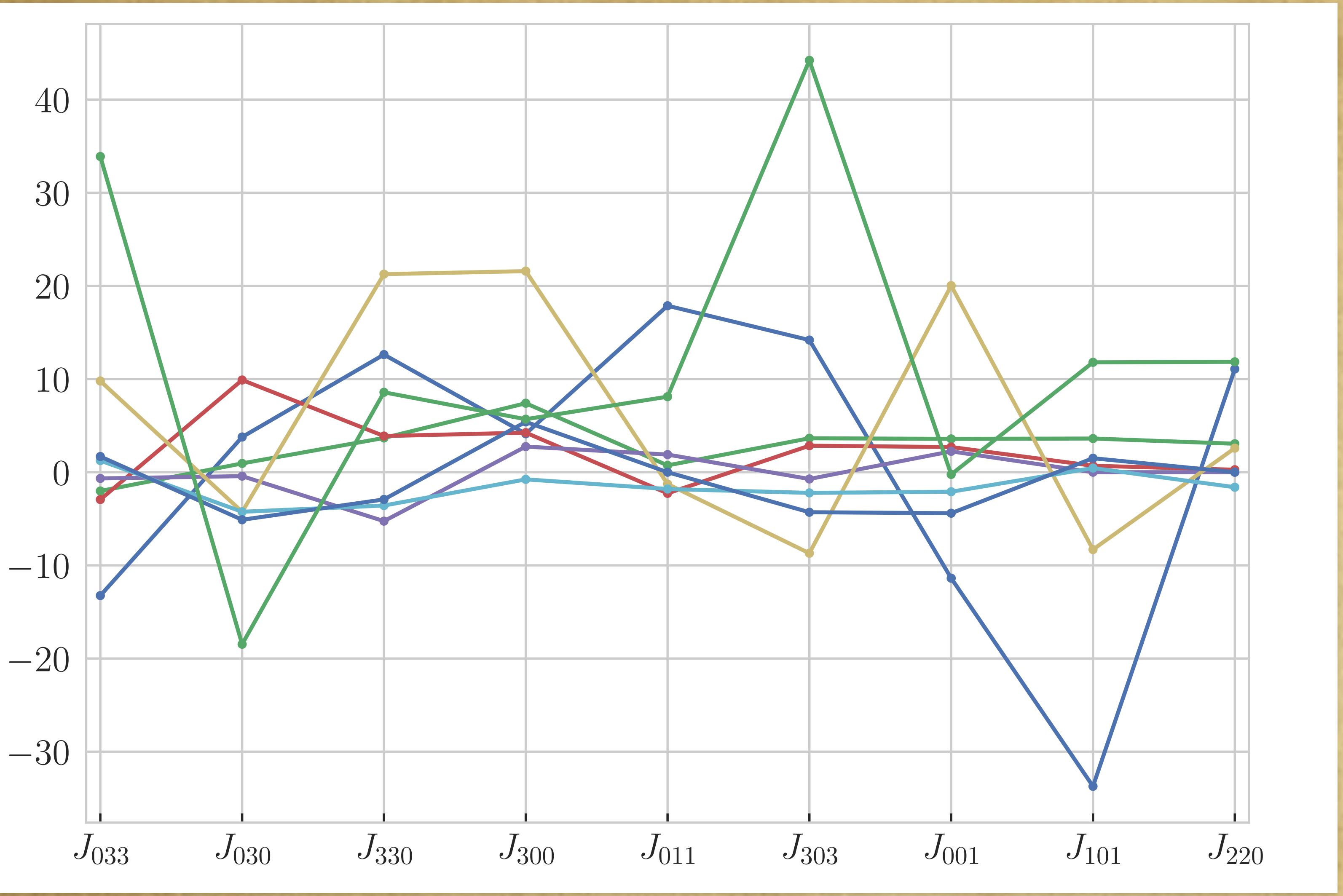
37 parameters $\Longrightarrow$ Enforce condition 2: reduces parameters

$$\tilde{\mathcal{H}}_{\text{Toff}} = J_{000} + J_{300}Z_1 + J_{030}Z_2 + J_{001}X_3 + Z_3[J_{303}(1 + Z_1) + J_{033}(1 + Z_2)]$$
$$+ (J_{101}X_1 + J_{011}X_2)(1 + X_3) + J_{220}(X_1X_2 + Y_1Y_2) + J_{330}Z_1Z_2.$$

$\Longrightarrow$ Too large for inverse eigenvalue approach

L. Innocenti, L. Banchi, A. Ferraro, S. Bose, and M. Paternostro, arXiv: 1803.07119

# Results: Toffoli




$$\tilde{\mathcal{H}}_{\rm Toff} = J_{000} + J_{300}Z_1 + J_{030}Z_2 + J_{001}X_3 + Z_3[J_{303}(1+Z_1) + J_{033}(1+Z_2)]$$
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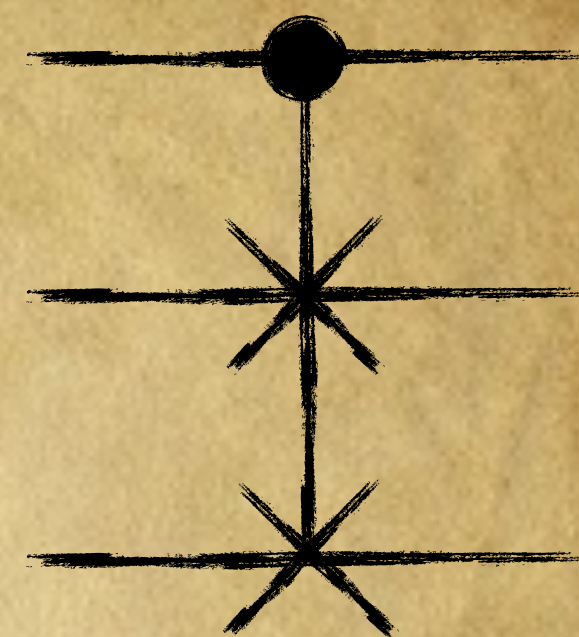
L. Innocenti, L. Banchi, A. Ferraro, S. Bose, and M. Paternostro, arXiv: 1803.07119

# Results: Fredkin

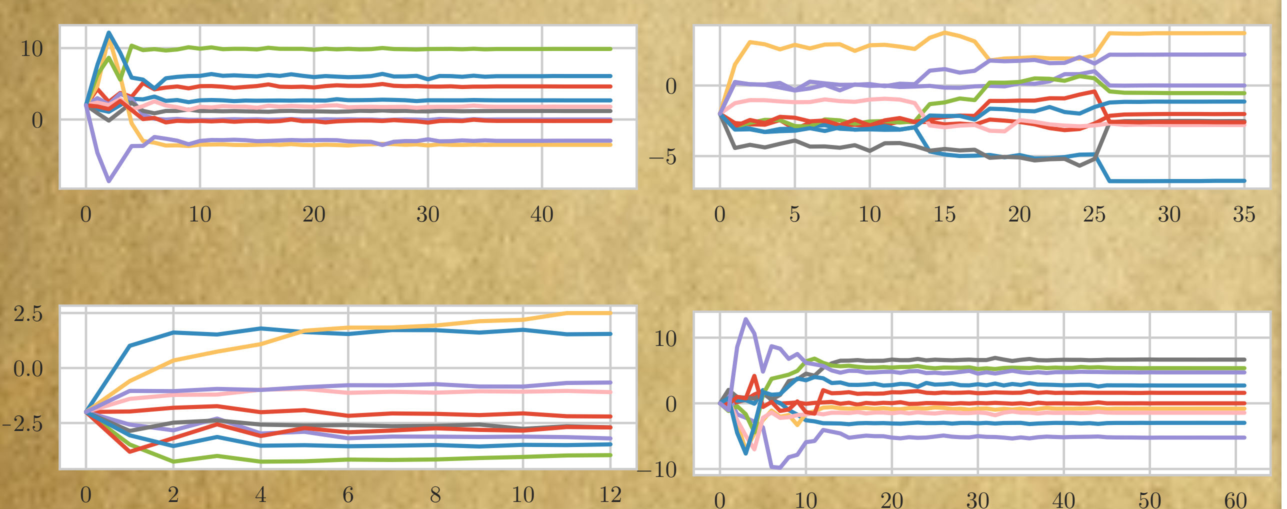
$$\mathcal{H}_{\text{Fred}} = \frac{\pi}{8}\left(\mathbb{1} - \sigma_1^z\right)\left[\mathbb{1} - \sum_{\alpha=x,y,z} \sigma_2^\alpha \sigma_3^\alpha\right]$$

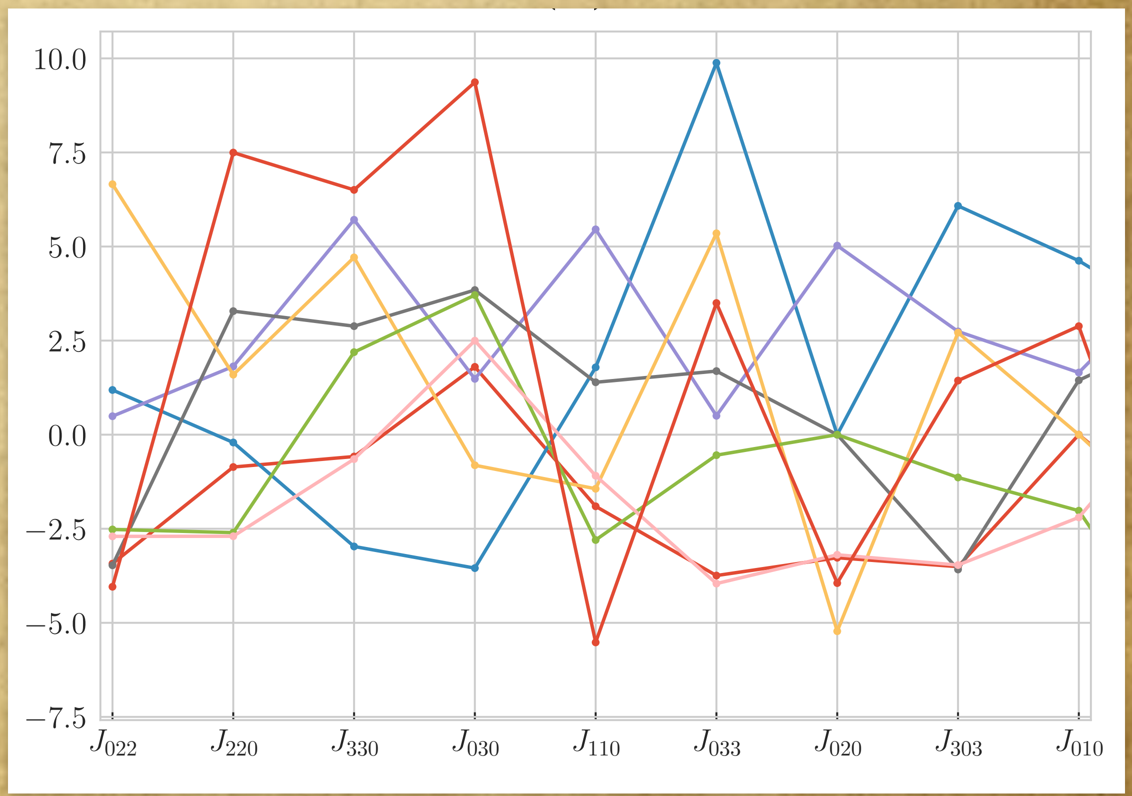


## Γ: only 2-qubit terms!

$$\tilde{\mathcal{H}}_{\text{Fred}} = \frac{\pi}{8}\left(\sqrt{\frac{143}{5}}\mathbb{1} + 5\sqrt{3}\sigma_1^x\right)(\sigma_2^x + \sigma_3^x) - \frac{3\pi}{8}\left(\sum_{\alpha=x,y,z}\sigma_2^\alpha\sigma_3^\alpha - \mathbb{1}\right)$$

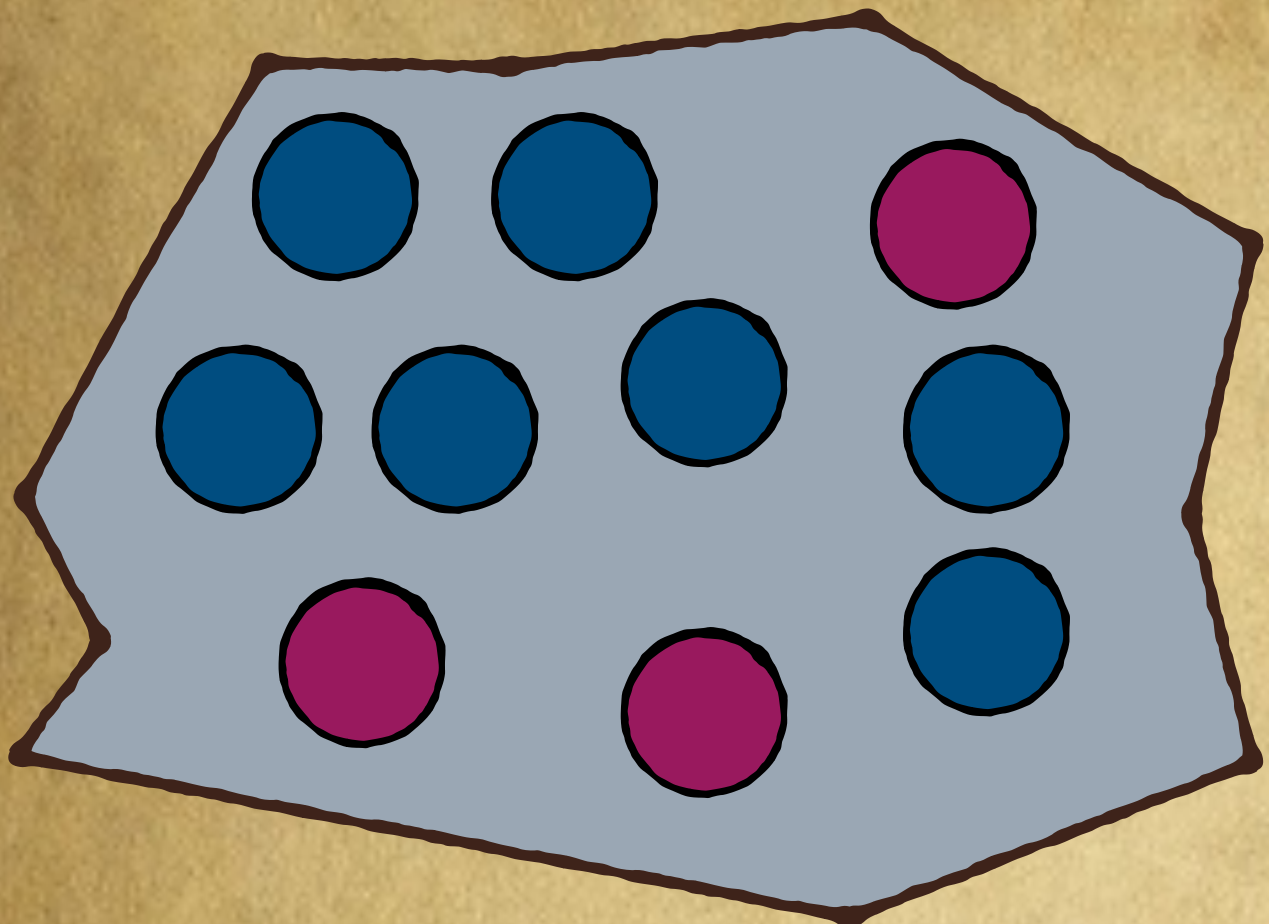
$$+ \frac{\pi}{2}\sigma_1^z\left[\frac{3}{2}\sqrt{\frac{7}{5}}(\sigma_2^z + \sigma_3^z) + \mathbb{1}\right]$$






L. Innocenti, L. Banchi, A. Ferraro, S. Bose, and M. Paternostro, arXiv: 1803.07119

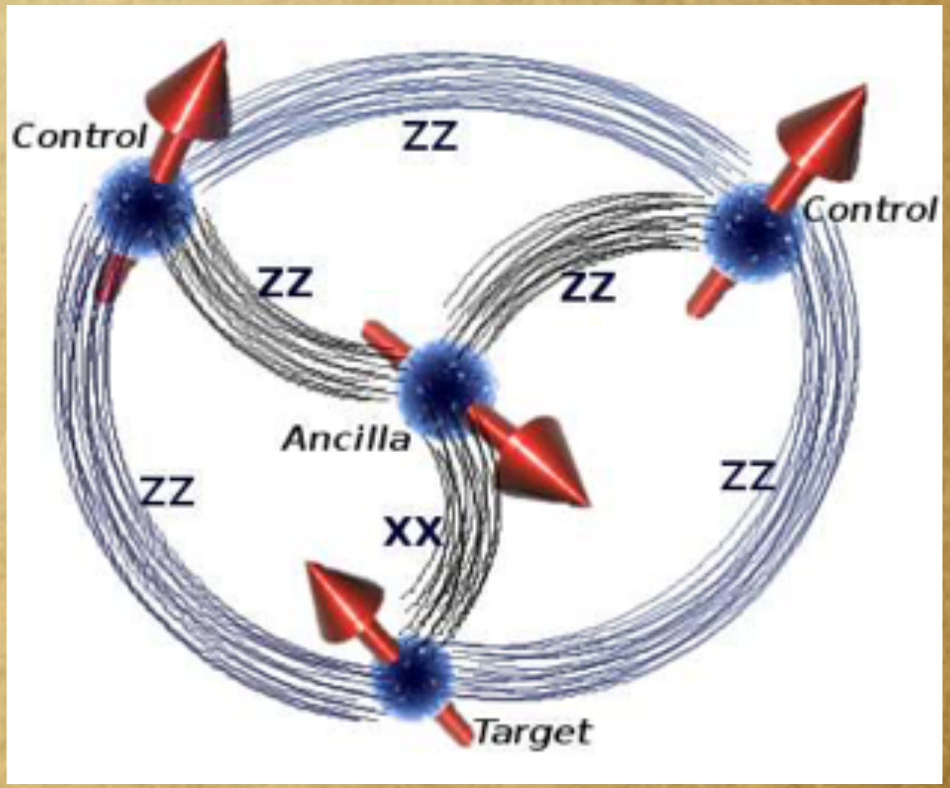
# Additional results: using ancillae



Set of information carriers

$|\psi\rangle_{\mathcal{S}}$ System

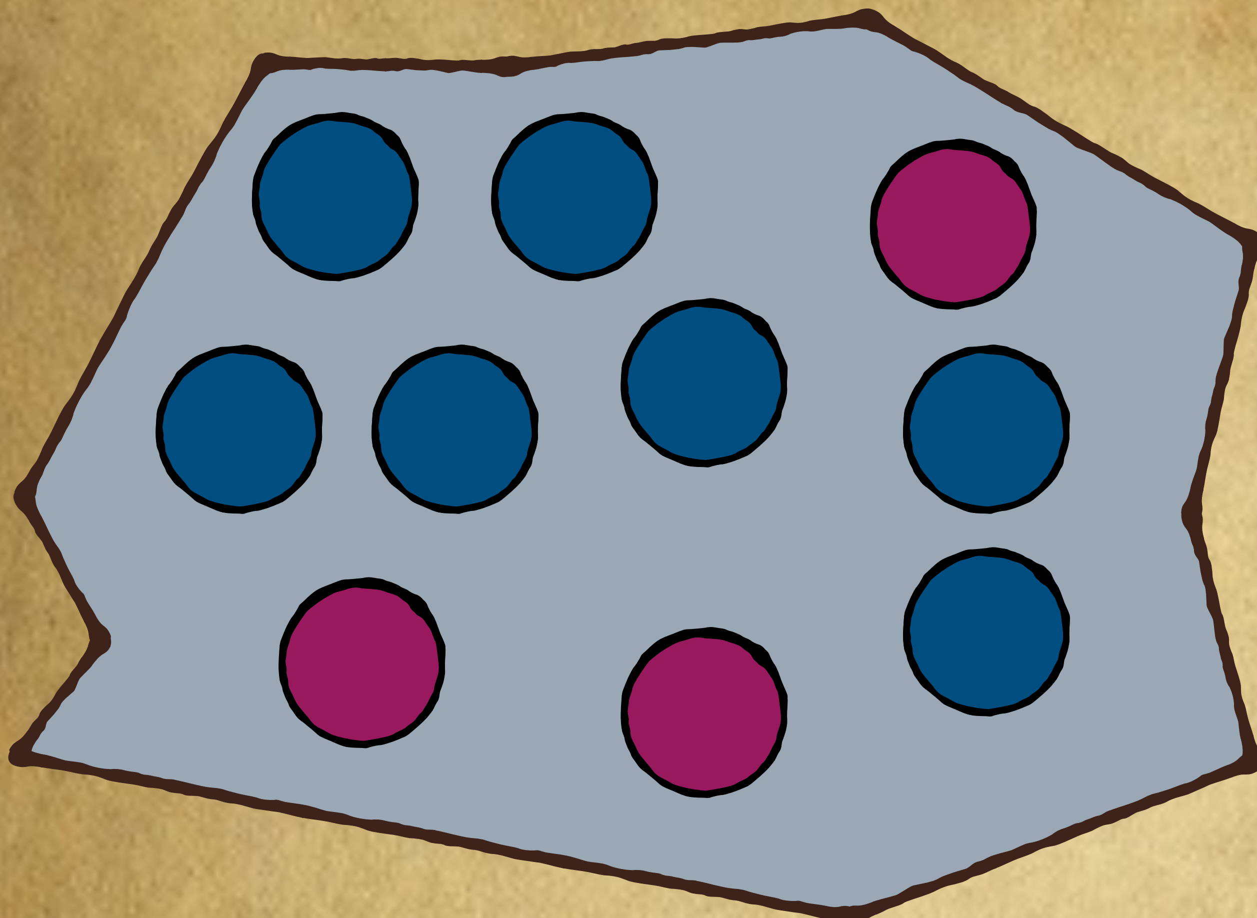
$|\phi\rangle_{\mathcal{A}}$ Ancilla




L. Banchi, N. Pancotti, S. Bose, npj QI 2, 16019 (216)

L. Innocenti, L. Banchi, S. Bose, A. Ferraro, and M. Paternostro, IJQI 16, 1840004 (218)

# Additional results: using ancillae



$|\psi\rangle_{\mathcal{S}}$ System

$|\phi\rangle_{\mathcal{A}}$ Ancilla

$$\rho_{\text{out}}^{\mathcal{S}}(t,\boldsymbol{\lambda}) = \text{Tr}_{\mathcal{A}}\left[\exp\left(it\mathcal{H}_{\boldsymbol{\lambda}}\right)(\psi\otimes\phi)\right]$$

$$\rho_{\text{out}}^{\mathcal{S}}\left(\boldsymbol{\lambda}_0\right) = \mathcal{U}_{target}(|\psi\rangle\langle\psi|_{\mathcal{S}})\,\mathcal{U}_{target}^{\dagger}, \quad \forall|\psi\rangle_{\mathcal{S}}$$

$$\mathcal{F}_{\boldsymbol{\lambda}}(\psi) = {}_{\mathcal{S}}\langle\psi|\,\mathcal{U}_{target}^{\dagger}\rho_{out}(\boldsymbol{\lambda})\mathcal{U}_{target}|\psi\rangle_{\mathcal{S}}$$

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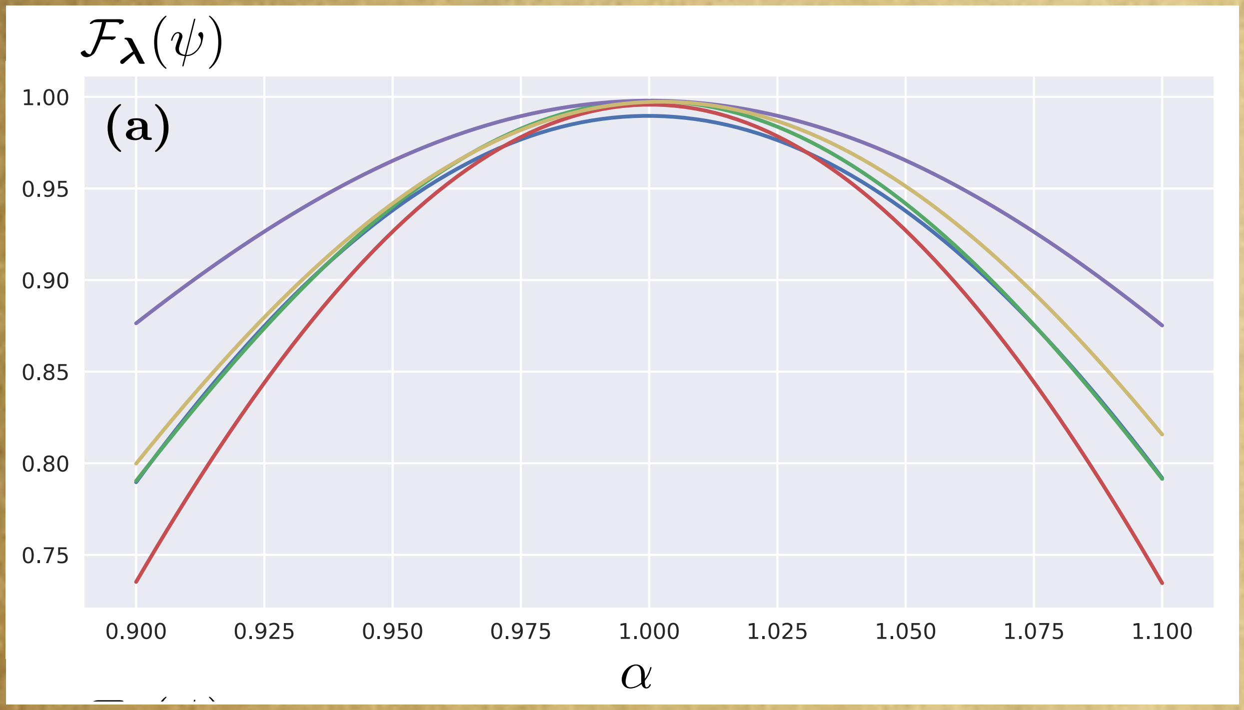
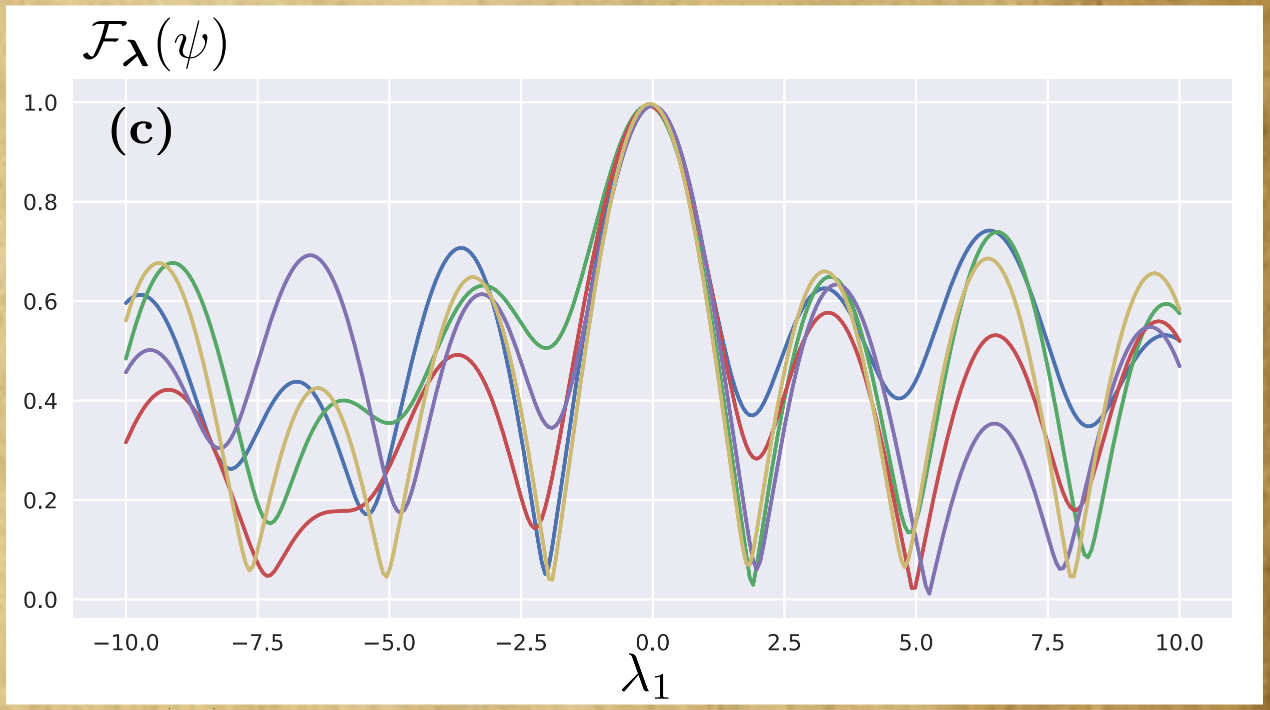
# Additional results: QFT

$$\mathrm{QFT}\,|a\rangle_1|b\rangle_2|c\rangle_3 = \frac{1}{\sqrt{8}}\left(|0\rangle + e^{i\pi c}|1\rangle\right)_1 \otimes \left(|0\rangle + e^{i\pi\left(b+\frac{c}{2}\right)}|1\rangle\right)_2 \otimes \left(|0\rangle + e^{i\pi\left(a+\frac{b}{2}+\frac{c}{4}\right)}|1\rangle\right)_3$$




$$\boldsymbol{\lambda} \to \alpha\boldsymbol{\lambda}$$

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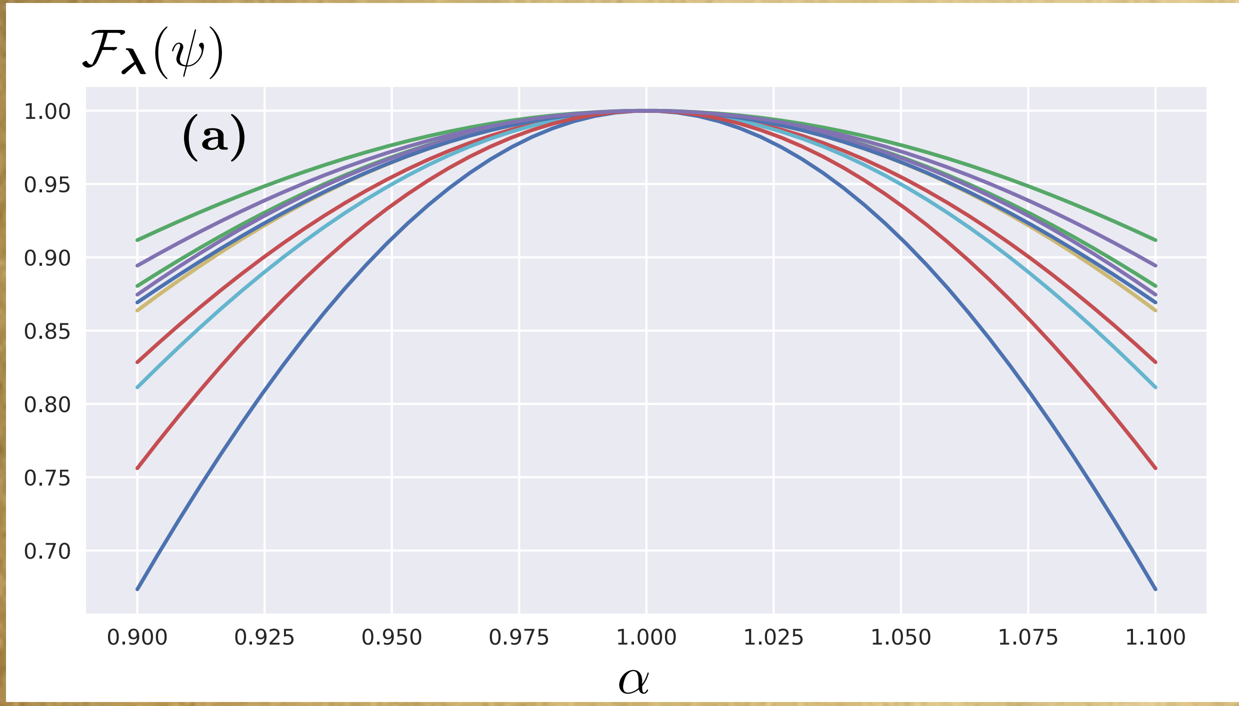
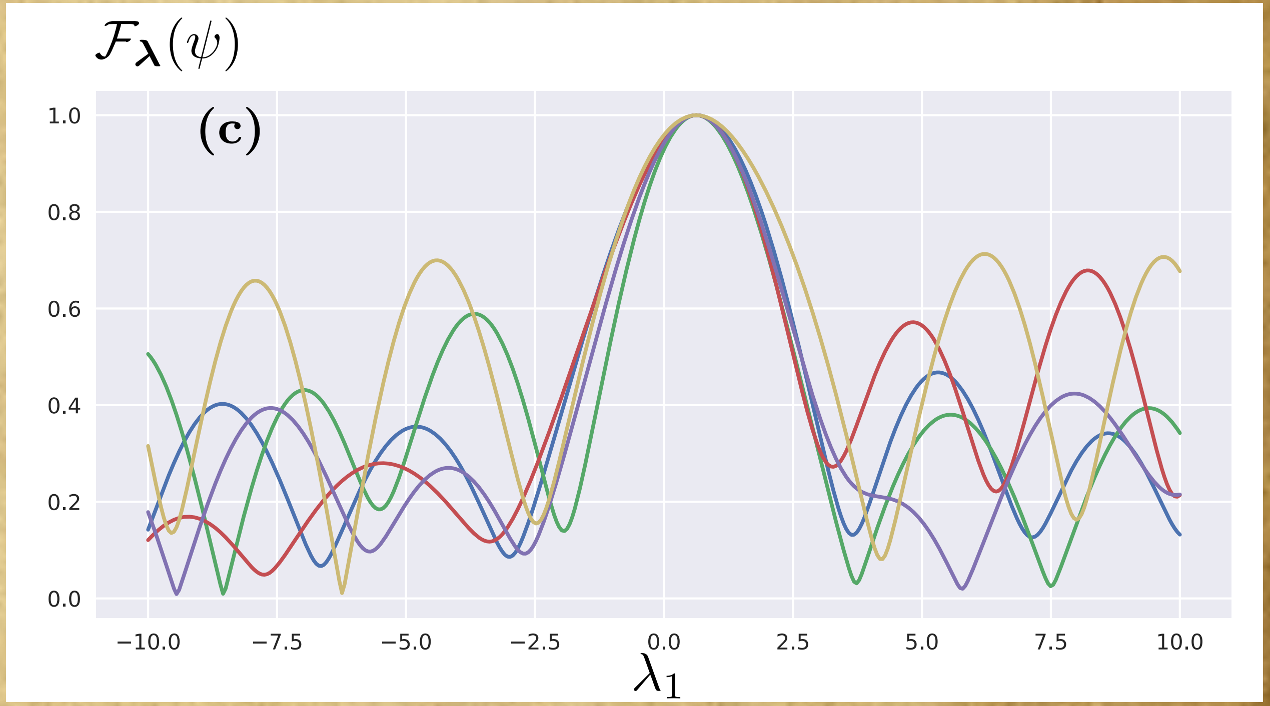
# Additional results: TofFredkin

$$\mathcal{U}_{\mathrm{TF}} = |0\rangle\langle 0|_1 \otimes \mathrm{CNOT}_{23} + |1\rangle\langle 1|_1 \otimes \mathrm{SWAP}_{23}$$




$$\boldsymbol{\lambda} \to \alpha\boldsymbol{\lambda}$$

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# Additional results: TofFredkin

$$\mathcal{U}_{\mathrm{TF}} = |0\rangle\langle 0|_1 \otimes \mathrm{CNOT}_{23} + |1\rangle\langle 1|_1 \otimes \mathrm{SWAP}_{23}$$

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 3 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 6 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 7 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 8 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.78 | 0.09 | 0.15 | 0.25 | 0.36 | 0.12 | 0.38 | 0.10 |
| 9 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.13 | 0.77 | 0.07 | 0.08 | 0.36 | 0.44 | 0.15 | 0.19 |
| 10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.10 | 0.05 | 0.54 | 0.74 | 0.07 | 0.08 | 0.34 | 0.13 |
| 11 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.16 | 0.03 | 0.78 | 0.54 | 0.10 | 0.12 | 0.06 | 0.20 |
| 12 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.38 | 0.43 | 0.07 | 0.10 | 0.72 | 0.36 | 0.01 | 0.02 |
| 13 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.16 | 0.34 | 0.11 | 0.03 | 0.44 | 0.75 | 0.28 | 0.12 |
| 14 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.18 | 0.05 | 0.07 | 0.24 | 0.07 | 0.21 | 0.15 | 0.91 |
| 15 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.37 | 0.31 | 0.21 | 0.14 | 0.01 | 0.21 | 0.78 | 0.22 |

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# Additional results: Half-adder gate

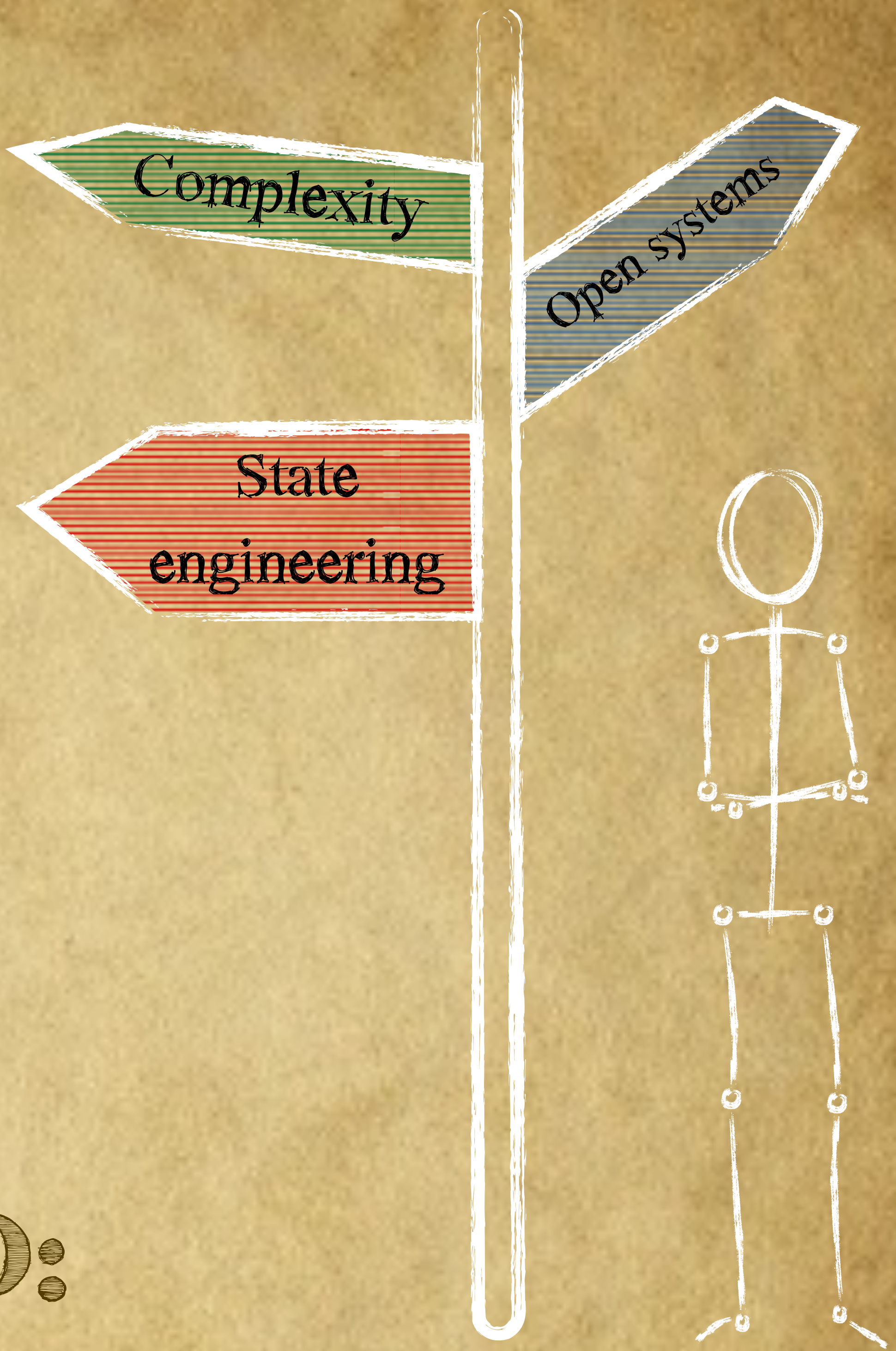
$$\mathcal{U}_{HA} = \mathrm{CNOT}_{12}\mathrm{CCNOT}_{123}$$

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 3 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 6 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 7 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 8 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 9 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 11 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 12 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.63 | 0.63 | 0.32 | 0.32 |
| 13 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.63 | 0.63 | 0.32 | 0.32 |
| 14 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.32 | 0.32 | 0.63 | 0.63 |
| 15 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.32 | 0.32 | 0.63 | 0.63 |

L. Innocenti, L. Banchi, S. Bose, A. Ferraro, and M. Paternostro, IJQI 16, 1840004 (218)

# PART 2

# LOOKING AHEAD: ML FOR QUANTUM STATE ENGINEERING



# ML, quantum walk & state engineering

Taira Giordani
Emanuele Polino
Alessia Suprano
Sabrina Emiliani
Nicolo' Spagnolo
Fabio Sciarrino

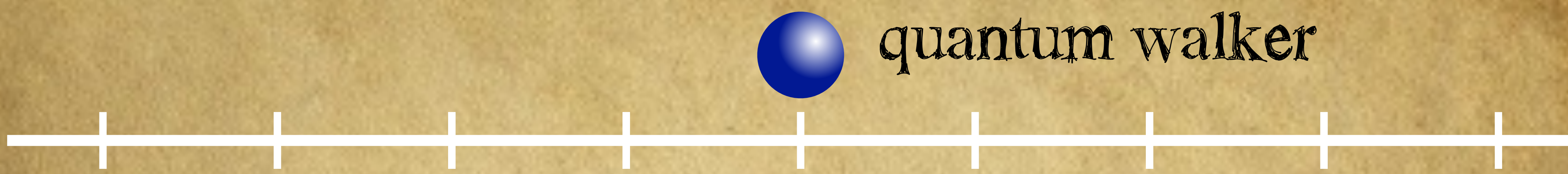
Luca Innocenti
Helena Majury
Alessandro Ferraro

Lorenzo Marrucci

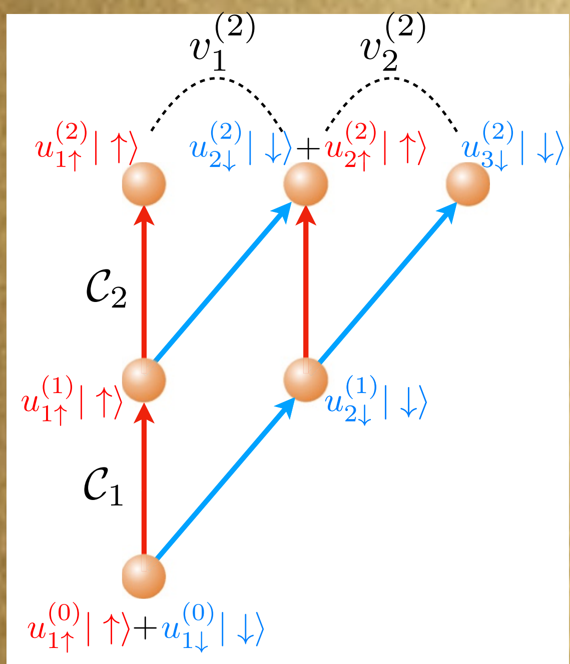
L. Innocenti, H. Majury, T. Giordani, N. Spagnolo, F. Sciarrino, M. Paternostro, A. Ferraro, PRA 96, 062326 (2017)

T. Giordani, E. Polino, S. Emiliani, A. Suprano, L. Innocenti, H. Majury, L. Marrucci, M. Paternostro, A. Ferraro, N. Spagnolo, & F. Sciarrino PRL 122, 020503 (2019)

# ML, quantum walk & state engineering

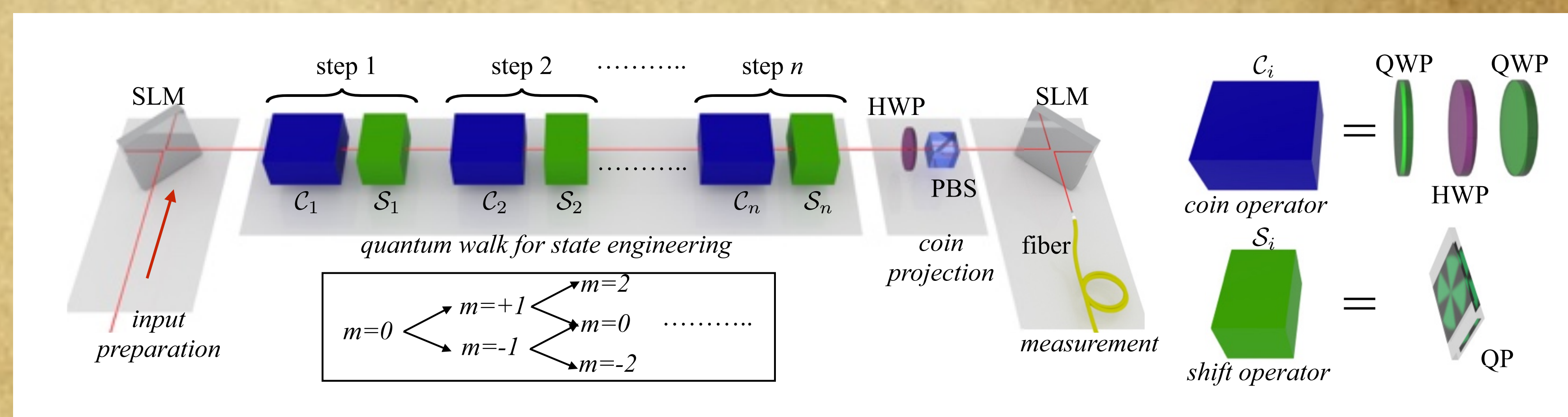



$-N$ **Spin-N $\Rightarrow$ Can we prepare arbitrary states?** $N$




**Use back-tracking optimisation ML approach to determine the optimal coin parameters and projection**

**Synthesis of arbitrary qudit states**

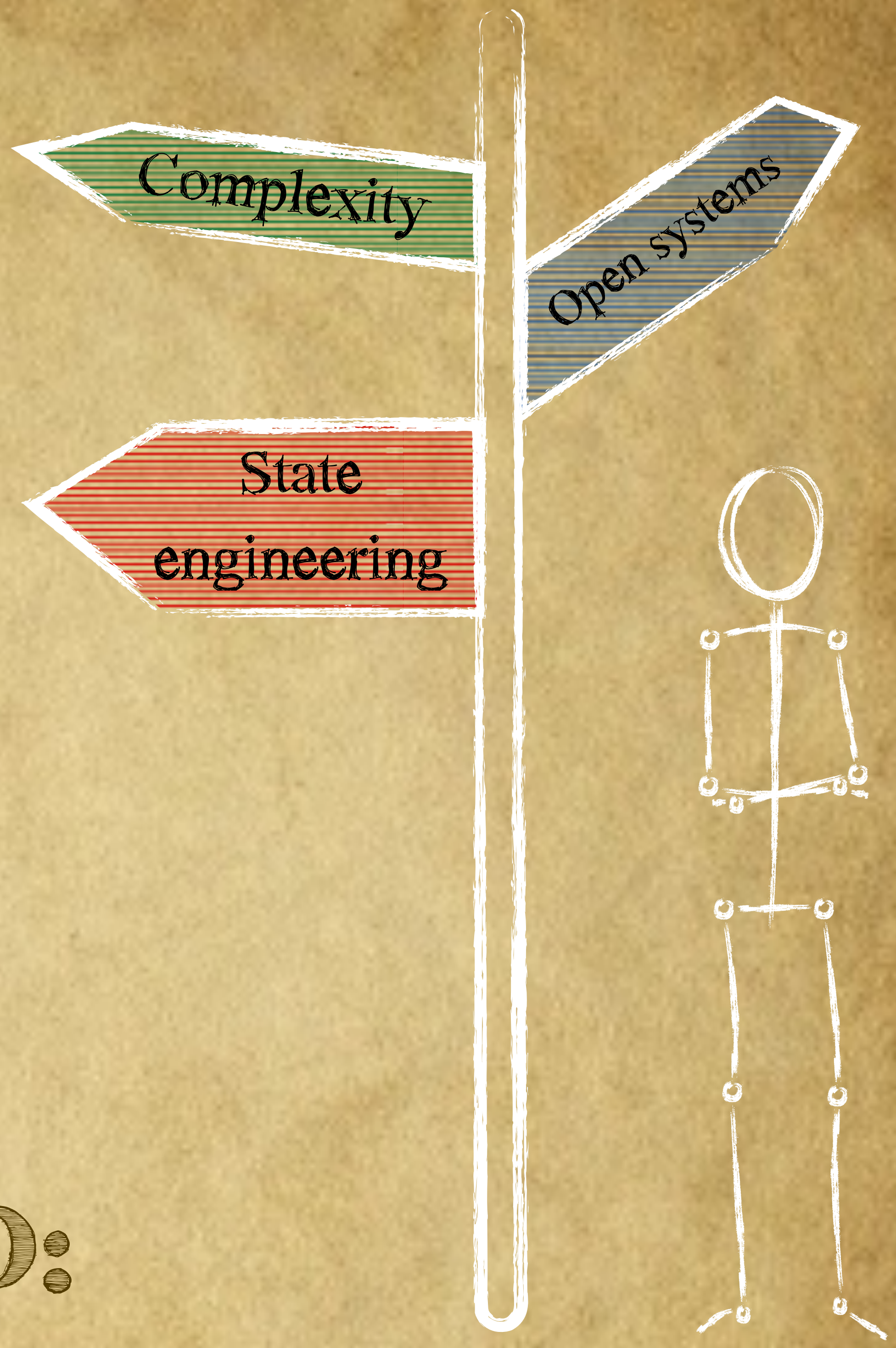



L. Innocenti, et al., PRA 96, 062326 (2017)

T. Giordani, E. Polino, S. Emiliani, A. Suprano, L. Innocenti, H. Majury, L. Marrucci, M. Paternostro, A. Ferraro, N. Spagnolo, & F. Sciarrino PRL 122, 020503 (2019)

# PART 3

# LOOKING AHEAD: ML FOR TAMING COMPLEXITY



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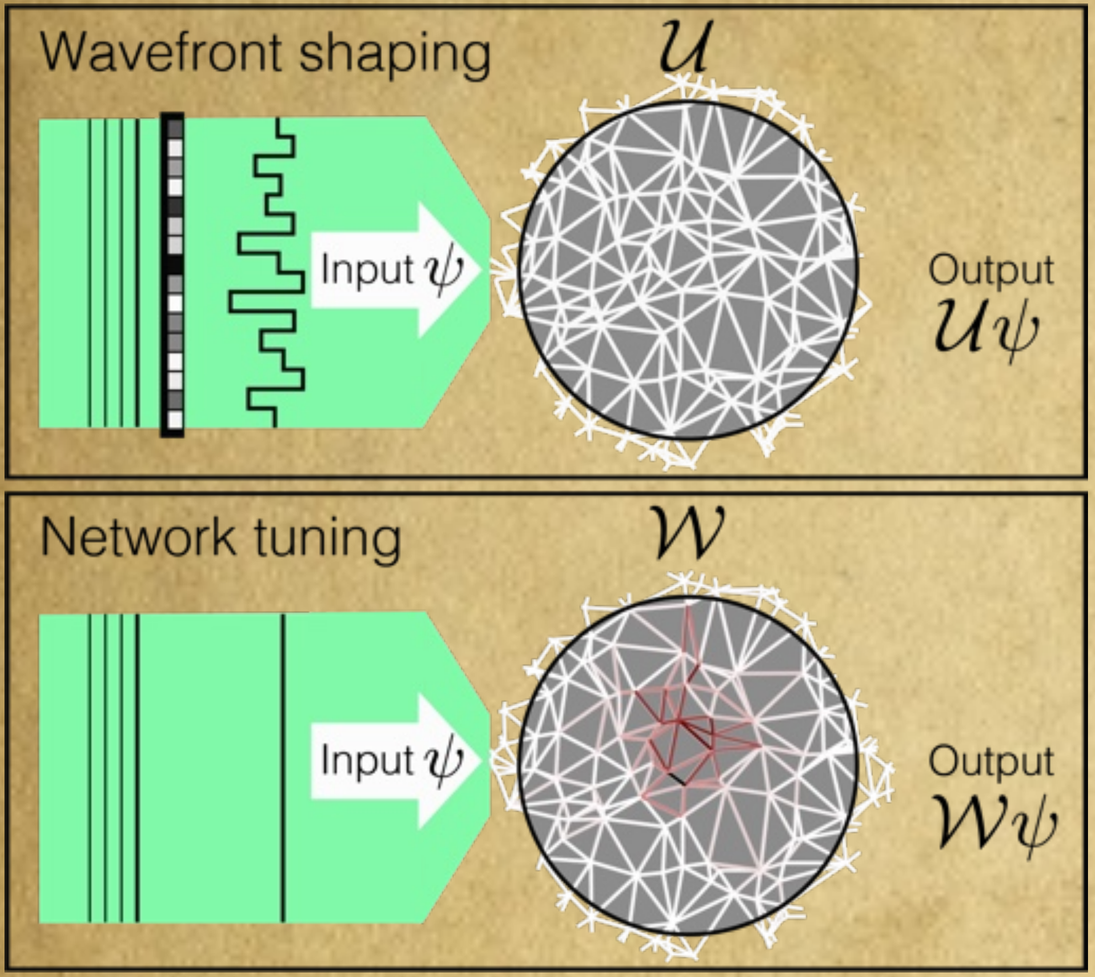
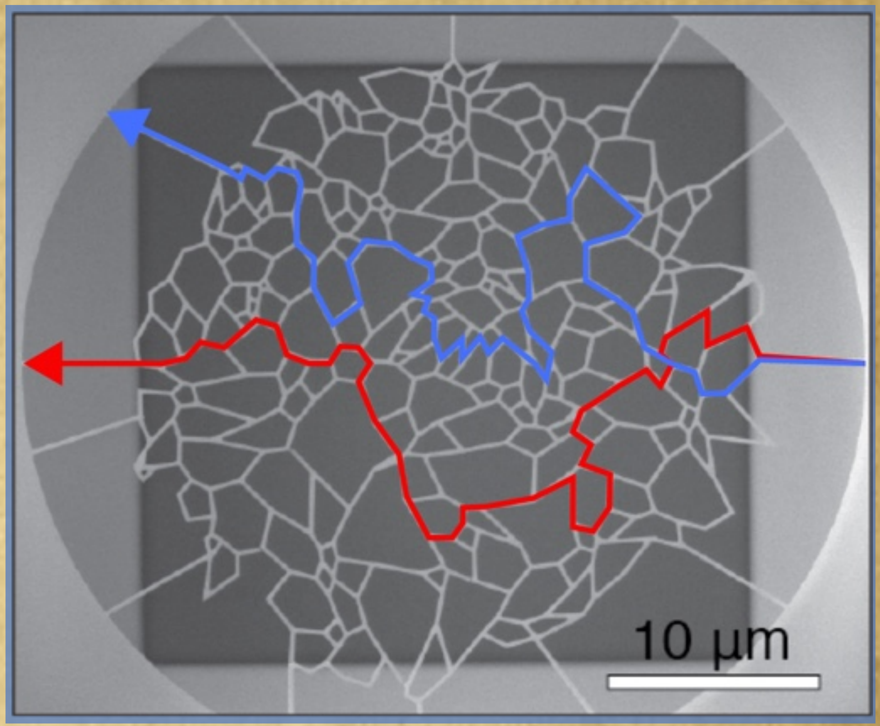
# Forward look: complexity

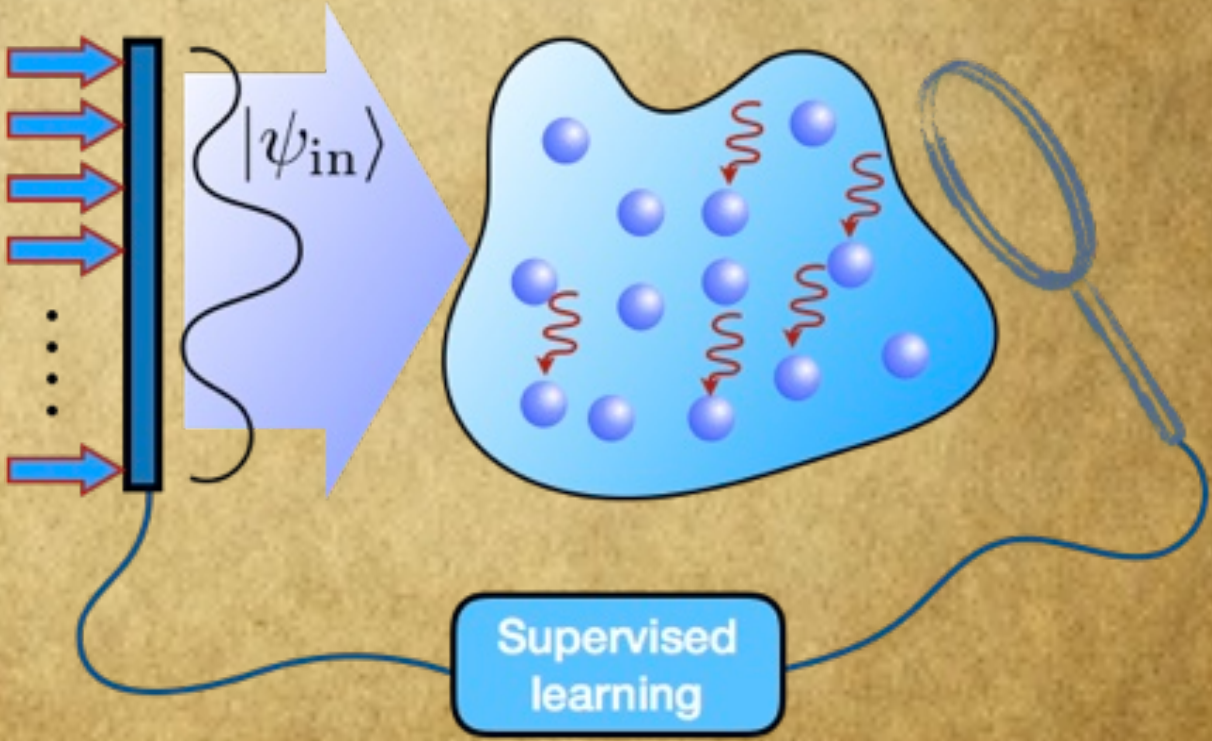
**Sylvain Gigan (LKB Paris, Sorbonne University)**

**Riccardo Sapienza (Imperial College London)**

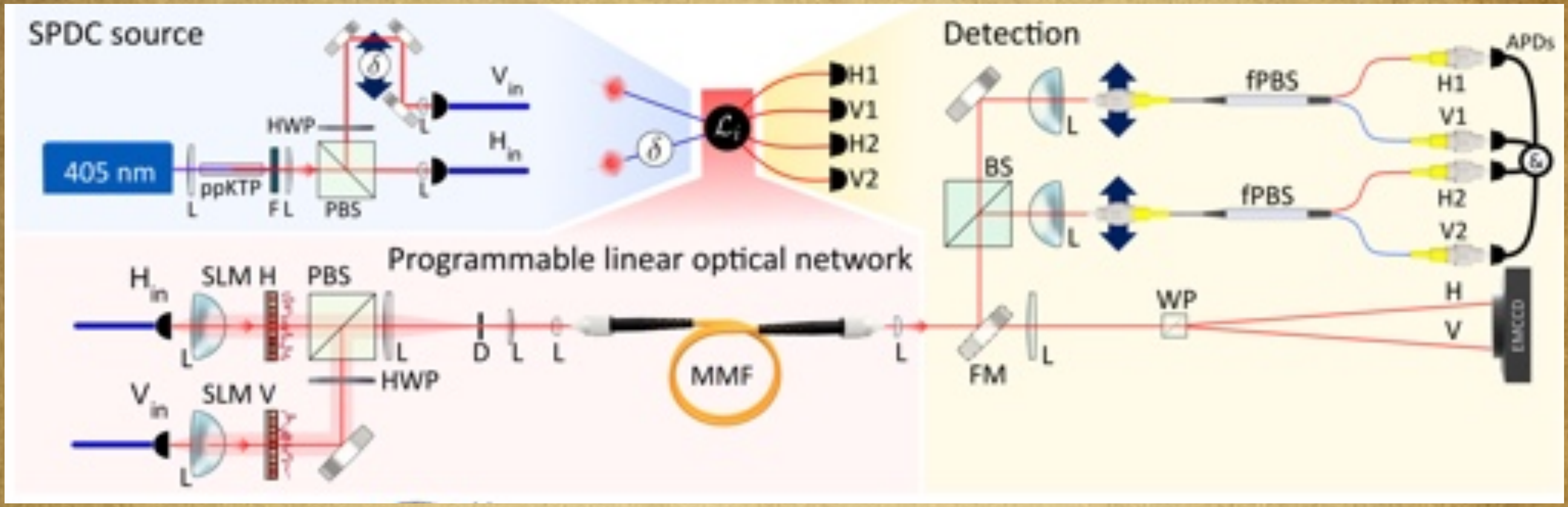
# Forward look: complexity



# Forward look: complexity




Circuit programmed to perform unable coherent absorption through wave-front shaping & high-mixing in complex media

S Leedumrongwatthanakun, L Innocenti, H Defienne, Th Juffmann, A Ferraro, M Paternostro, and S Gigan,, arXiv: 1902.10678 (2019)

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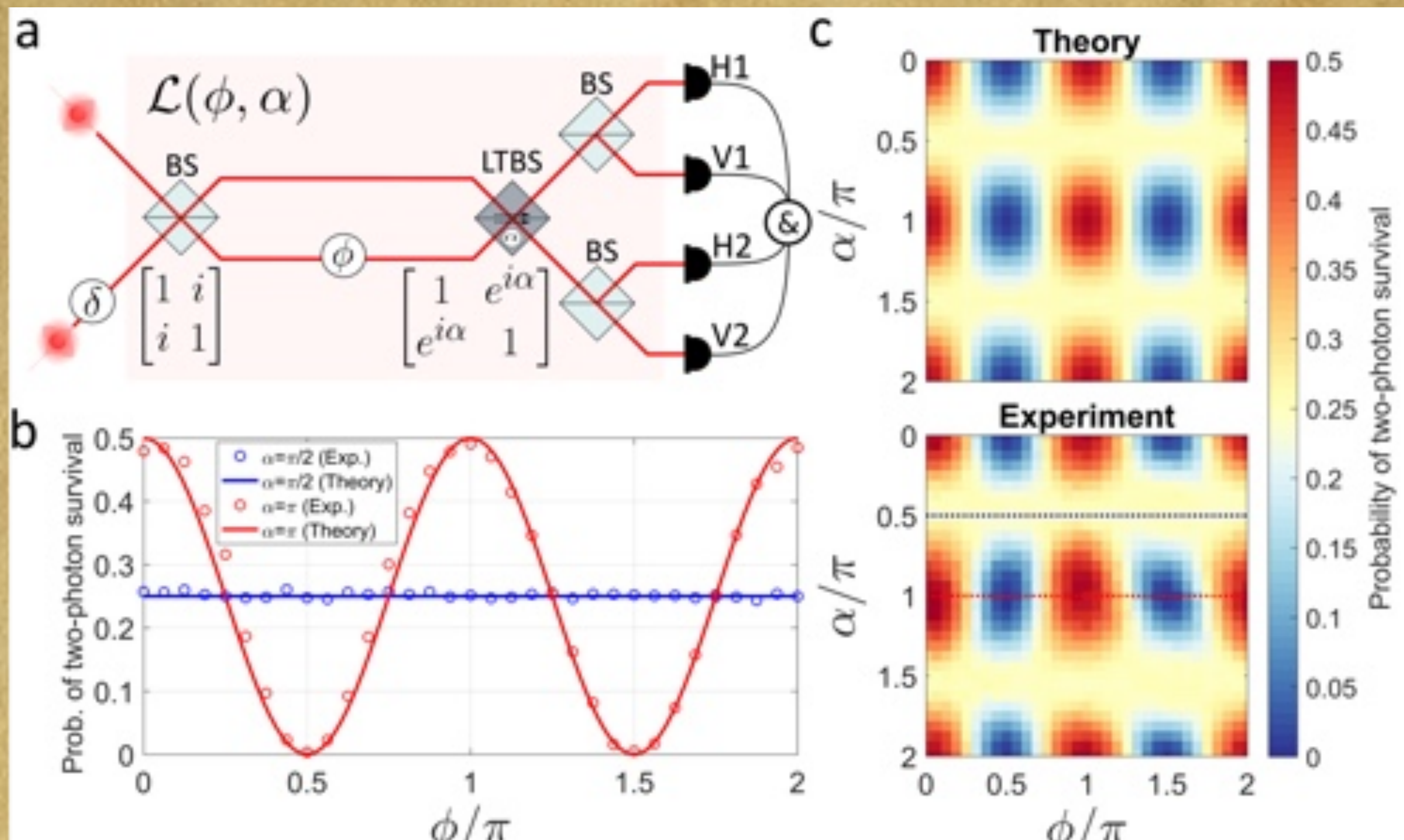
# Forward look: complexity




**Circuit programmed to perform unable coherent absorption through wave-front shaping & high-mixing in complex media**

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# Bread on tables..

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# The Belfast crew

# THANK YOU