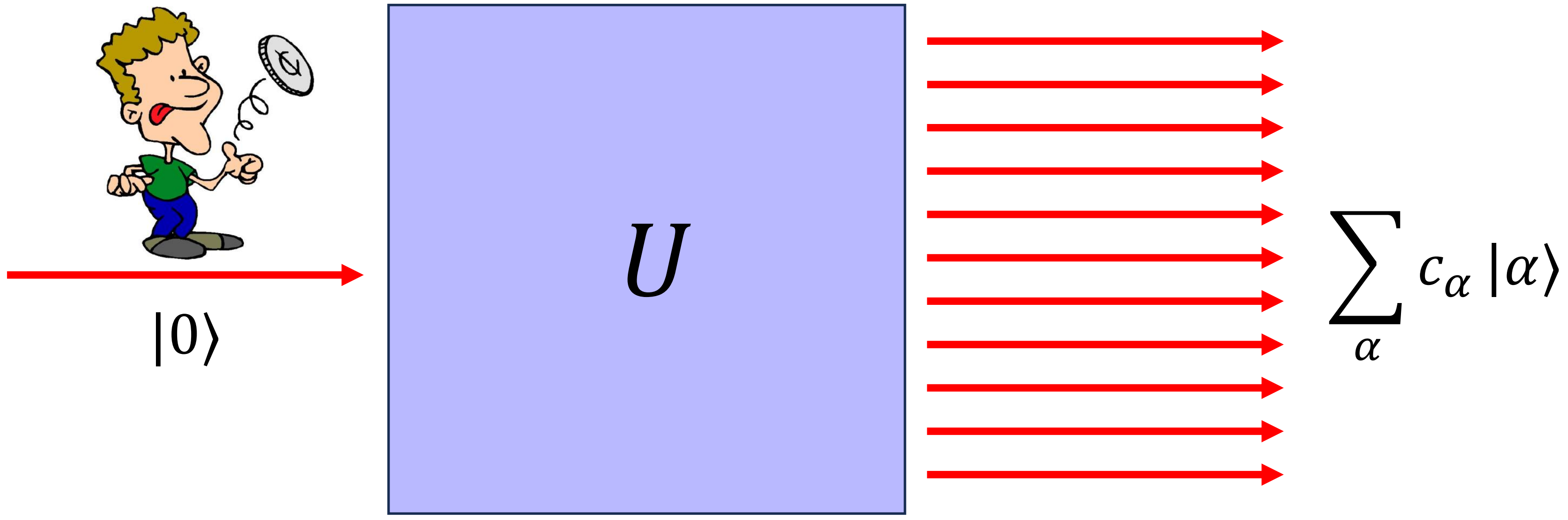
Large-scale quantum walks via complex polarization transformations



UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

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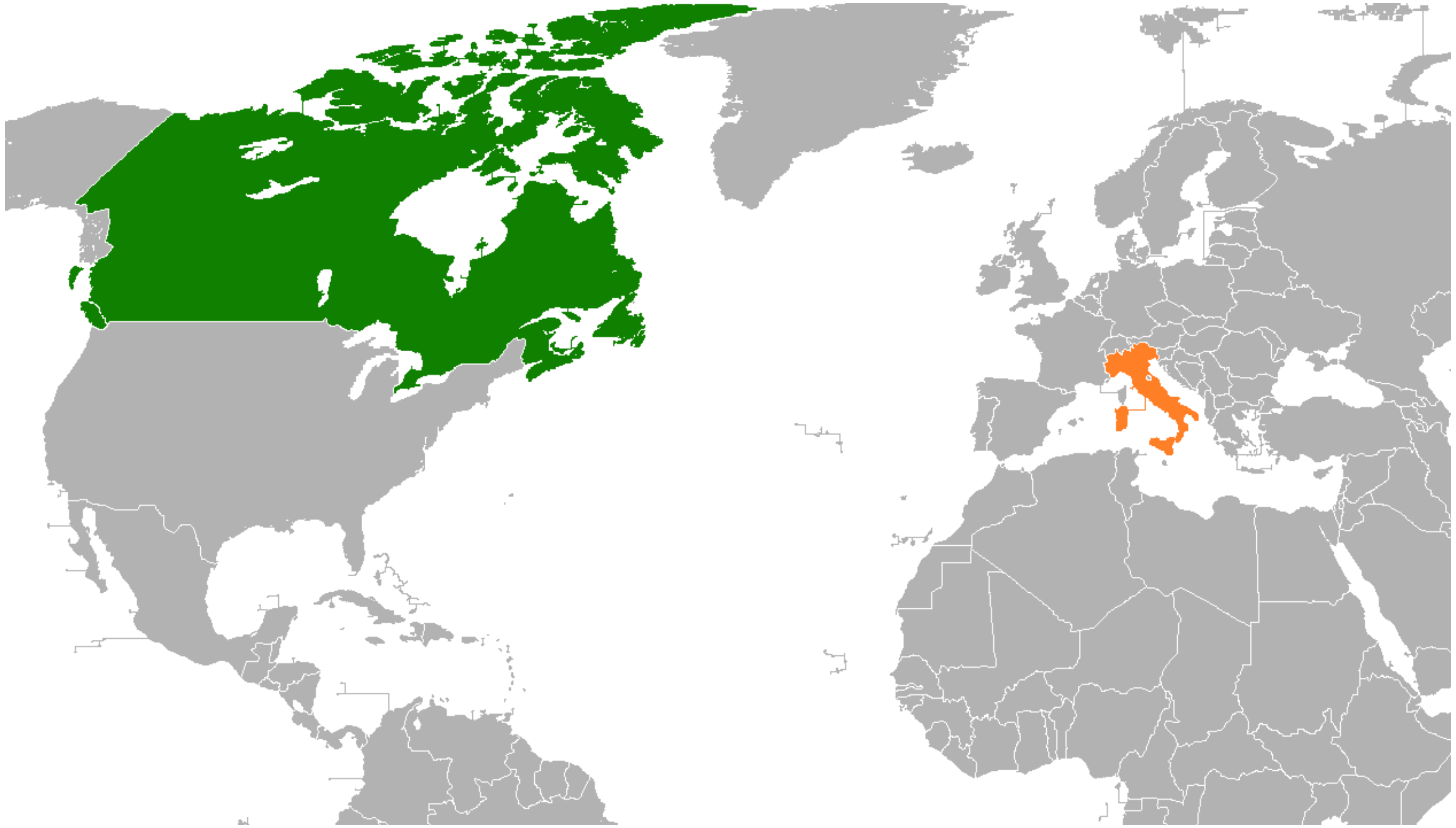
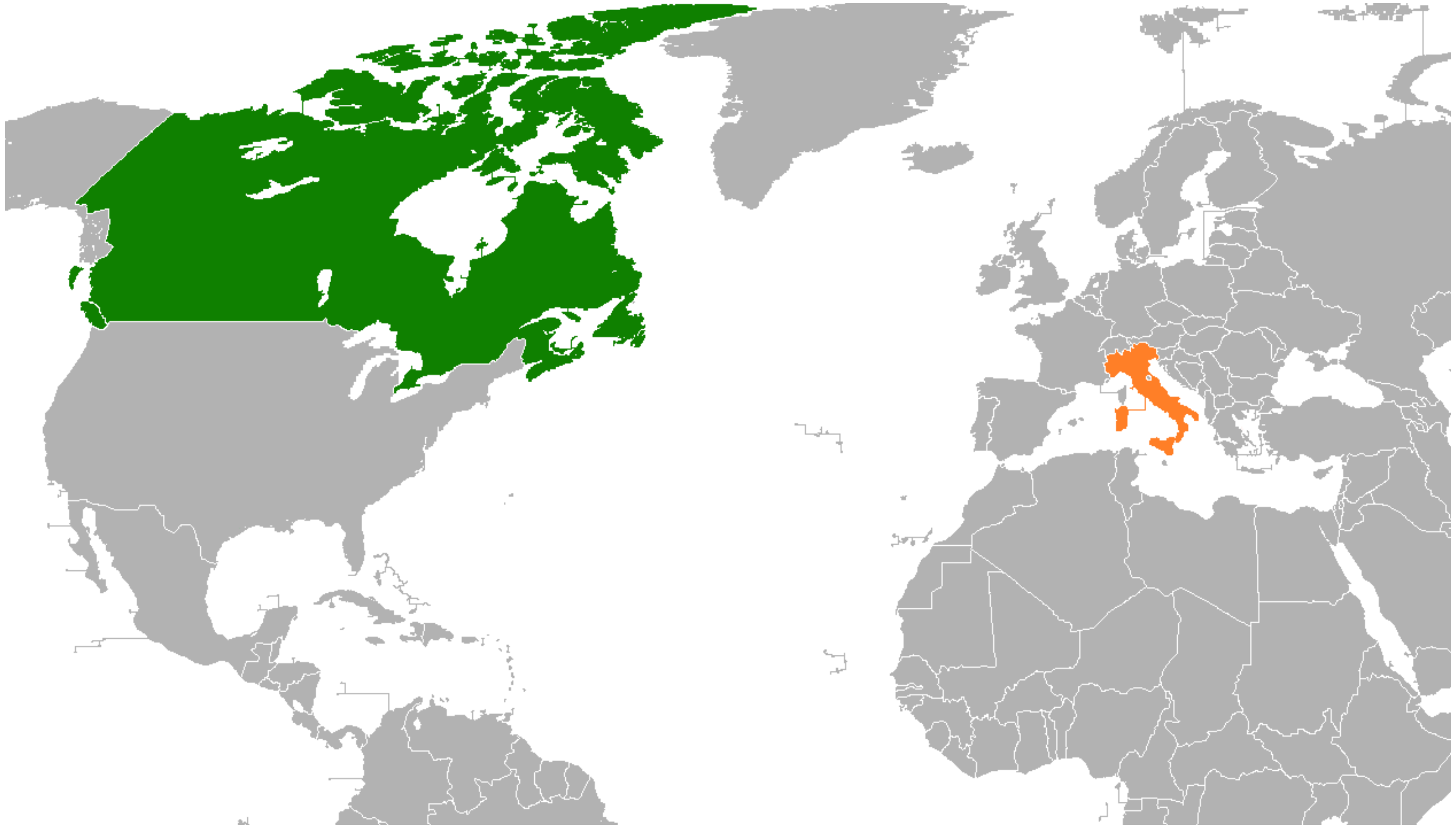
Francesco Di Colandrea

11th International conference on Quantum Simulation and Quantum Walks

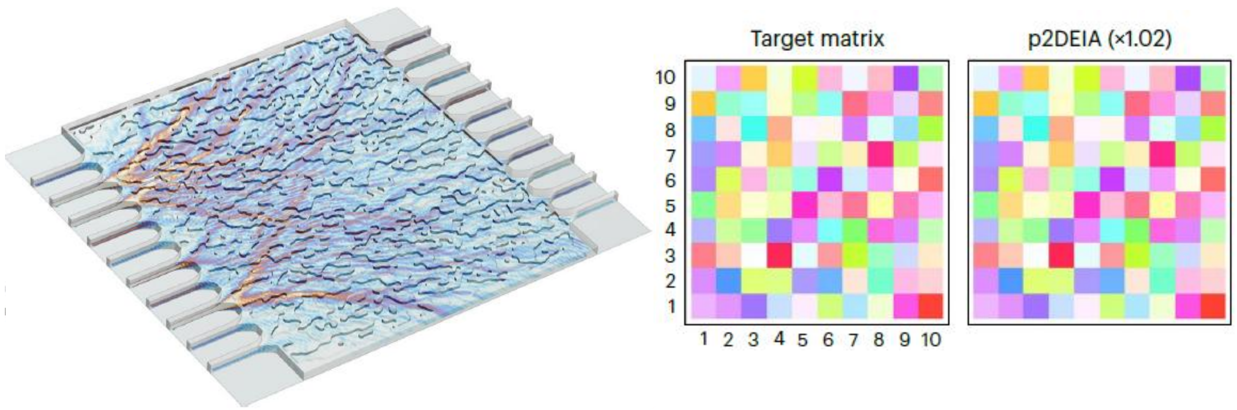



SLAM group

Photonic circuits

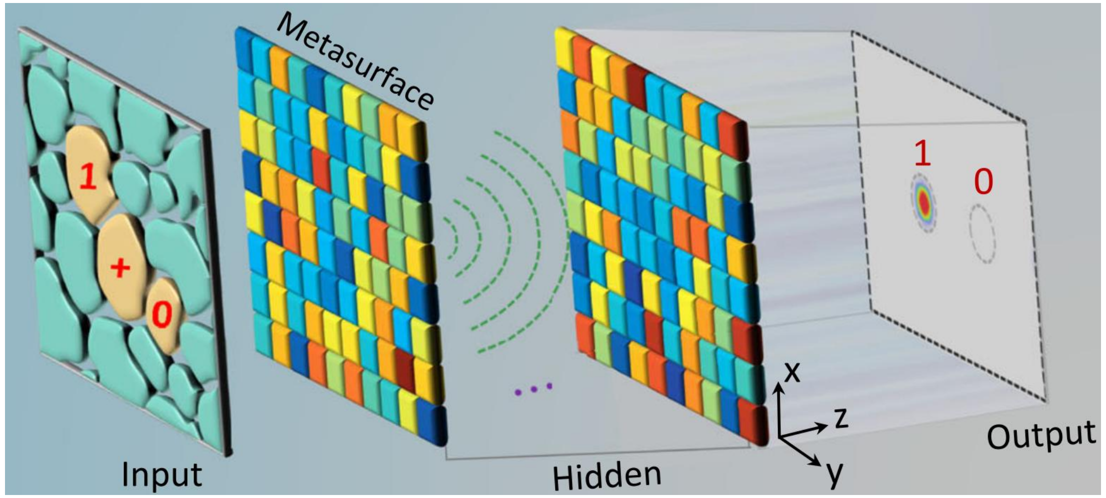
W. Bogaerts et al., Nature 586, 207 (2020)

Analogue computation



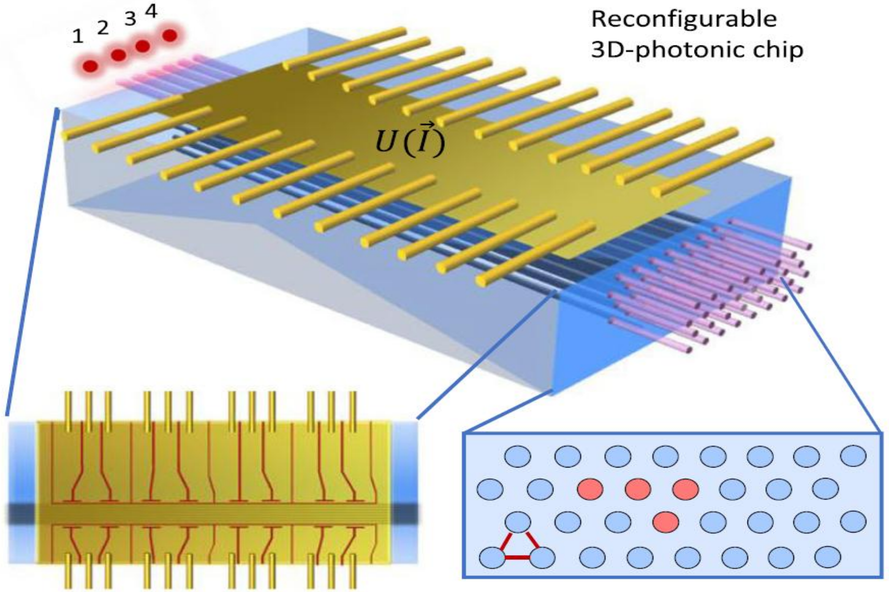
V. Nikkhah et al., Nat. Photonics 18, 501 (2024)

Optical neural networks



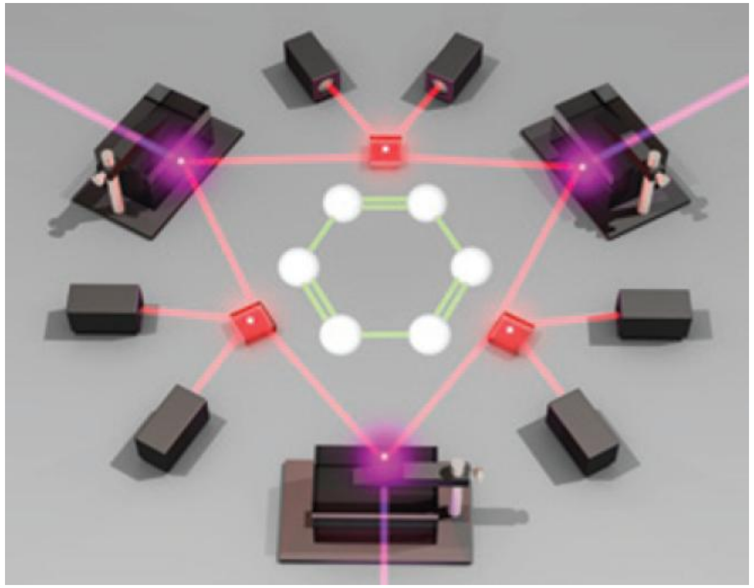
C. Qian et al., Light Sci. Appl. 9, 59 (2020)

Unitary operations



F. Hoch et al., npj Quantum Inf. 8, 55 (2022)

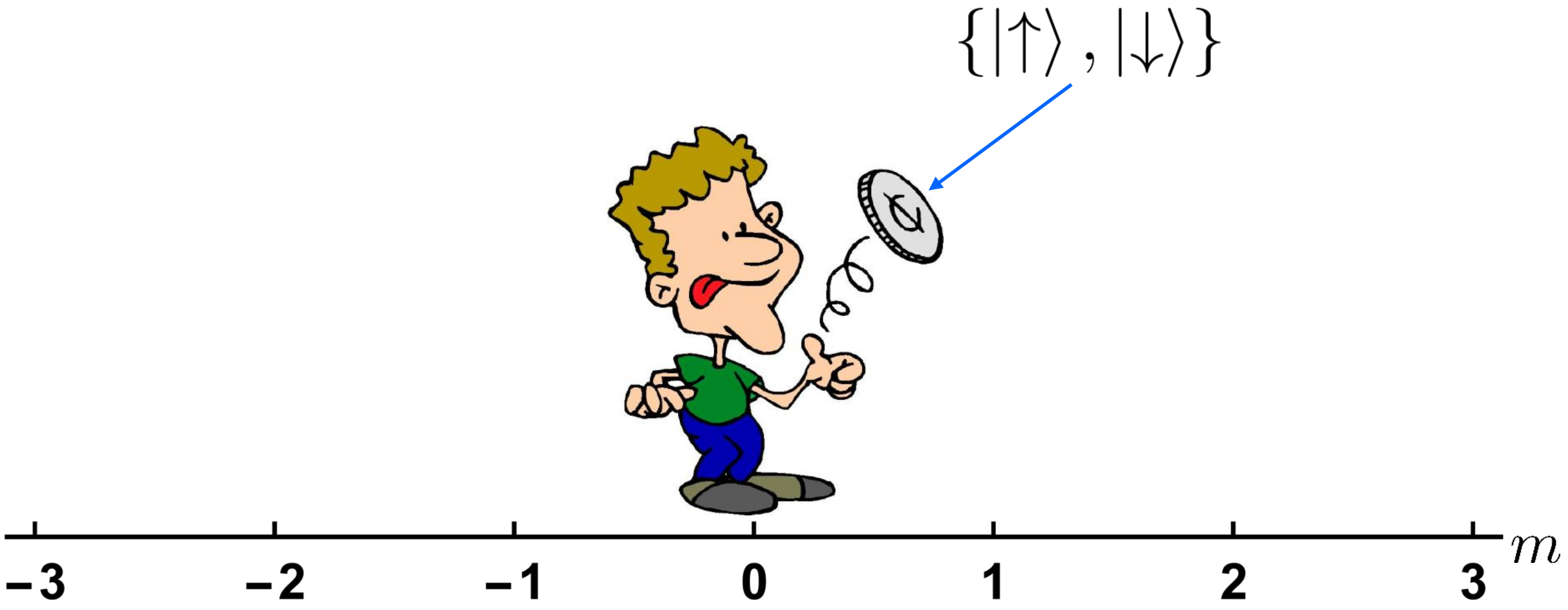
Quantum simulations



A. Aspuru-Guzik and P. Walther, Nat. Phys. 8, 285 (2022)

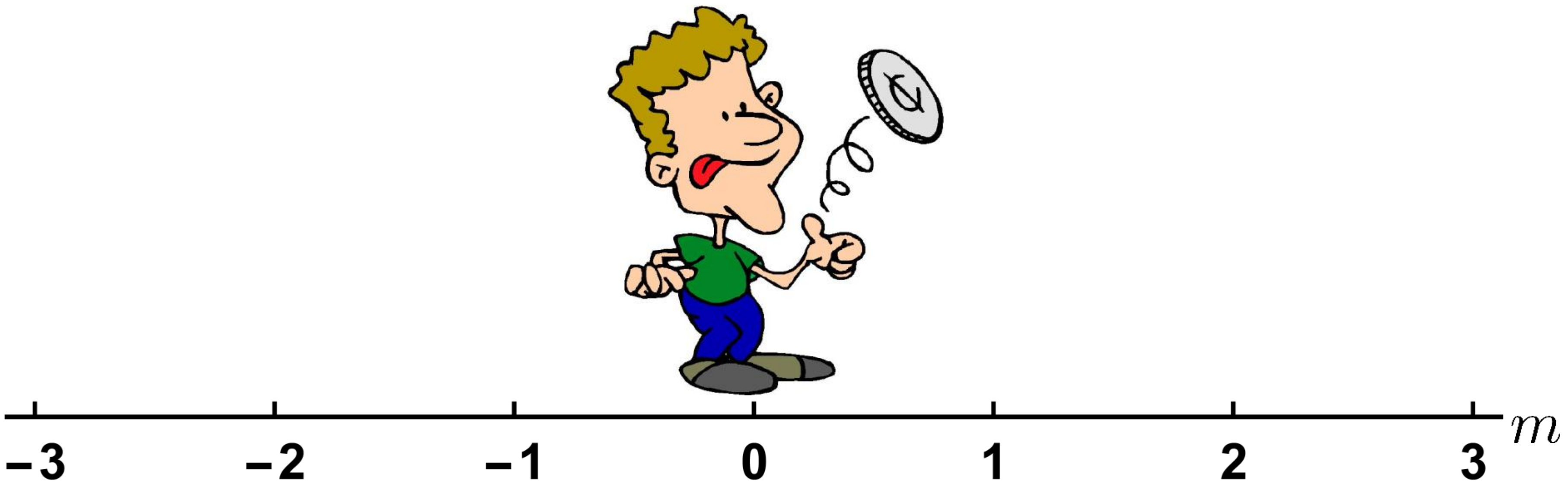
Quantum walks

The quantum walk

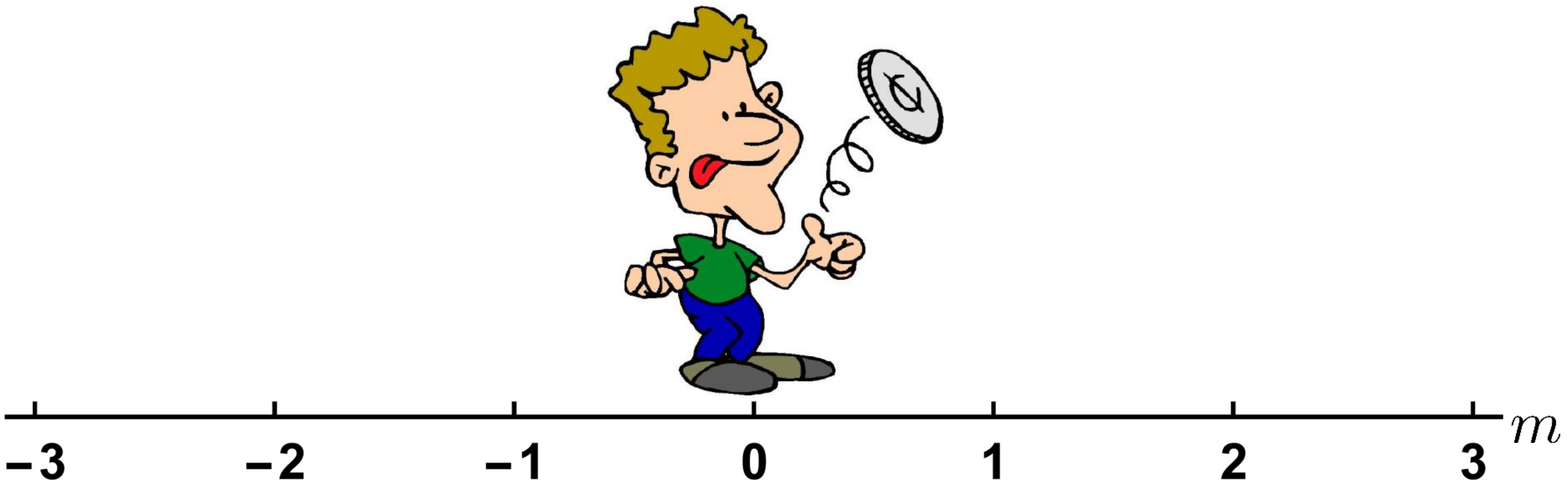


A few rules:

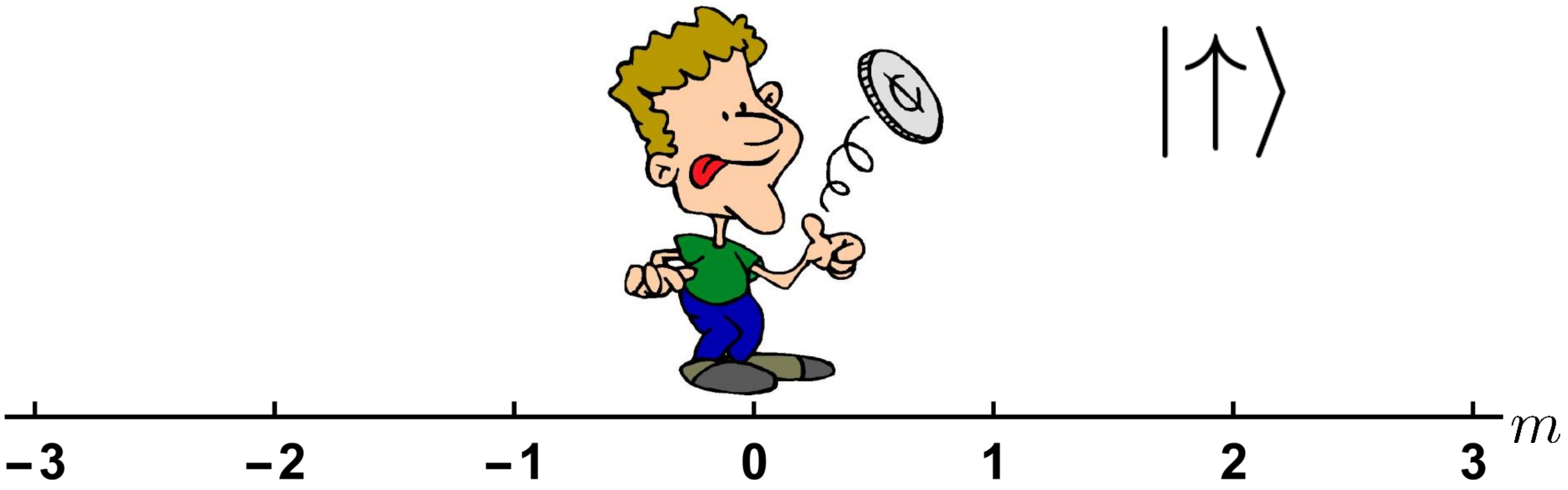
1) Toss the coin
2) Move according to the coin state
3) Repeat



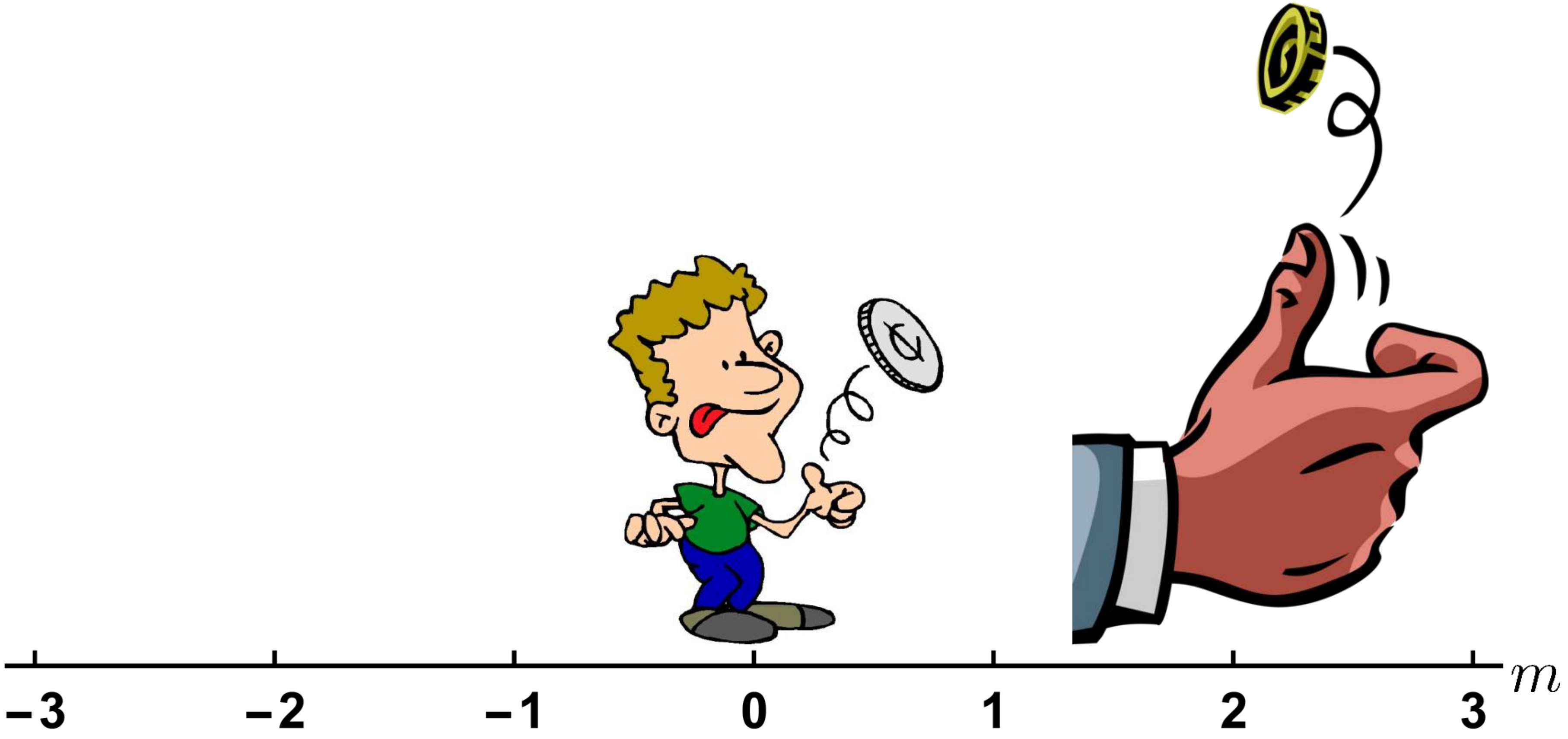
Let’s (quantum) walk!



1st time step



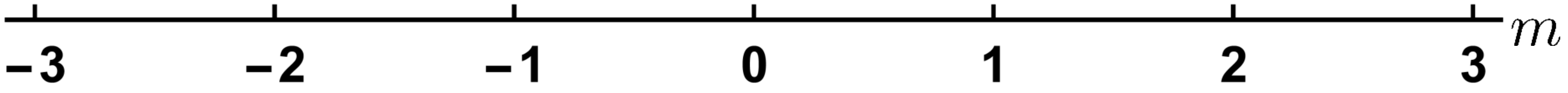
1st time step



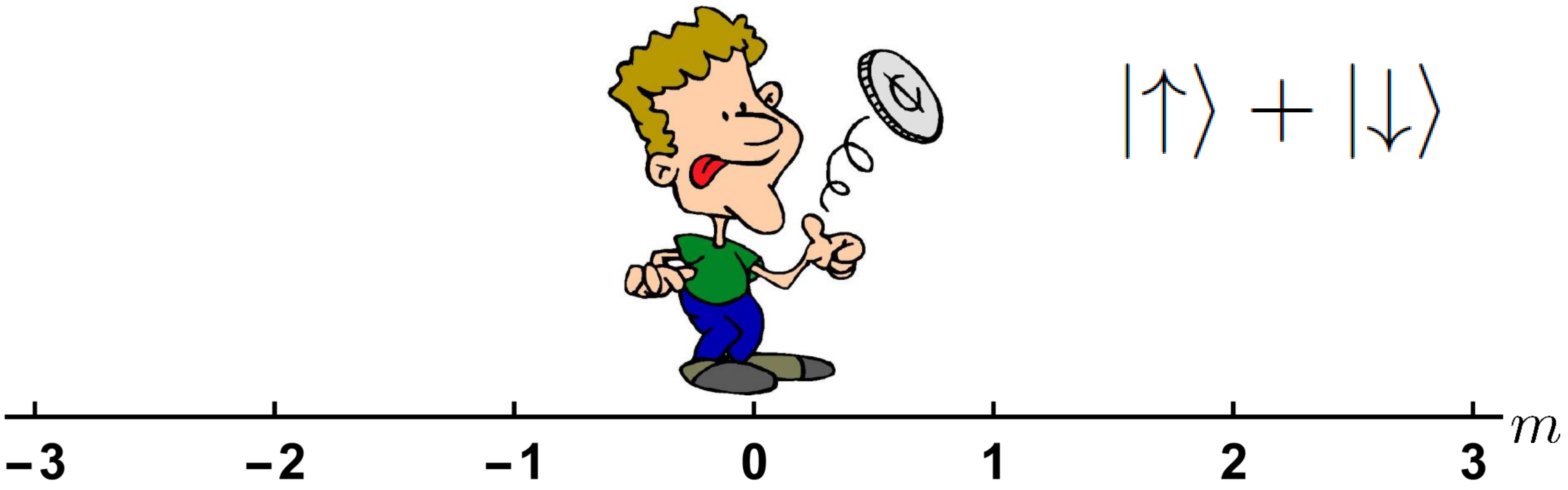
1st time step

$$|\uparrow\rangle \longrightarrow |\uparrow\rangle + |\downarrow\rangle$$

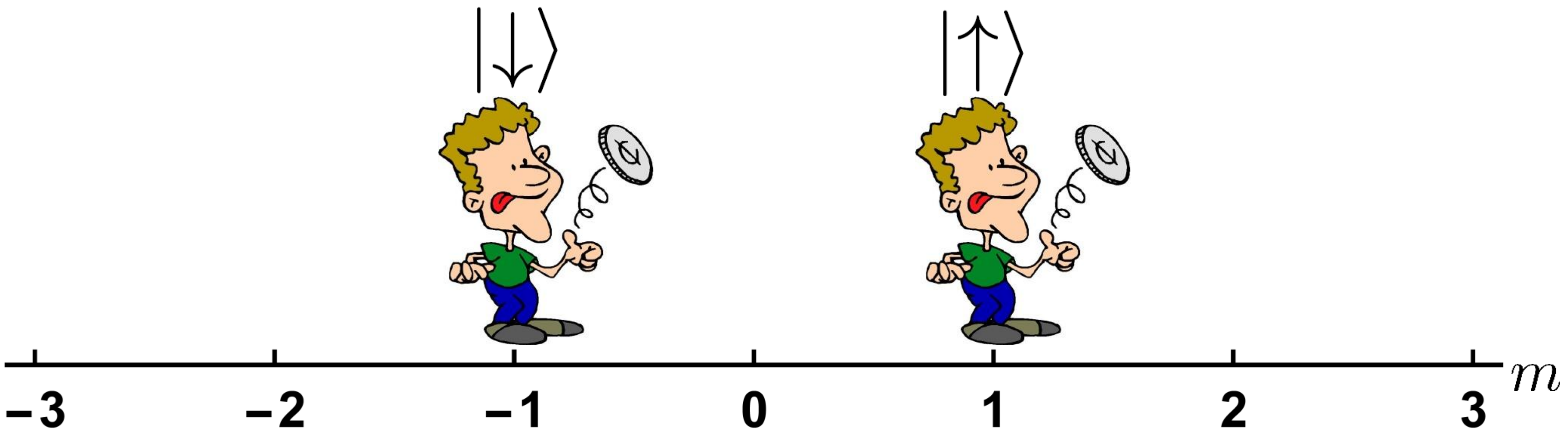
$$|\downarrow\rangle \longrightarrow |\uparrow\rangle - |\downarrow\rangle$$



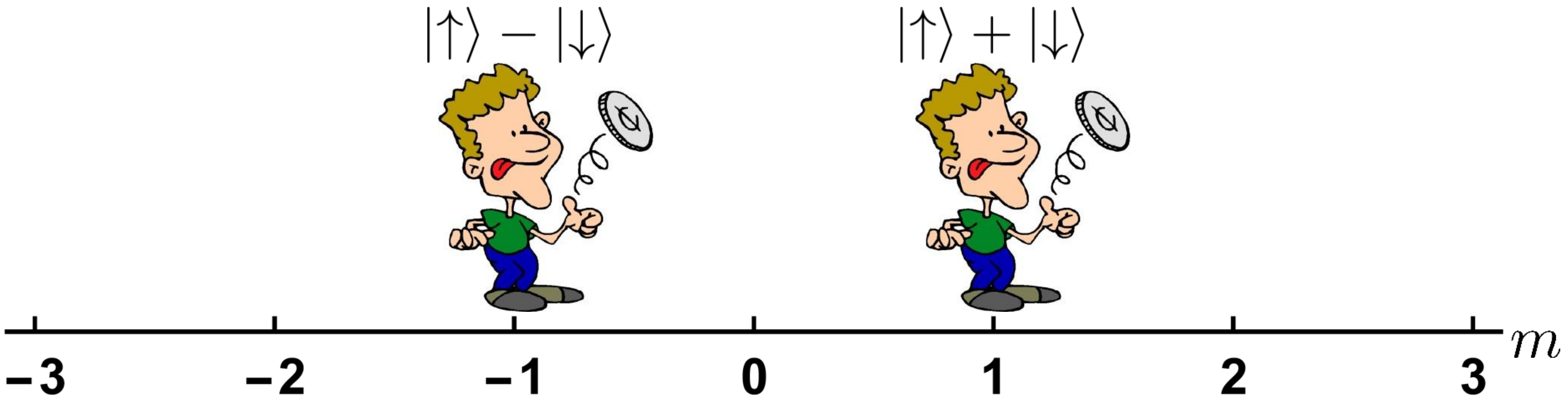
1st time step



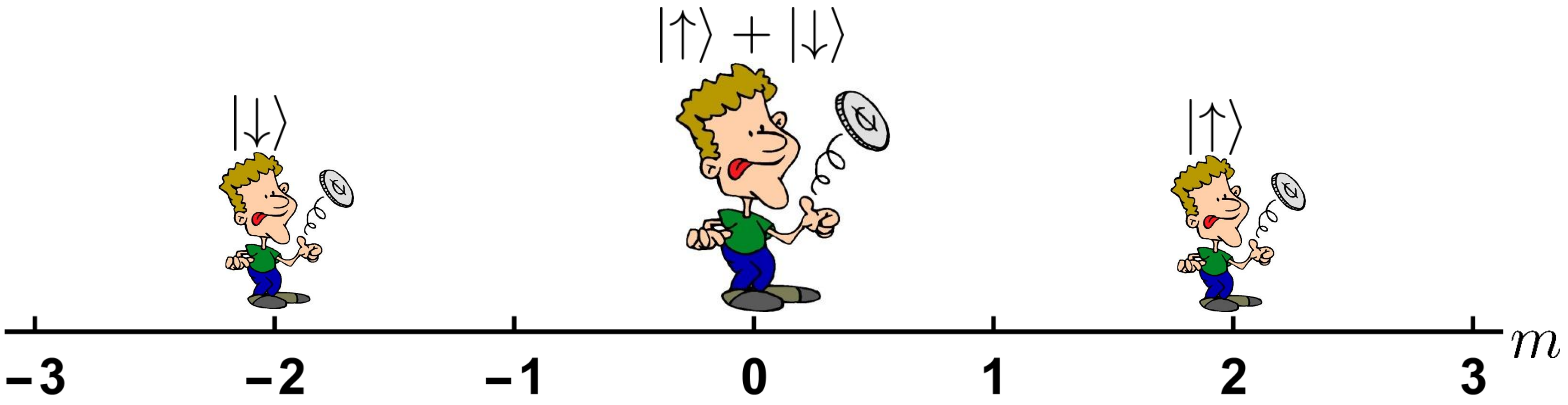
1st time step



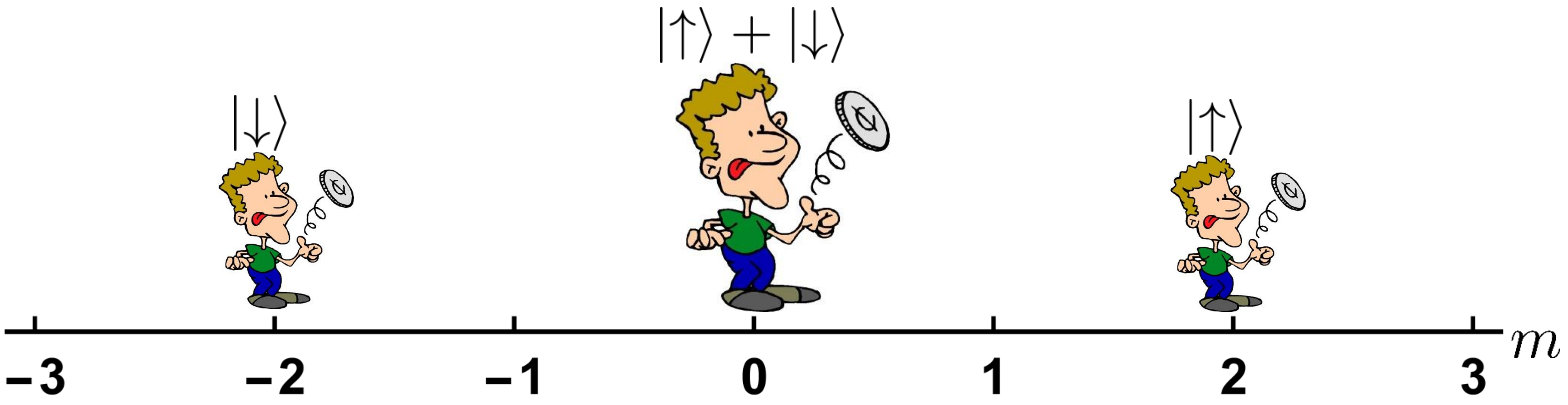
2nd time step



2^{nd} time step



… and so on!



$|\downarrow\rangle$
$|\uparrow\rangle + |\downarrow\rangle$
$|\uparrow\rangle$
m
–3
–2
–1
0
1
2
3

Why?

Topological simulator

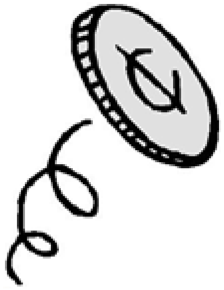
Quantum search algorithm

Entanglement generator

Transport phenomena

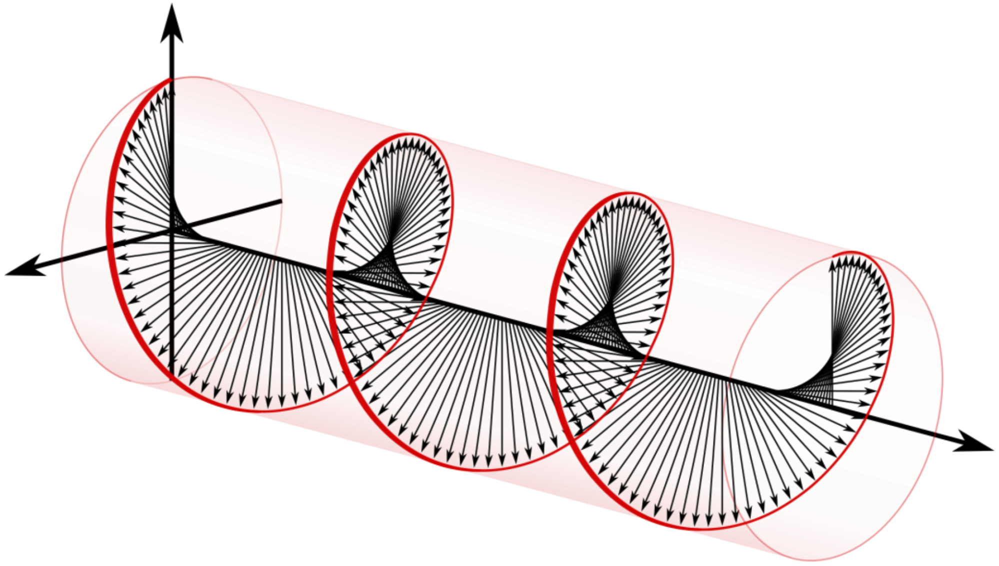
Photonic quantum walks

Photonic quantum walks (coin)



COIN

$\{|\uparrow\rangle, |\downarrow\rangle\}$



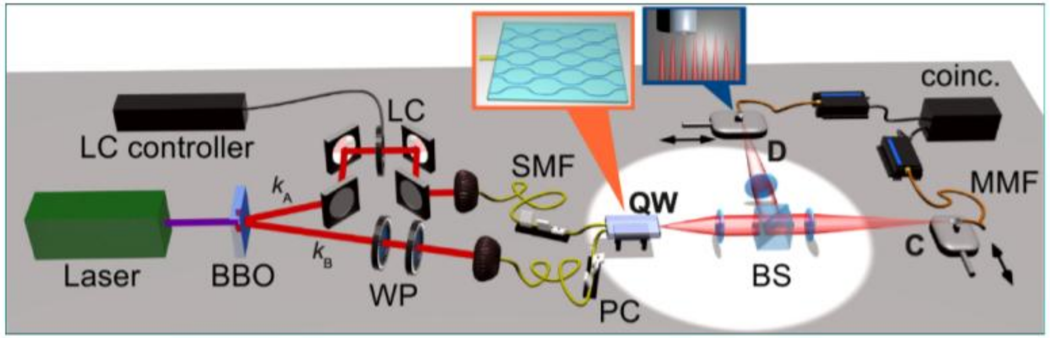
POLARIZATION

$\{|L\rangle, |R\rangle\}$

Photonic quantum walks (walker)

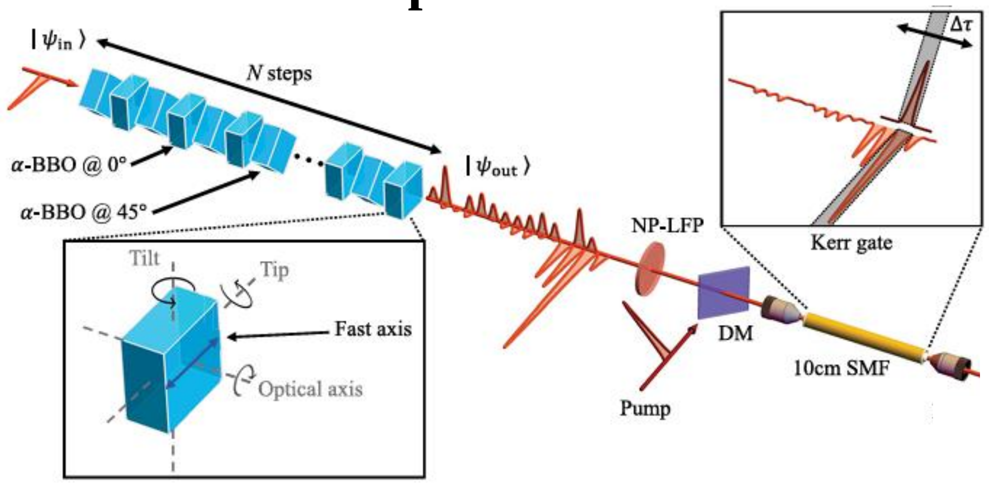
$|m\rangle$

position modes



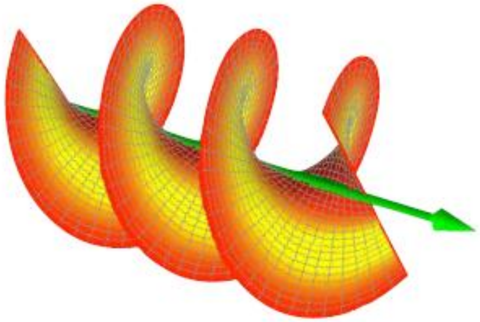
L. Sansoni et al., Phys. Rev. Lett. 108, 010502 (2012)

temporal modes



K. Fenwick et al., Optica 11, 1017 (2024)

helical modes

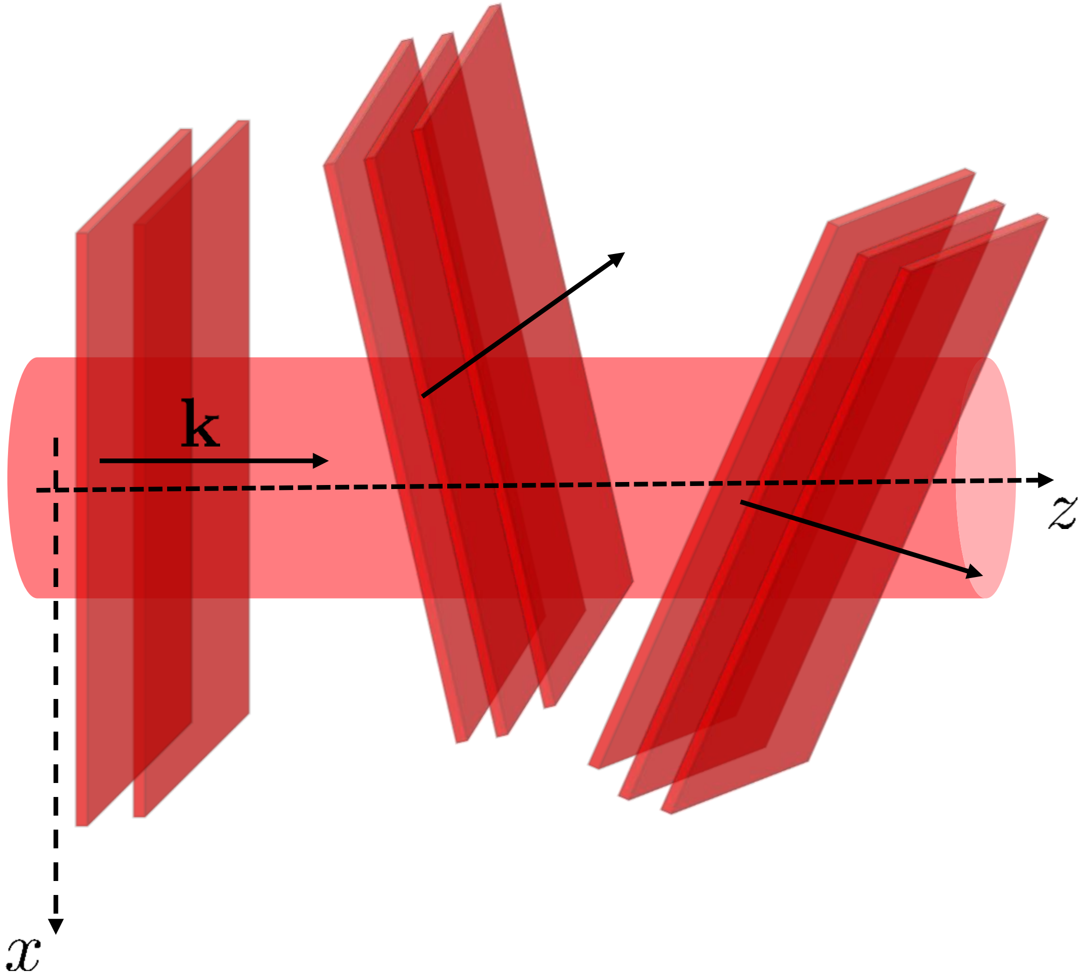


F. Cardano et al., Sci. Adv. 1, e1500087 (2015)

Our walker

$|m\rangle$

transverse momentum modes



A. D'Errico et al., Optica 7, 108 (2020)

Quantizing light transverse momentum

$$E(x, y, z) = E_0(x, y, z)e^{ik_z z}e^{ik_x x}$$

Quantizing light transverse momentum

$$E(x,y,z) = E_0(x,y,z)e^{ik_z z}e^{im\Delta k_\perp x} \qquad \Delta k_\perp = \frac{2\pi}{\Lambda} \qquad m \in \mathbb{Z}$$

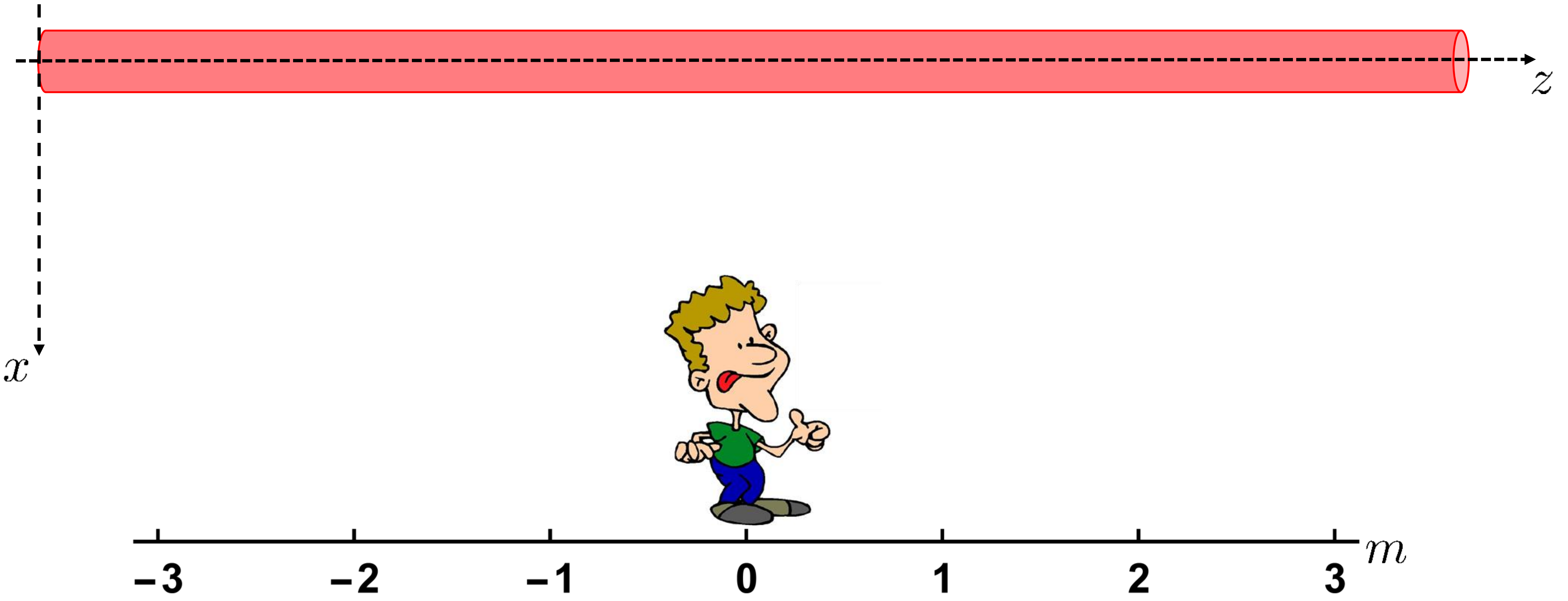
Quantizing light transverse momentum

$$|m\rangle = E_0(x, y, z)e^{ik_z z}e^{im\Delta k_\perp x} \qquad \Delta k_\perp = \frac{2\pi}{\Lambda} \qquad m \in \mathbb{Z}$$

Quantizing light transverse momentum

$$|0\rangle = E_0(x,y,z)e^{ik_z z}$$

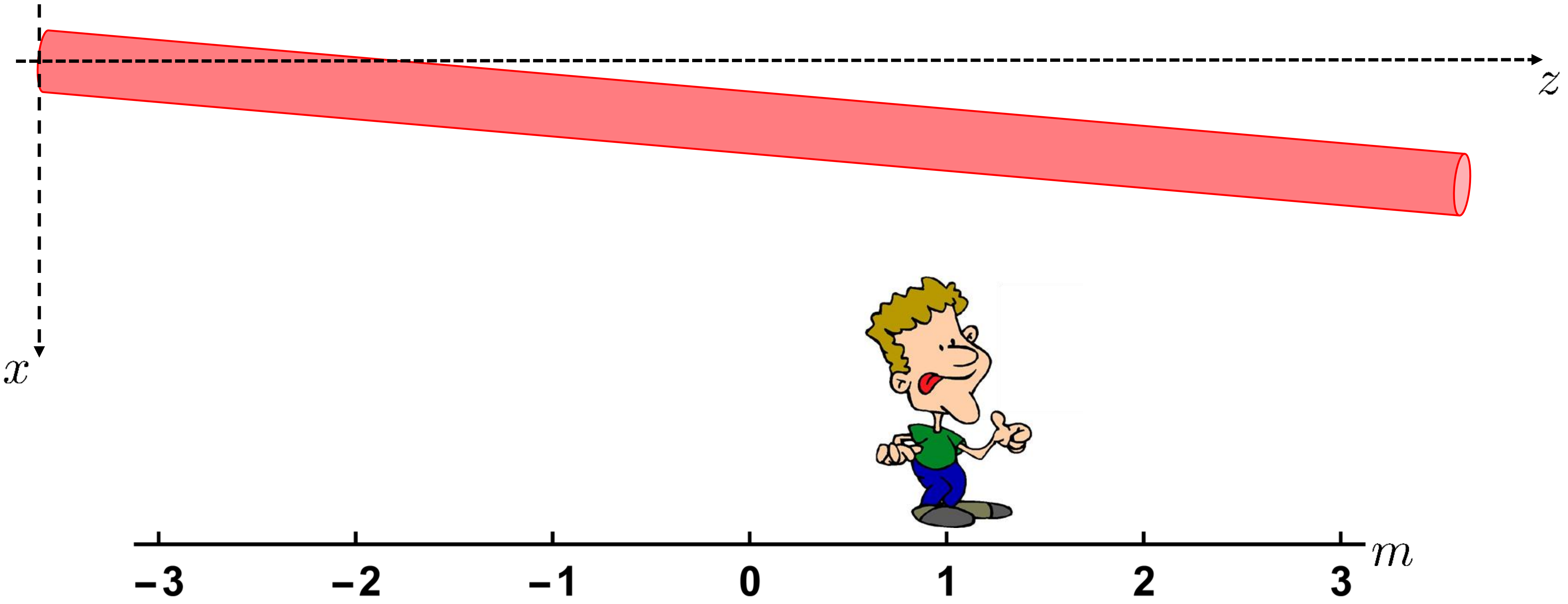
$$\Delta k_\perp = \frac{2\pi}{\Lambda} \qquad m = 0$$



Quantizing light transverse momentum

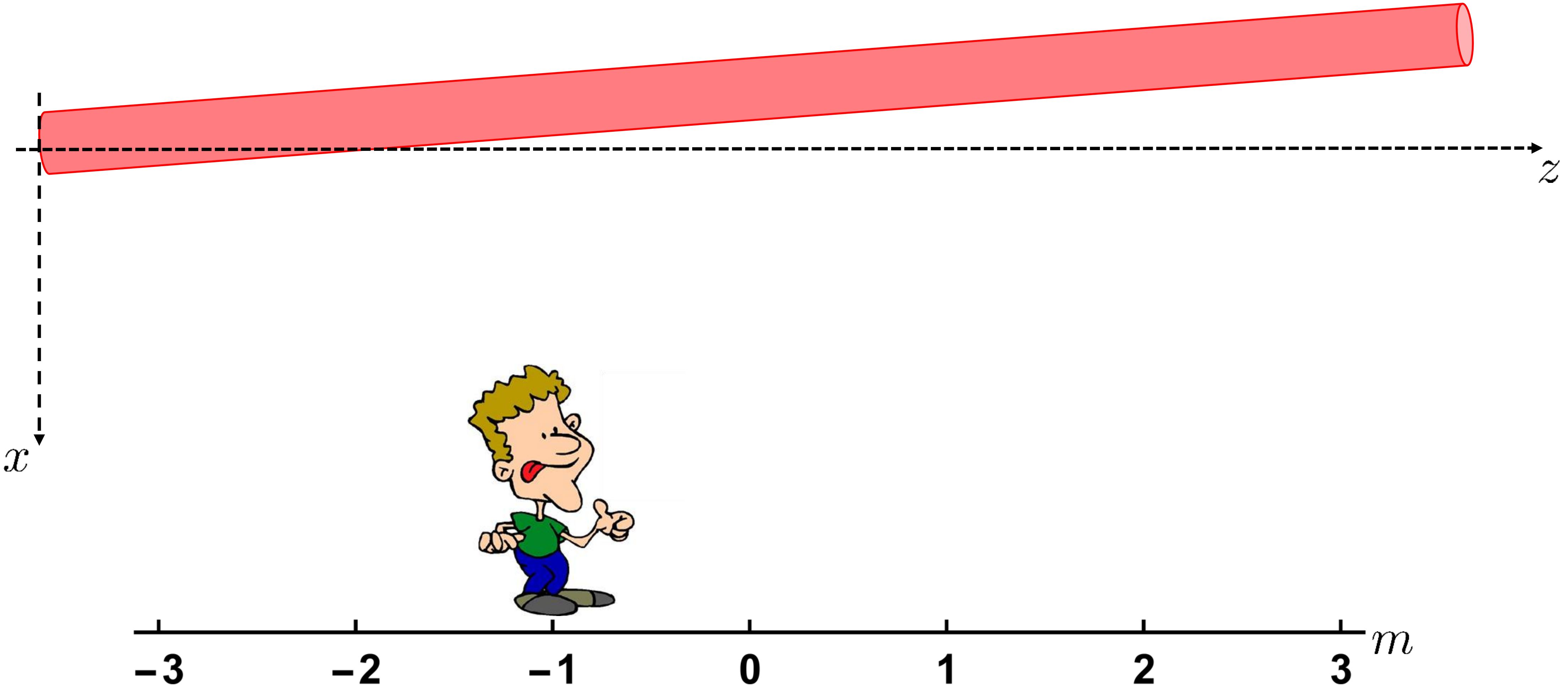
$$|1\rangle = E_0(x,y,z)e^{ik_z z}e^{+i\Delta k_\perp x}$$

$$\Delta k_\perp = \frac{2\pi}{\Lambda} \qquad m = 1$$



Quantizing light transverse momentum

$$|-1\rangle = E_0(x,y,z)e^{ik_z z}e^{-i\Delta k_\perp x} \qquad \Delta k_\perp = \frac{2\pi}{\Lambda} \qquad m = -1$$



Keep in mind

Light momenta $\longleftrightarrow$ Walker positions

Light positions $\longleftrightarrow$ Walker momenta

Talk by Alessio D’Errico (Tomorrow, 9.30)

Talk by Farid Ghobadi (Thursday, 15:40)

Poster by Maria Gorizia Ammendola (Tomorrow, 16:00-18:00)

Photonic implementation of the QW dynamics

Waveplate operator

$$L_\delta(\theta) = \begin{pmatrix} \cos(\delta/2) & i\sin(\delta/2)e^{-2i\theta} \\ i\sin(\delta/2)e^{2i\theta} & \cos(\delta/2) \end{pmatrix}$$

optical retardation
(birefringence)

optic-axis orientation

Coin rotation

$$W = L_{\pi/2}(0) = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix}$$ quarter-wave plate

Coin-dependent translation

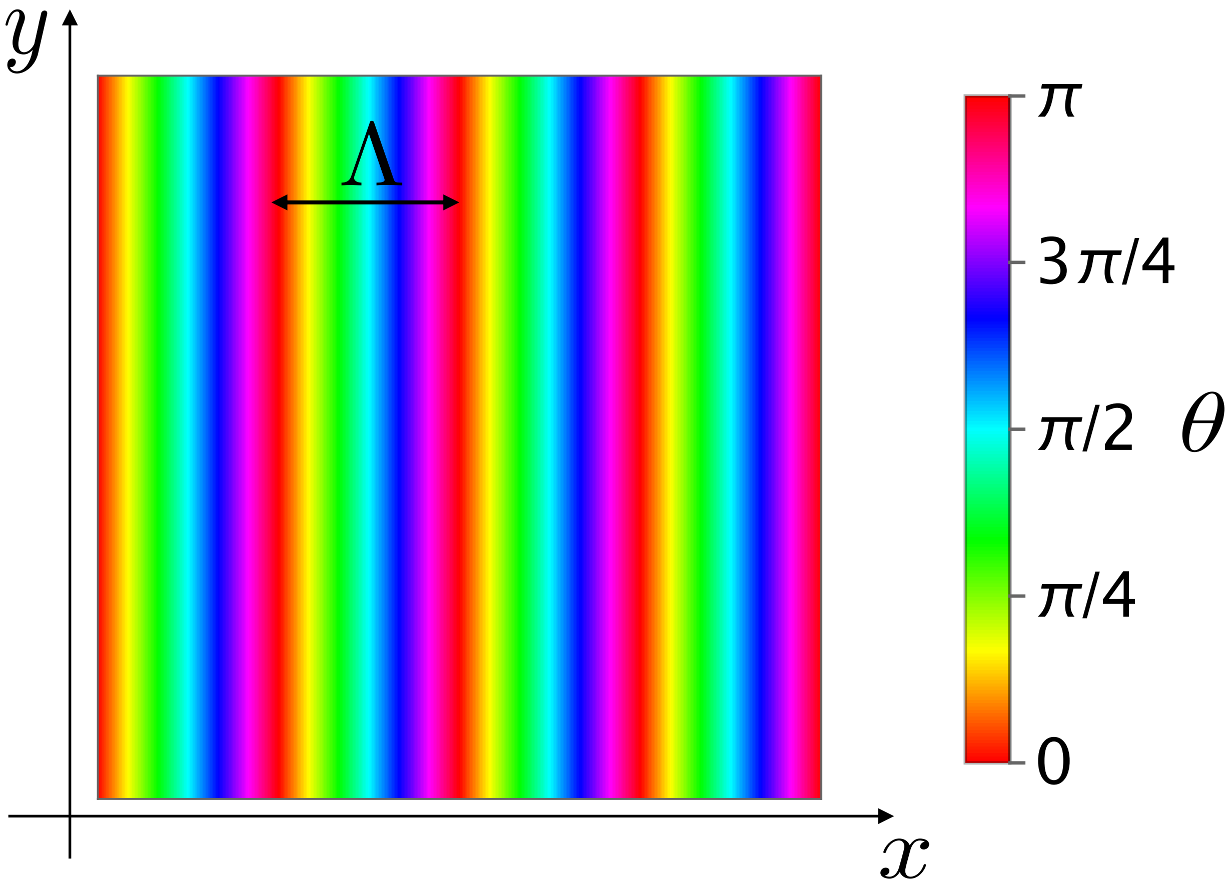
$$T_\delta = L_\delta(\theta(x)) = \begin{pmatrix} \cos(\delta/2) & i\sin(\delta/2)e^{-\boxed{2i\theta(x)}} \\ i\sin(\delta/2)e^{\boxed{2i\theta(x)}} & \cos(\delta/2) \end{pmatrix}$$

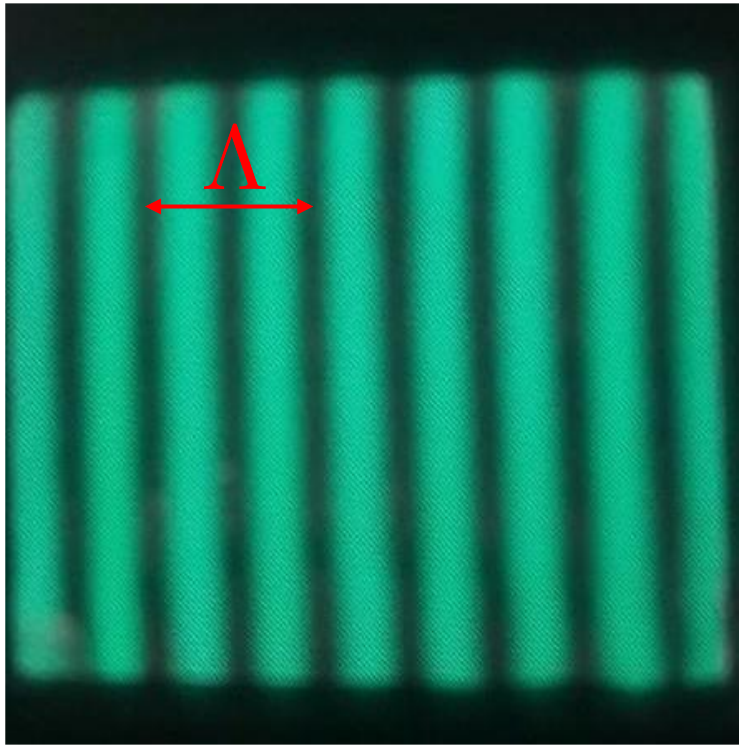
$$\theta(x) = \frac{\pi}{\Lambda}x$$ *g*-plate

Liquid-crystal metasurfaces

$$\theta(x,y) = \theta_0 + \frac{\pi}{\Lambda}x$$

g-plate





δ electrically tuned

Optimizing photonic simulations

F. Di Colandrea et al., Optica 10, 324 (2023)

Standard approach

$$|\psi_\tau\rangle = U^\tau |\psi_0\rangle = UUU...UU |\psi_0\rangle$$

Rotation + Translation
(or a combination of them)

Standard approach

$$|\psi_\tau\rangle = U^\tau |\psi_0\rangle = UUU...UU |\psi_0\rangle$$

Rotation + Translation
(or a combination of them)

→

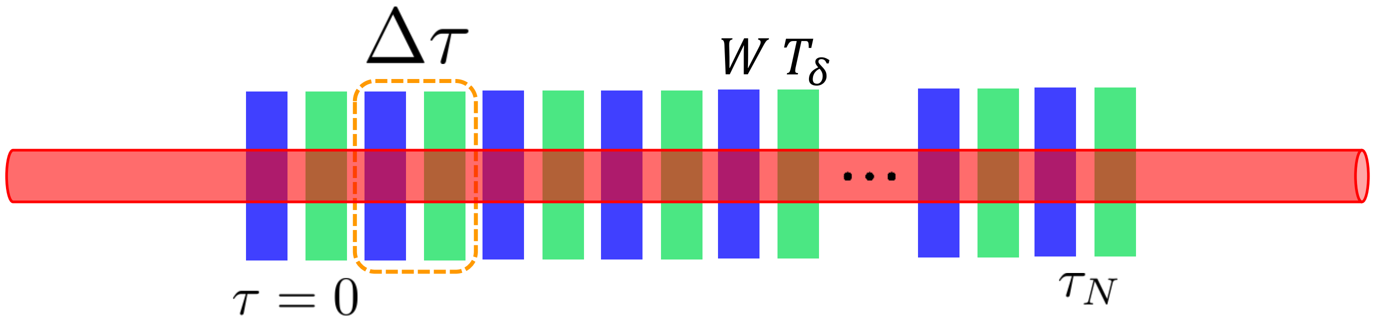
(at least) 2 optical elements
for each time step

Standard approach

$$|\psi_\tau\rangle = U^\tau |\psi_0\rangle = UUU...UU |\psi_0\rangle$$

Rotation + Translation
(or a combination of them)

(at least) 2 optical elements
for each time step

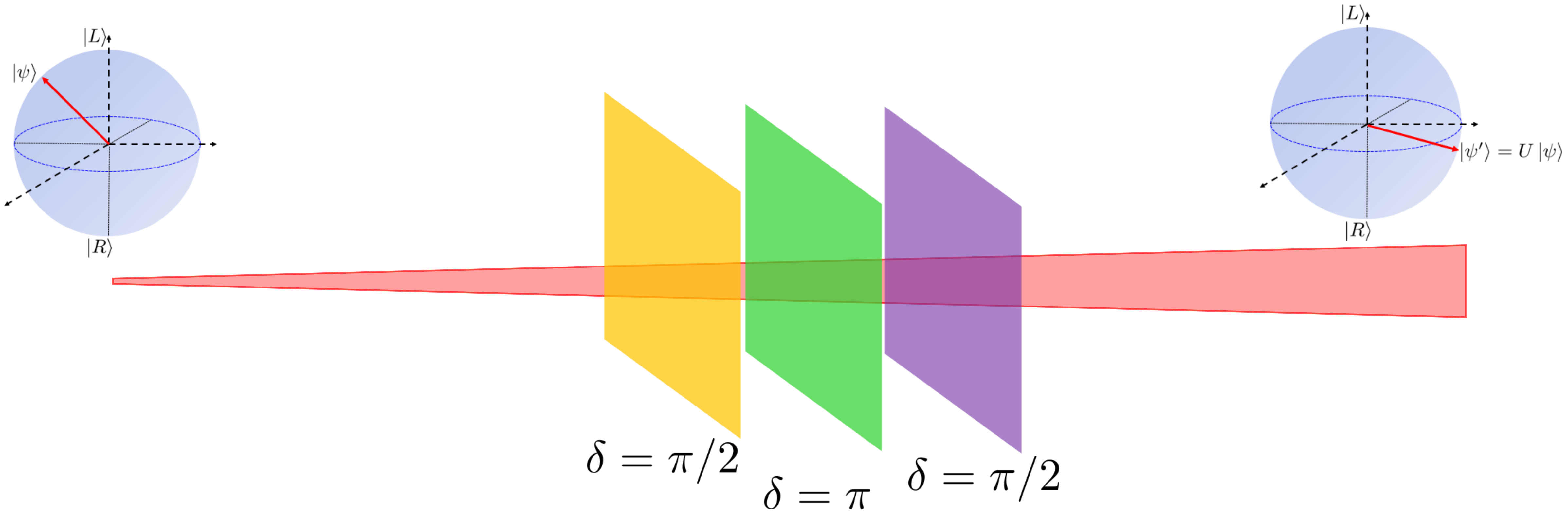


$$|\psi_\tau\rangle = \prod_{i=1}^{\tau}\left[\begin{pmatrix} \cos\frac{\delta}{2} & i\sin\frac{\delta}{2}e^{-2i\frac{\pi}{\Lambda}x} \\ i\sin\frac{\delta}{2}e^{+2i\frac{\pi}{\Lambda}x} & \cos\frac{\delta}{2} \end{pmatrix}\begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{i}{\sqrt{2}} \\ \frac{i}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}\right]|\psi_0\rangle$$

$$|\psi_\tau\rangle = \begin{pmatrix} \alpha(x) & -\beta(x) \\ \beta^*(x) & \alpha^*(x) \end{pmatrix}|\psi_0\rangle$$

Position-dependent polarization rotation

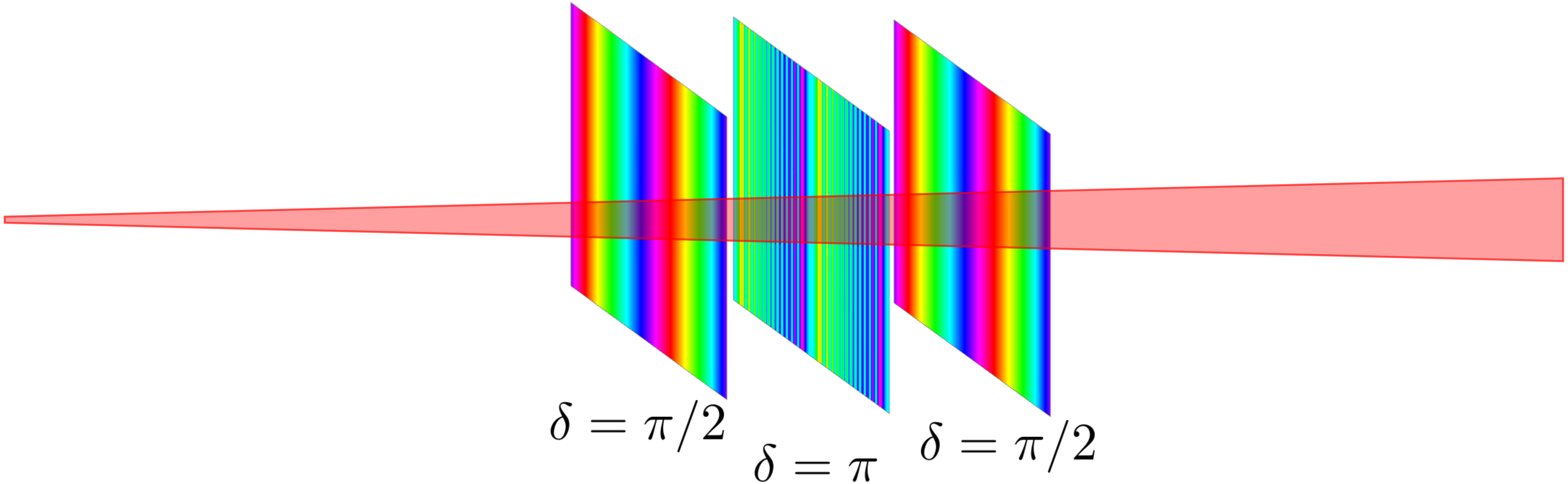
Uniform polarization rotation U



$$U = L_{\pi/2}(\theta_1)L_{\pi}(\theta_2)L_{\pi/2}(\theta_3) \equiv \mathcal{L}(\theta_1, \theta_2, \theta_3)$$

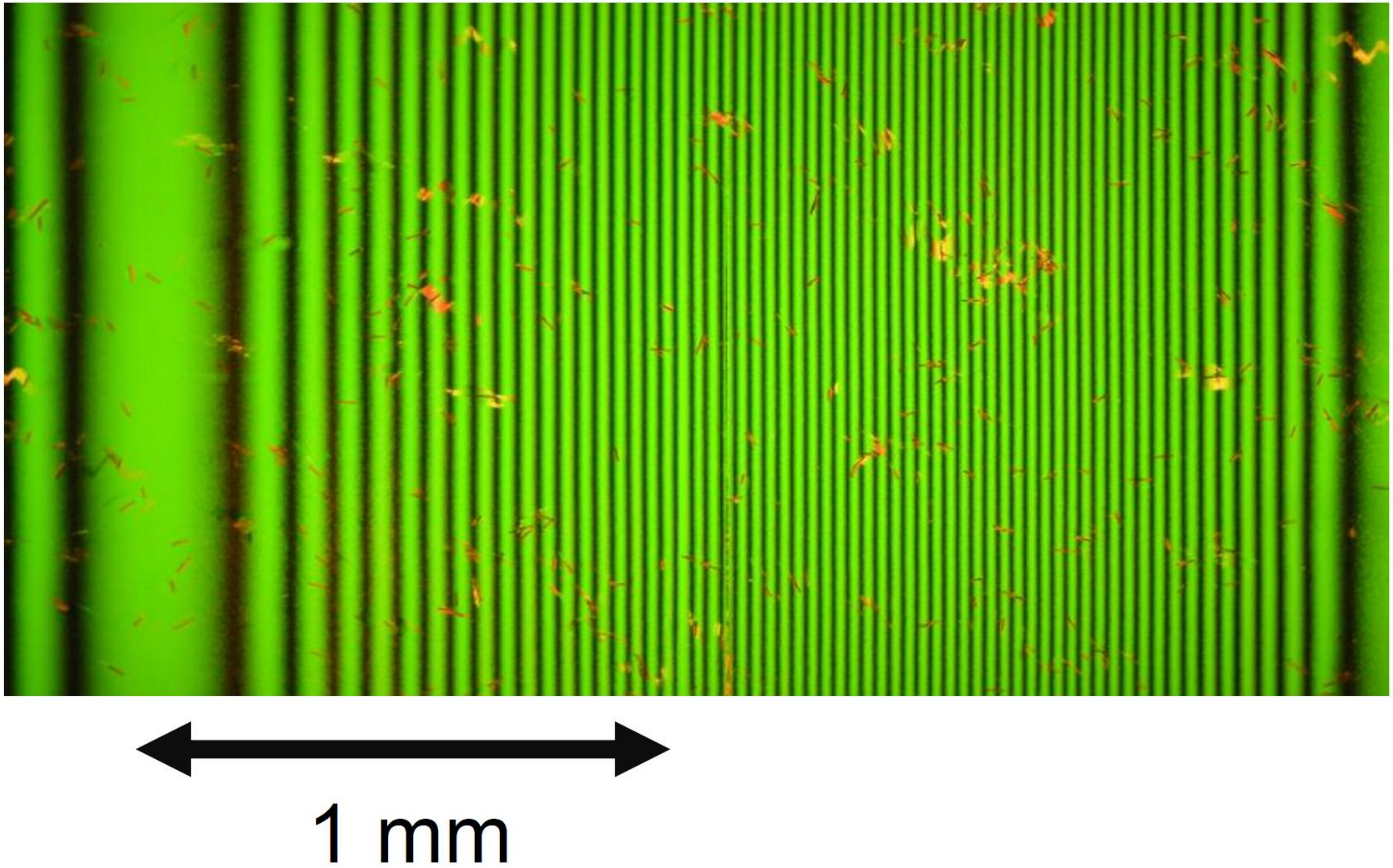
R. Simon & N. Mukunda, Phys. Lett. A 143, 165–169 (1990)

Non-Uniform polarization rotation $U(x)$



$$U(x) = L_{\pi/2}(\theta_1(x))L_{\pi}(\theta_2(x))L_{\pi/2}(\theta_3(x)) \equiv \mathcal{L}(\theta_1(x), \theta_2(x), \theta_3(x))$$

Non-Uniform polarization rotation $U(x)$



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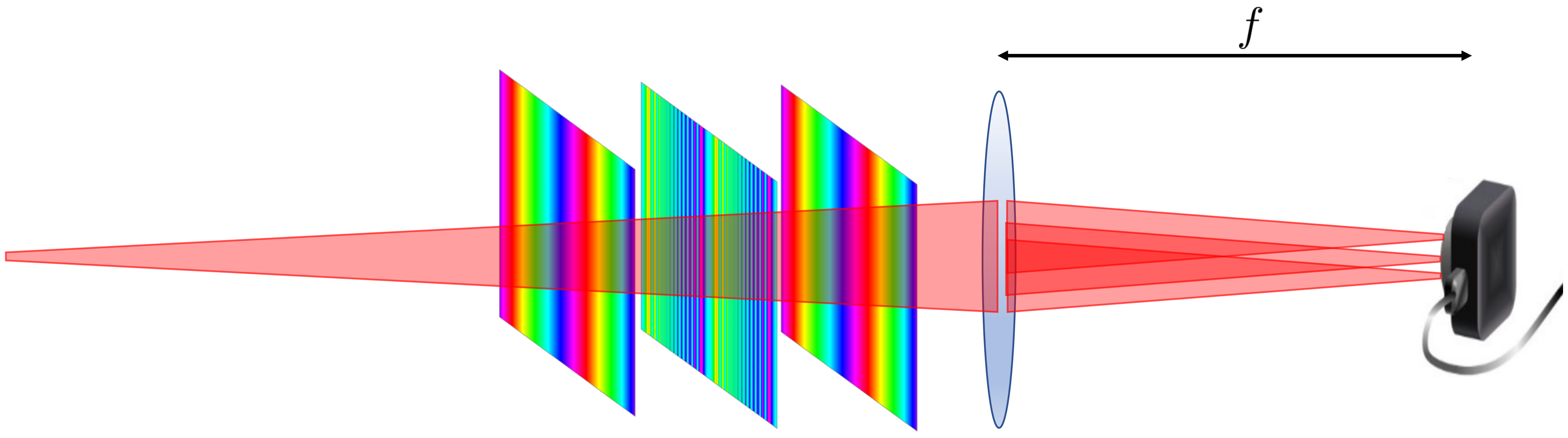
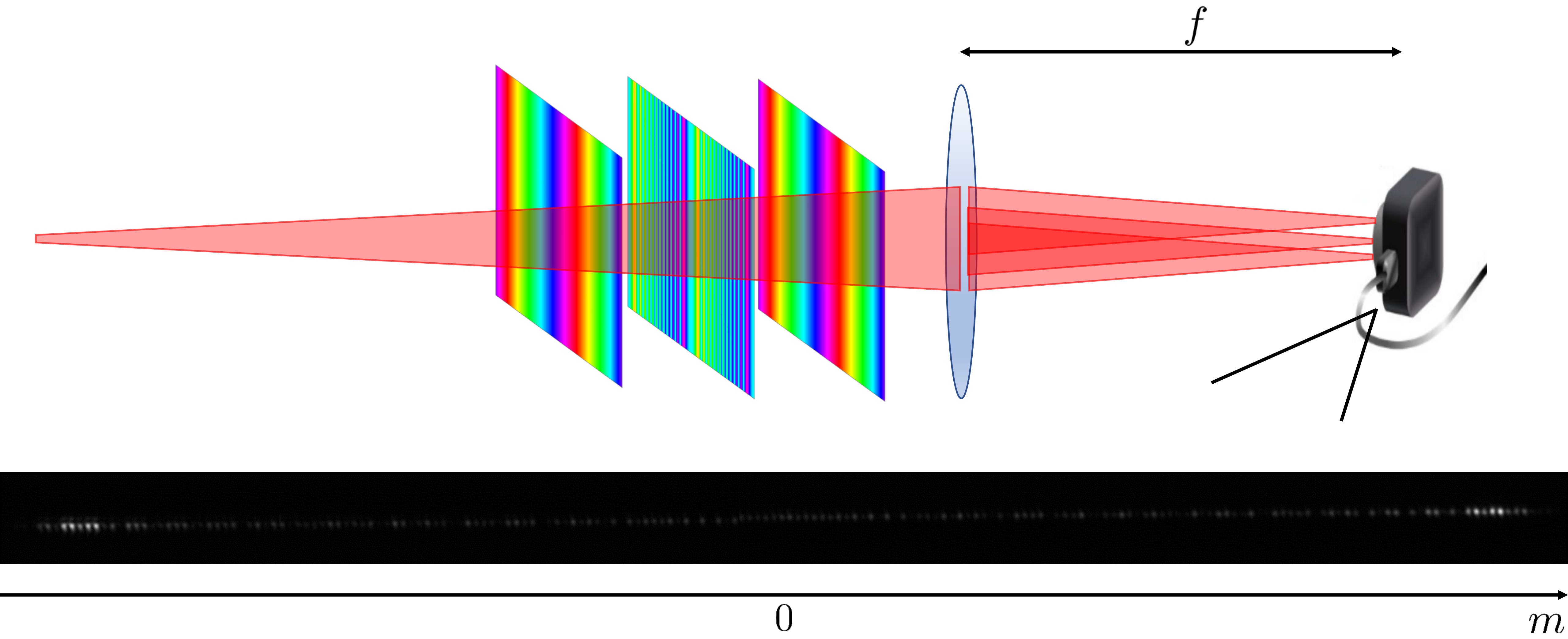
Ultra-long quantum walks

F. Di Colandrea et al., Optica 10, 324 (2023)

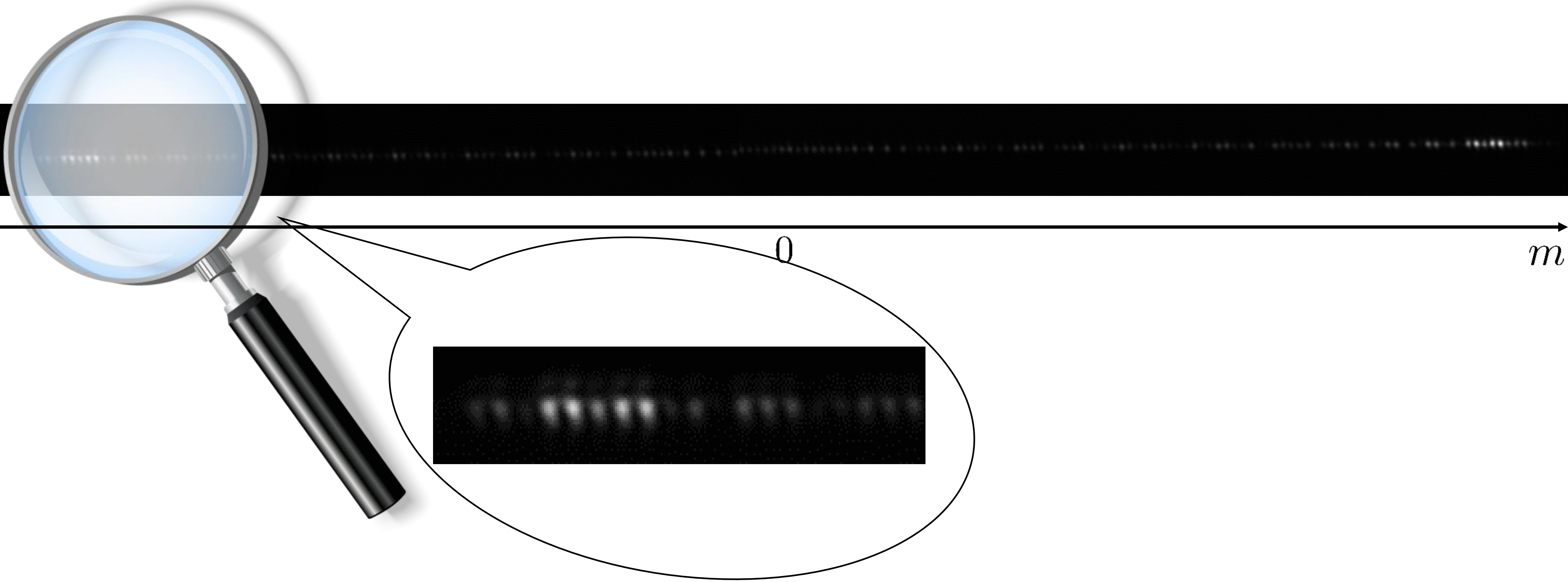
240-step quantum walk



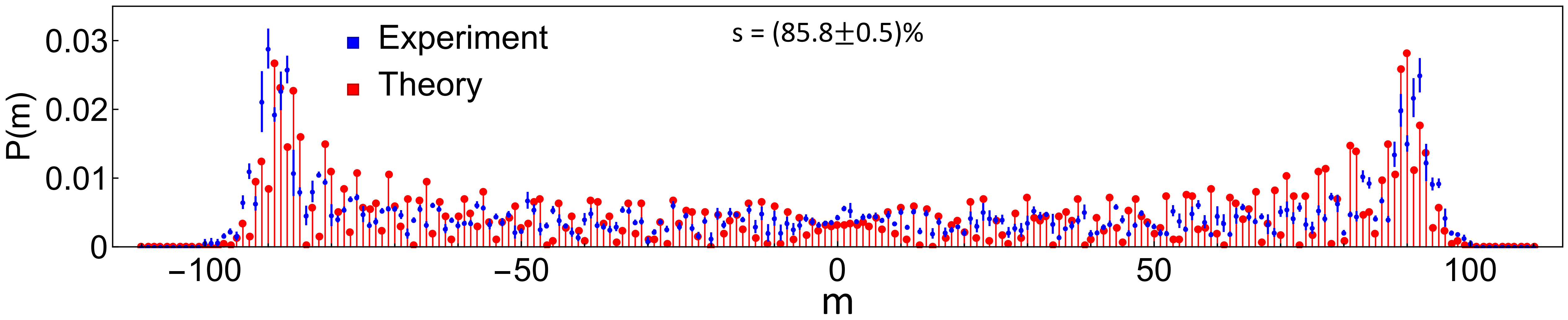
240-step quantum walk



240-step quantum walk

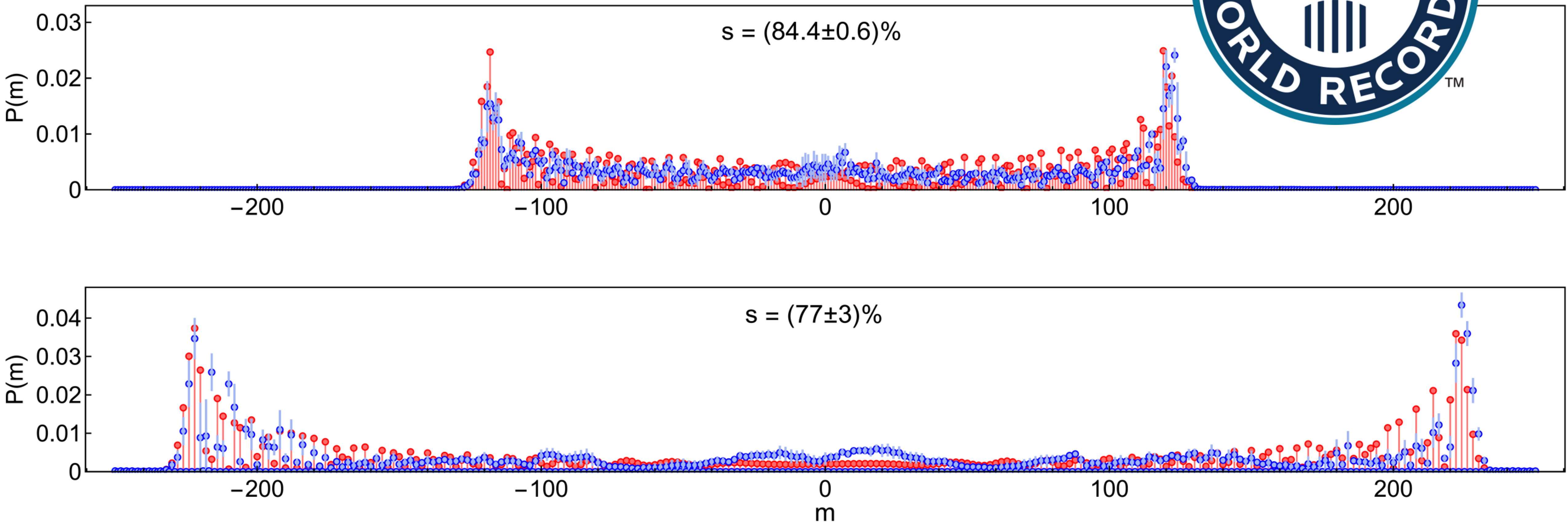


240-step quantum walk



F. Di Colandrea et al., Optica 10, 324 (2023)

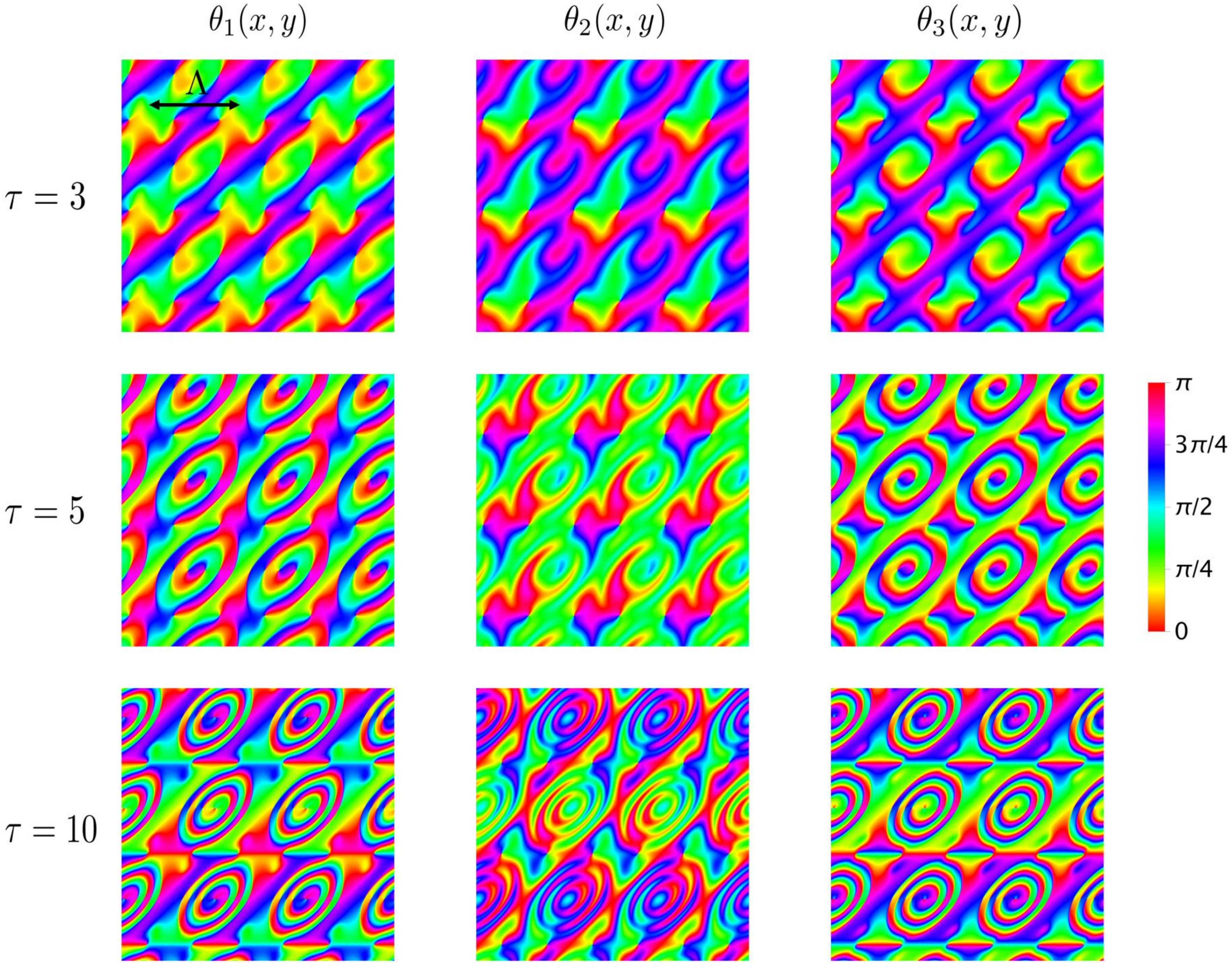
320-step quantum walk (160+160)

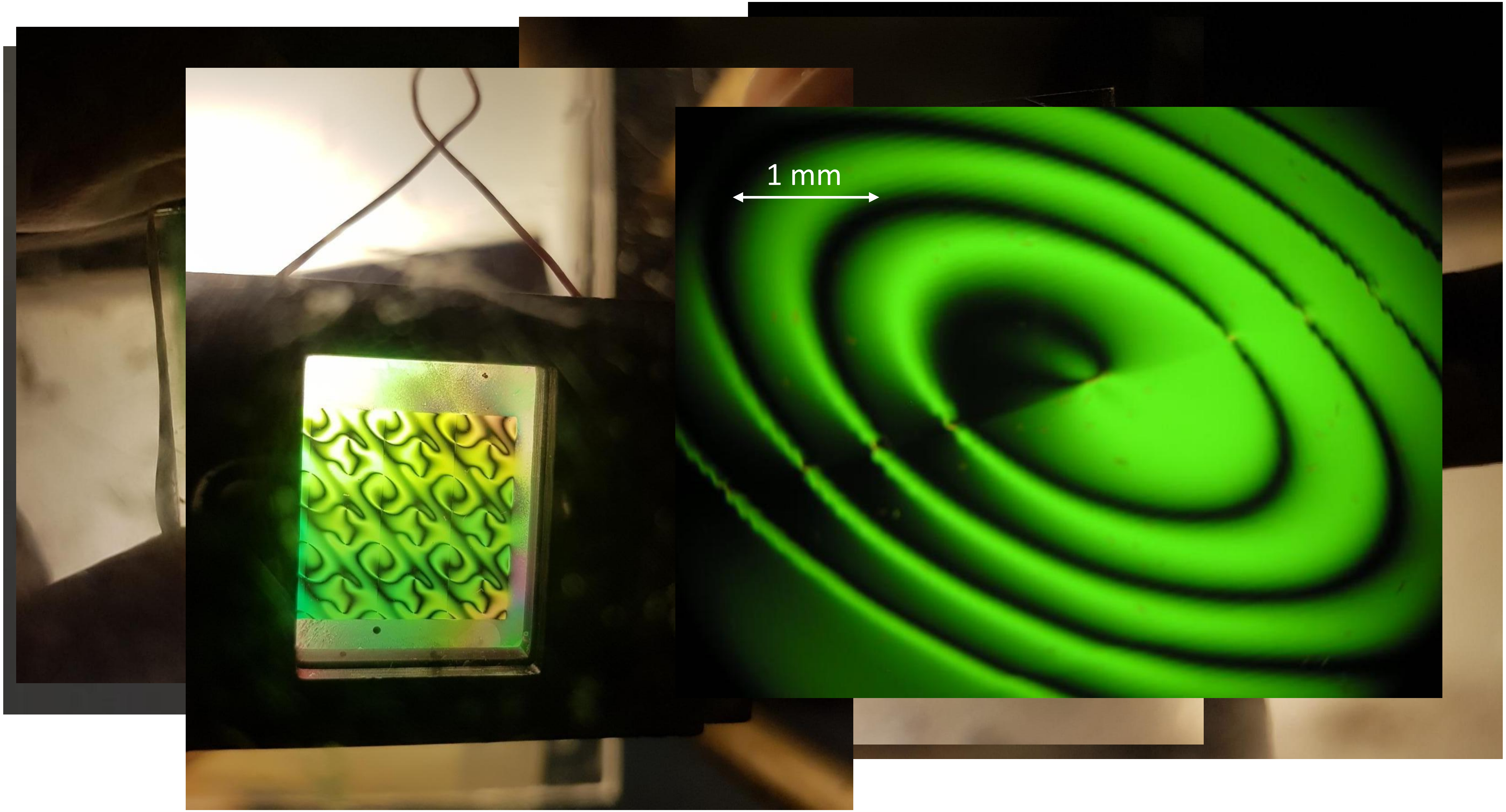


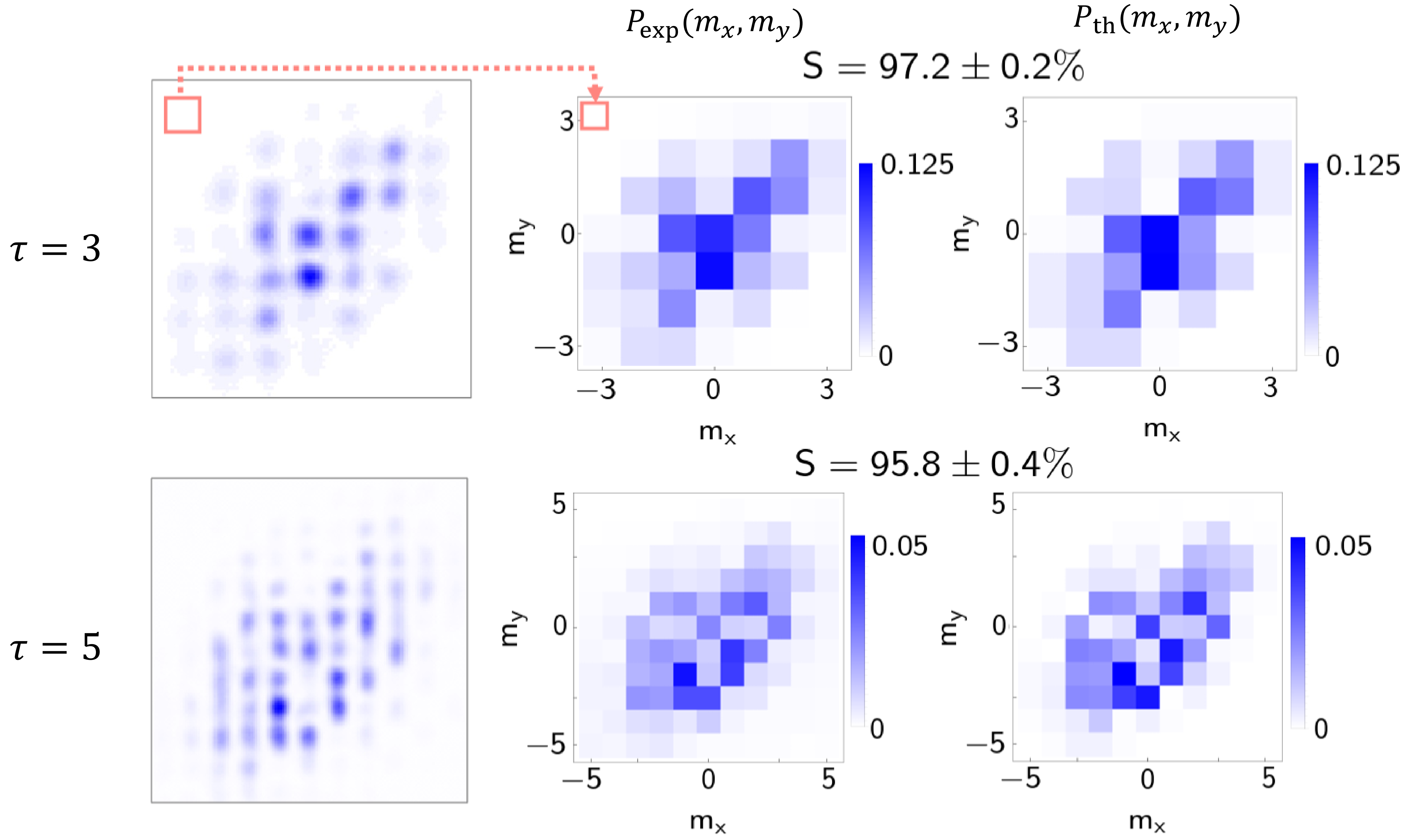
F. Di Colandrea et al., Optica 10, 324 (2023)

Large-scale 2D quantum walks

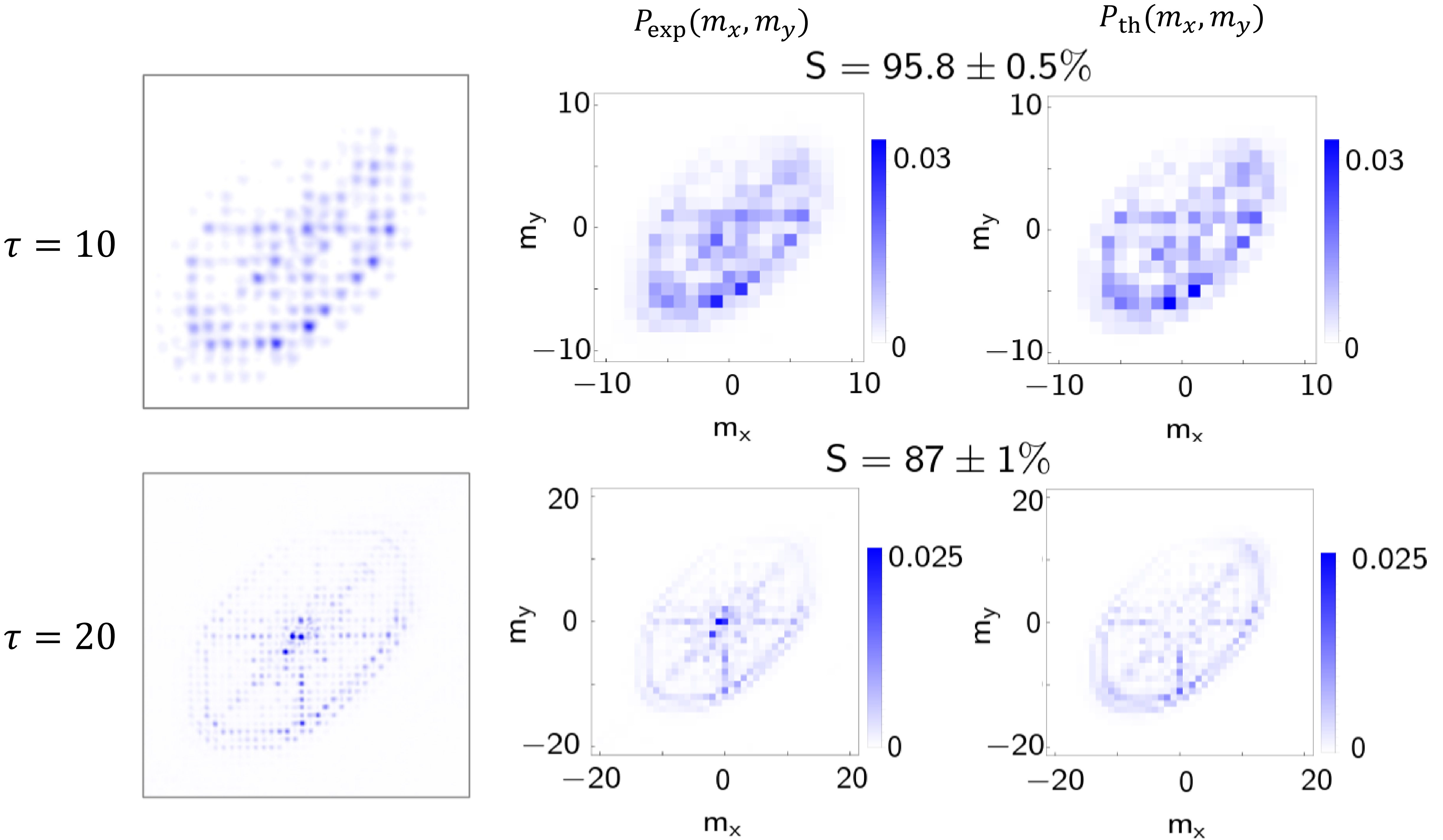
M.G. Ammendola et al., arXiv:2406.08652
Advanced Photonics *(in press)*


$\theta_1(x,y)$
$\theta_2(x,y)$
$\theta_3(x,y)$
Λ
$\tau = 3$
$\tau = 5$
$\tau = 10$
π
$3\pi/4$
$\pi/2$
$\pi/4$
0


1 mm



$P_{\exp}(m_x, m_y)$
$P_{\text{th}}(m_x, m_y)$
$S = 97.2 \pm 0.2\%$
$\tau = 3$
3
0
−3
m_y
m_x
0.125
0
$S = 95.8 \pm 0.4\%$
$\tau = 5$
5
−5
0.05

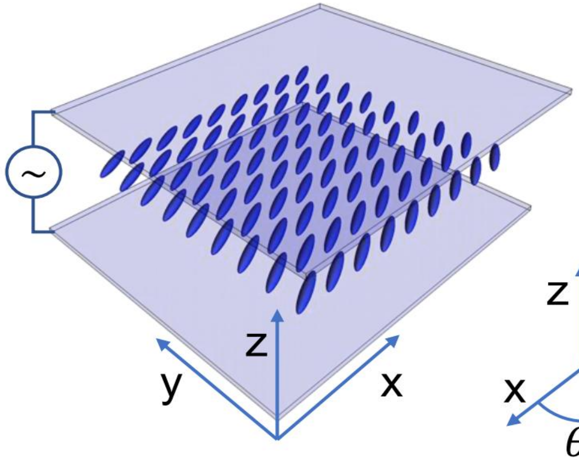


$P_{\mathrm{exp}}(m_x, m_y)$
$P_{\mathrm{th}}(m_x, m_y)$
$\tau = 10$
S = 95.8 ± 0.5%
m_y
m_x
10
0
−10
0.03
$\tau = 20$
S = 87 ± 1%
20
−20
0.025

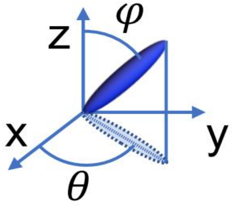
Programmable photonic circuit

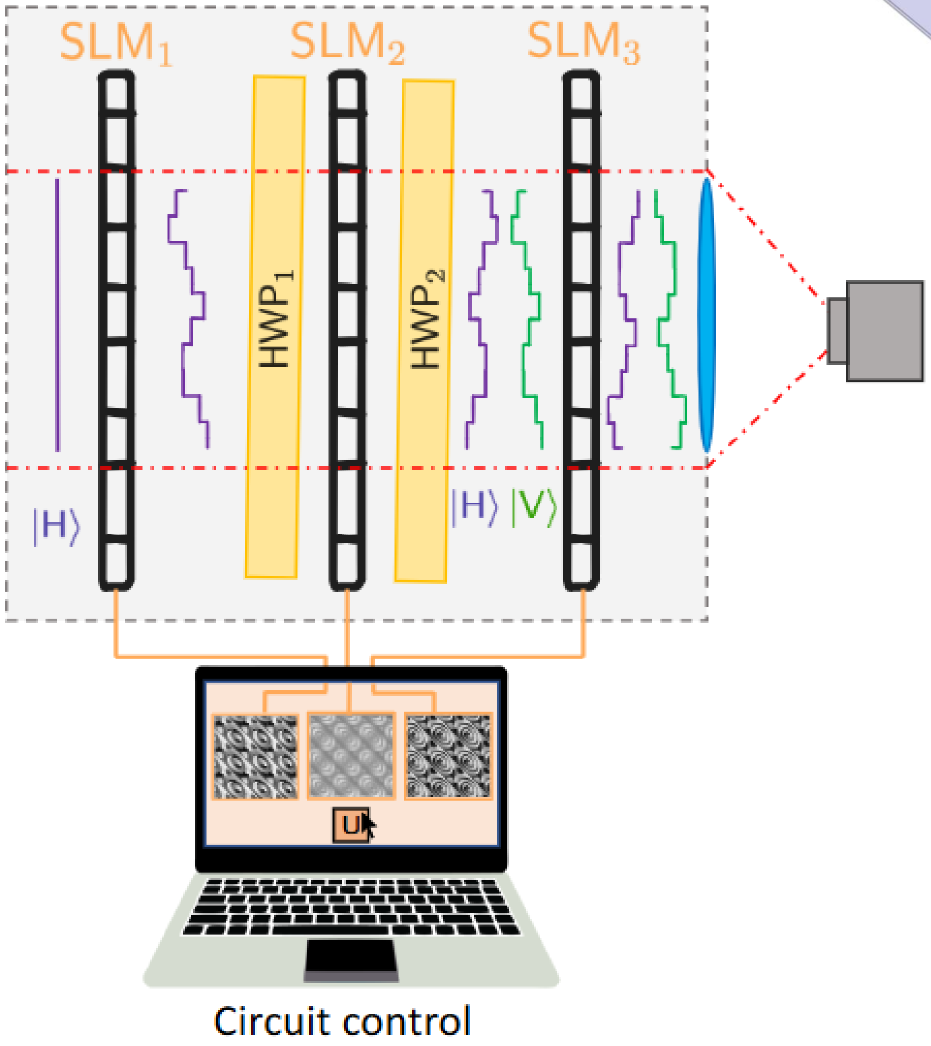
M.G. Ammendola et al., *in preparation*

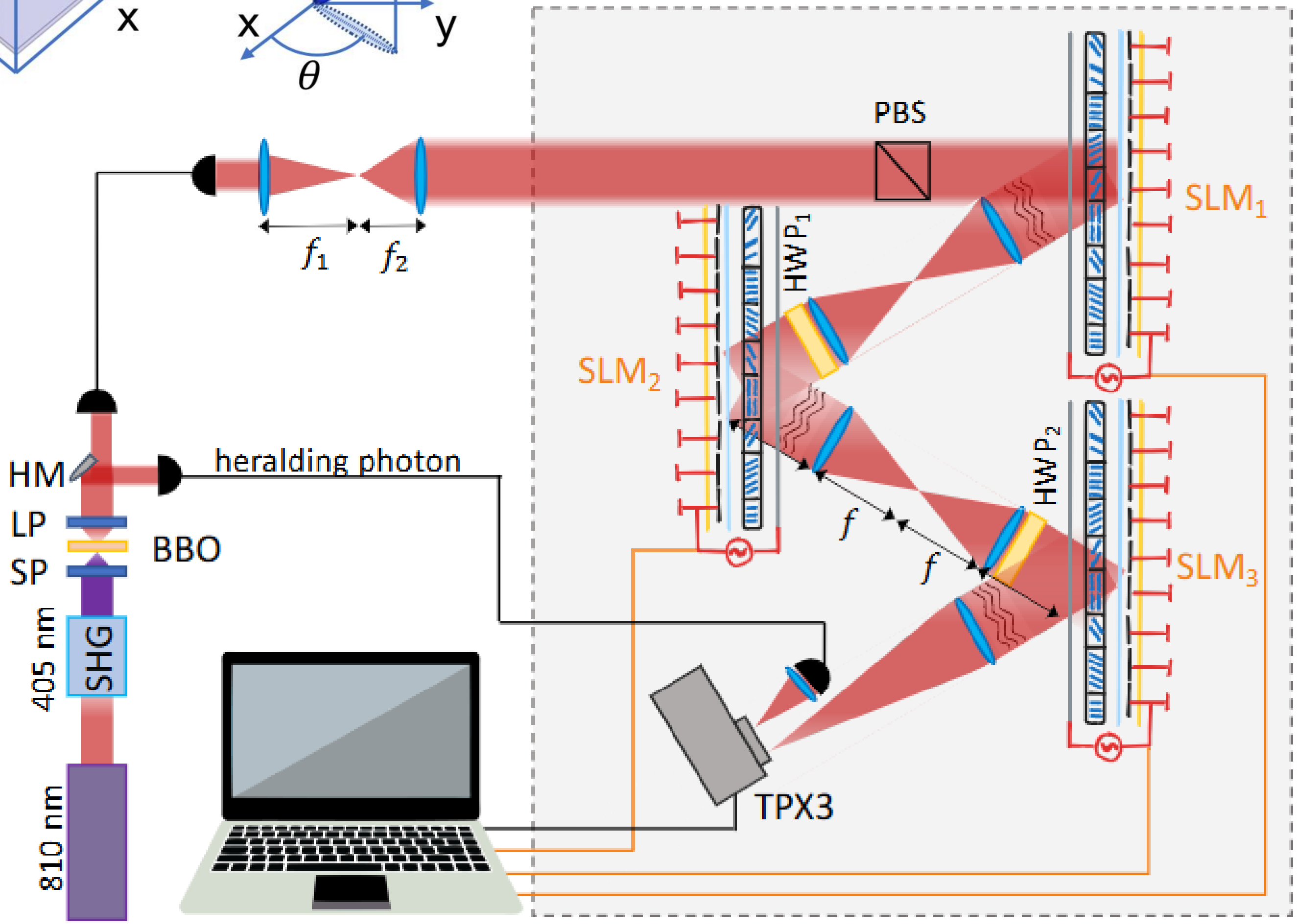
Spatial Light Modulators



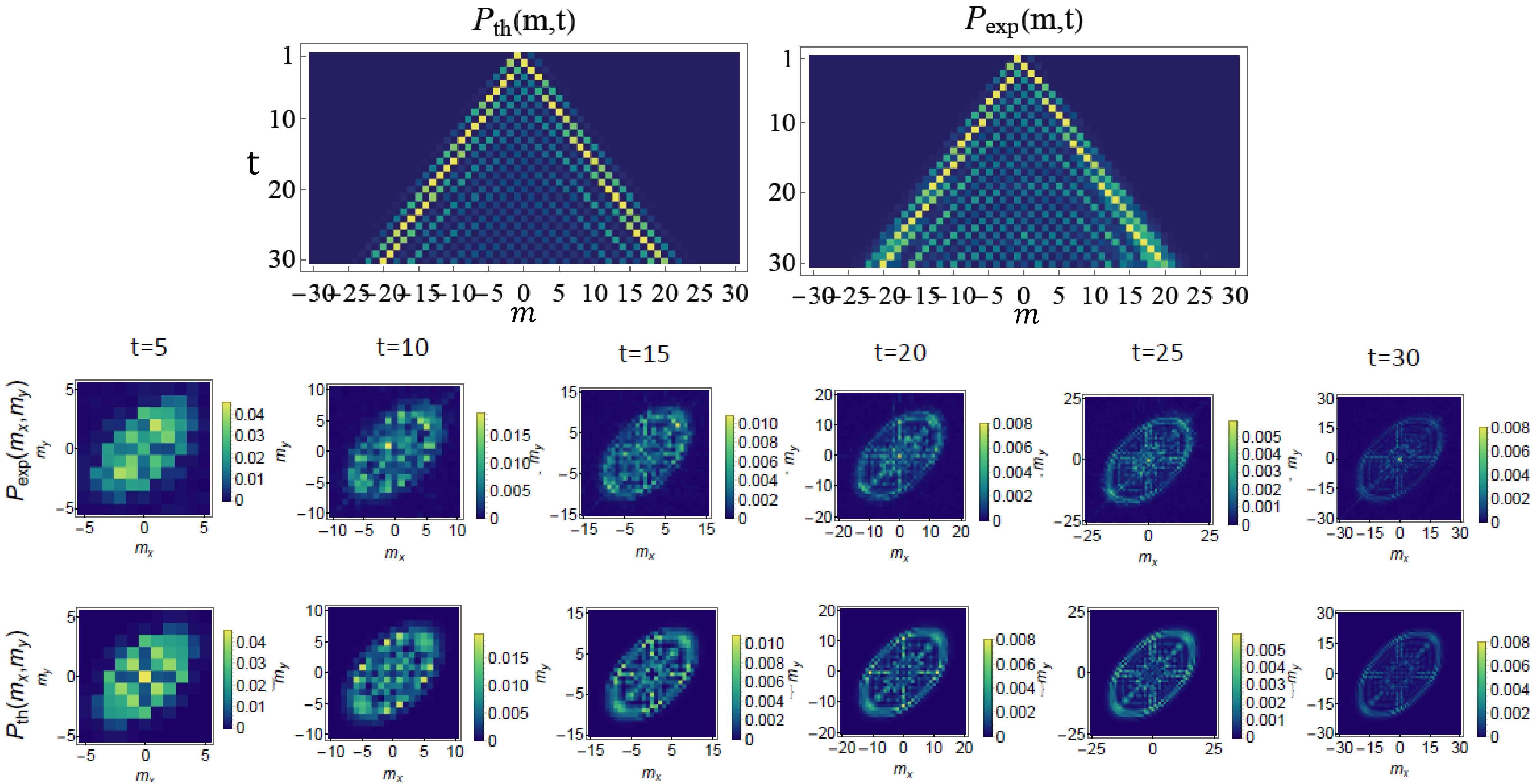
$$\boxed{\theta(x, y) \to \delta(x, y)}$$







Results



M.G. Ammendola et al., *in preparation*

Conclusions

Take-home message

- Compact liquid-crystal-based photonic circuits enabling extreme quantum simulations

Acknowledgments

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ICFO

Institut de Ciències Fotòniques

P. Massignan

A. Dauphin

+

N. Dehghan

uOttawa

F. Di Colandrea E. Karimi A. D’Errico


Thanks!

Similarity estimator

$$s = \left(\sum_m \sqrt{P_{\text{exp}}(m) P_{\text{th}}(m)} \right)^2$$

Operator description

COIN ROTATION

$$W = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix}$$

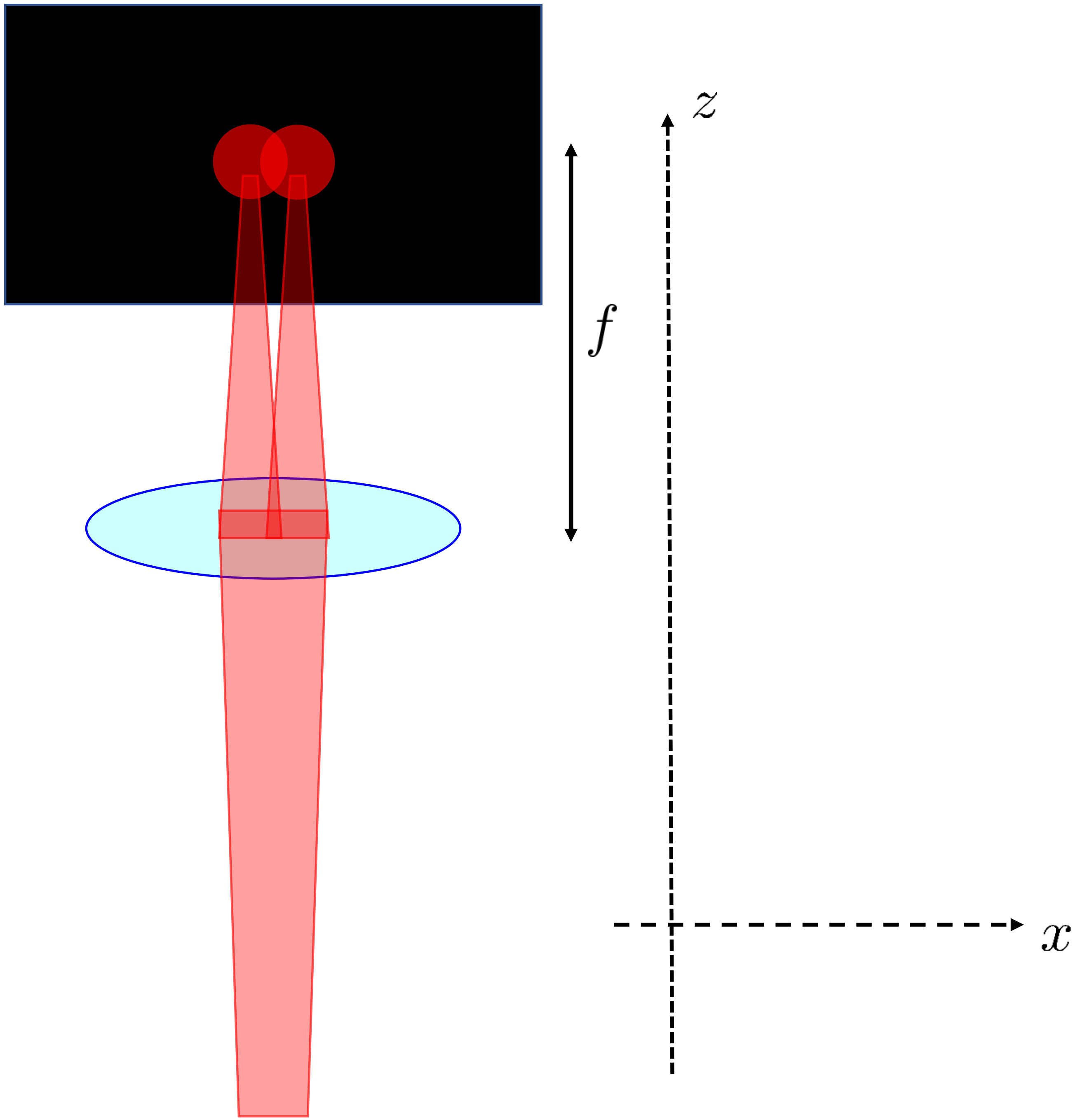
COIN-DEPENDENT TRANSLATION

$$T(\delta) = \boxed{\cos\left(\frac{\delta}{2}\right)} I + i \boxed{\sin\left(\frac{\delta}{2}\right)} \sum_m \left(|{\uparrow}\rangle\langle{\downarrow}|\, |m-1\rangle\langle m| + |{\downarrow}\rangle\langle{\uparrow}|\, |m+1\rangle\langle m| \right)$$

$$|\psi_\tau\rangle = U^\tau |\psi_0\rangle$$

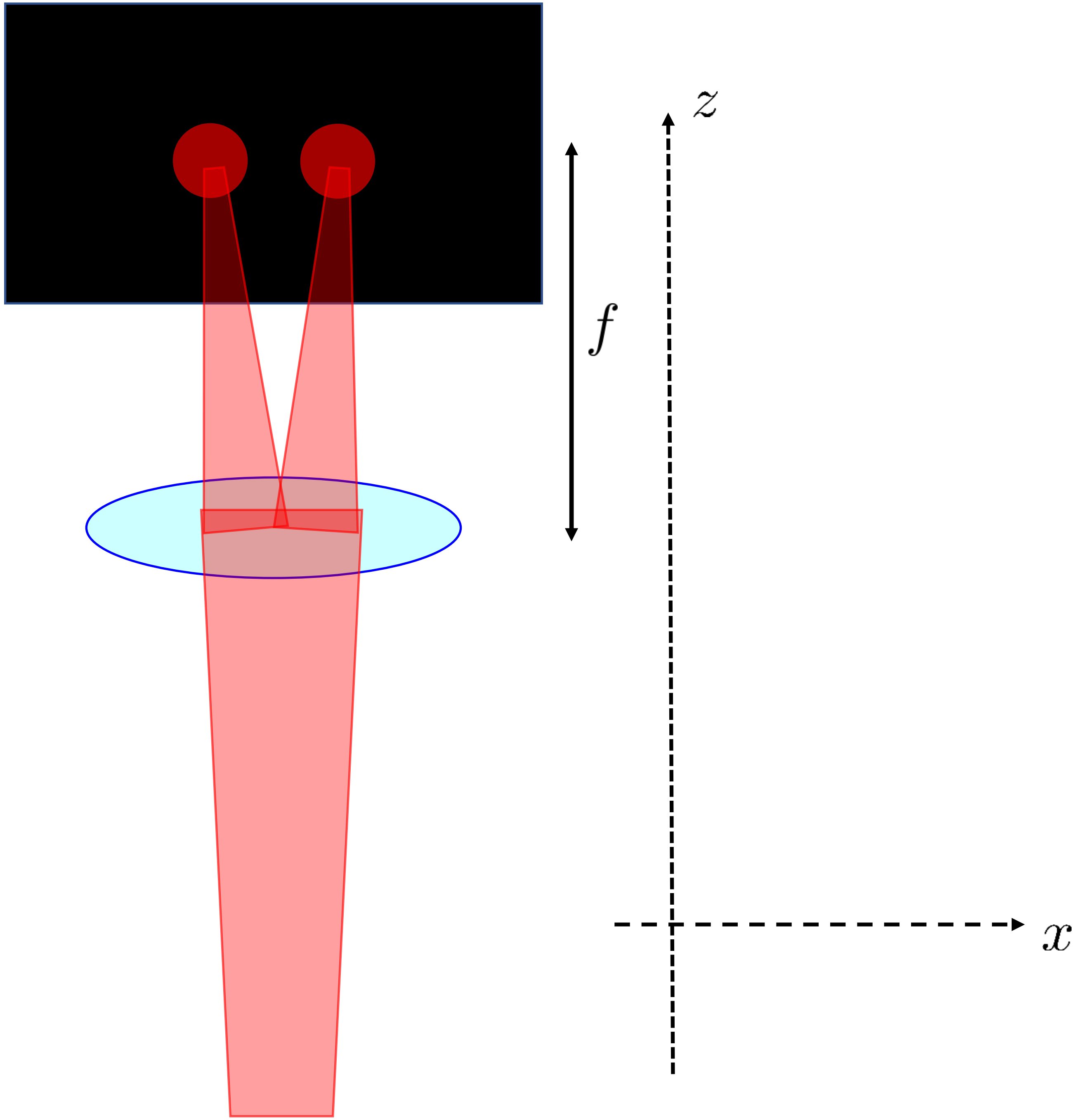
Orthogonality?

$\langle m|m'\rangle \neq 0$



Orthogonality?

$$\langle m | m' \rangle \simeq 0$$

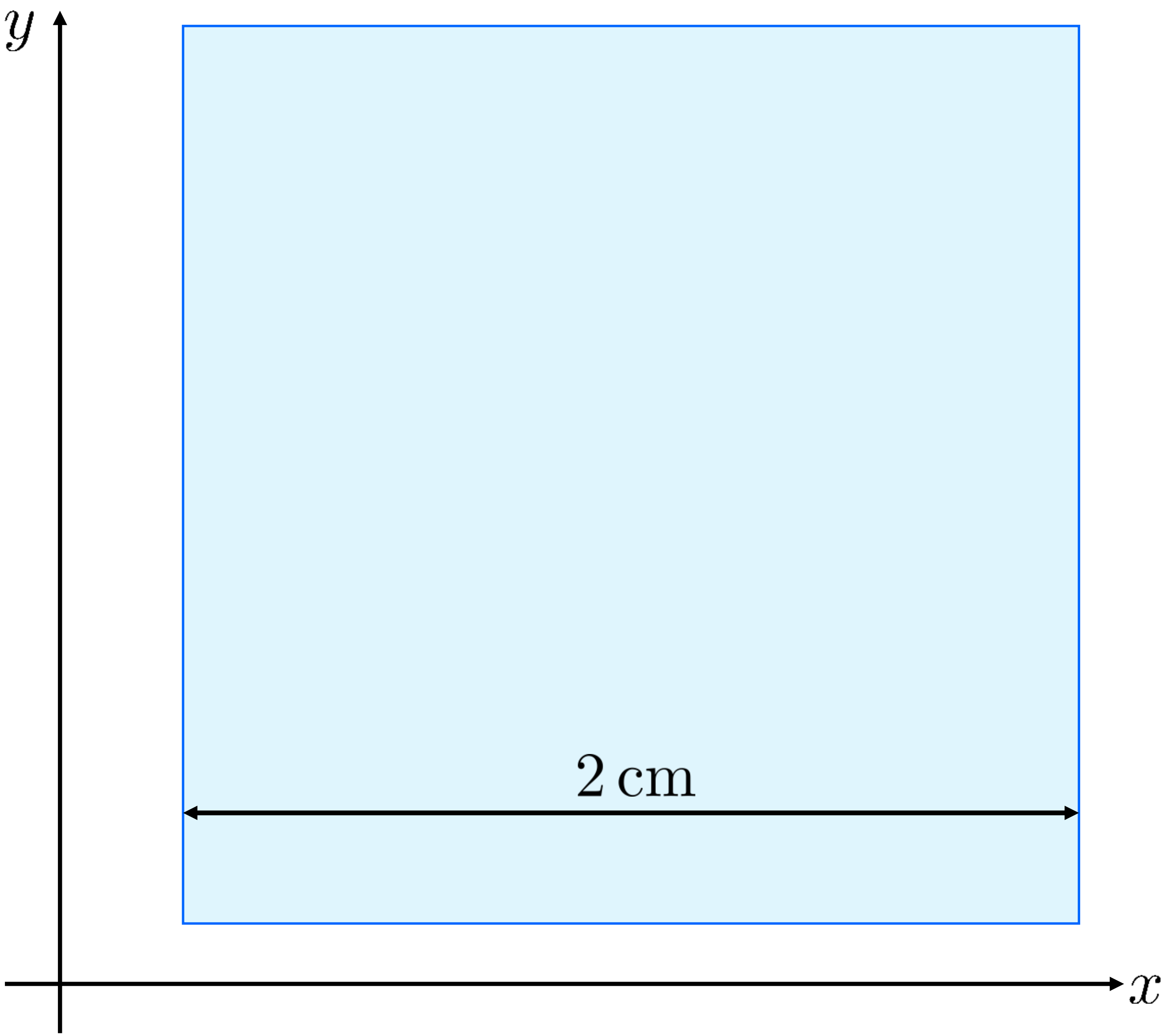


Liquid-crystal metasurfaces

LC patterned waveplates with electrically-tuned birefringence

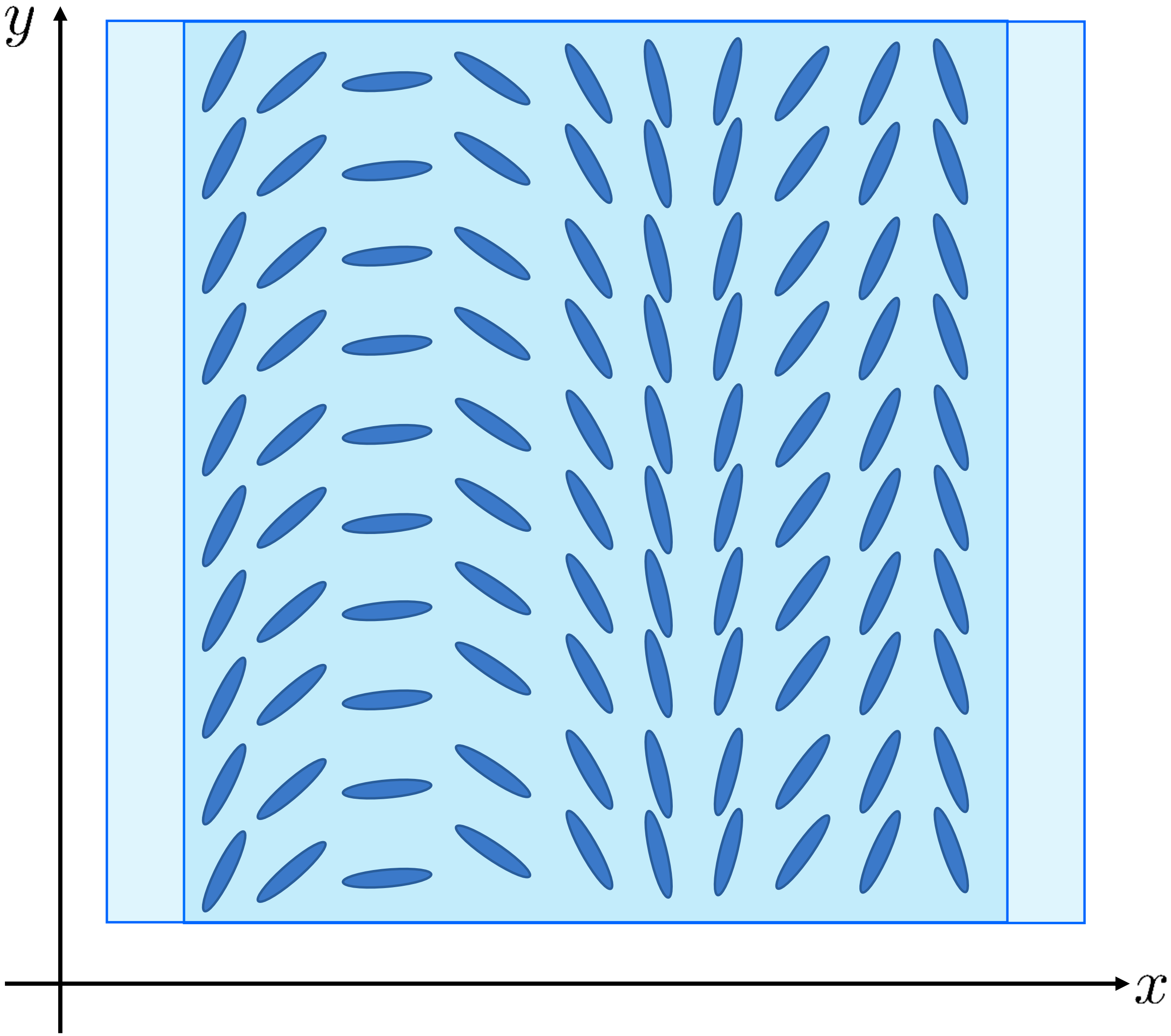
Liquid-crystal metasurfaces

LC patterned waveplates with electrically-tuned birefringence



Liquid-crystal metasurfaces

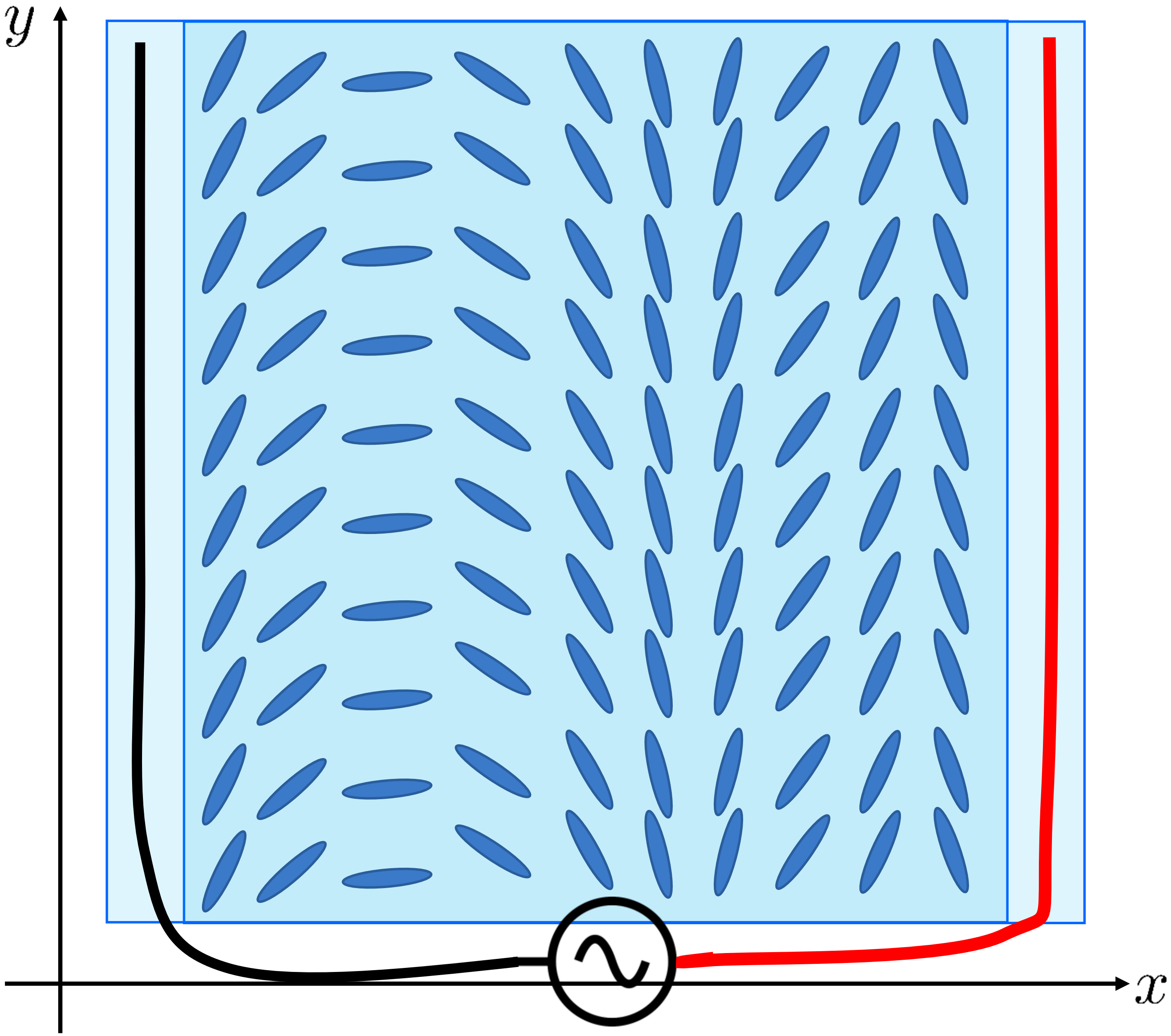
LC patterned waveplates with electrically-tuned birefringence



$$\theta(x, y)$$

Liquid-crystal metasurfaces

LC patterned waveplates with electrically-tuned birefringence



$\delta(V)$