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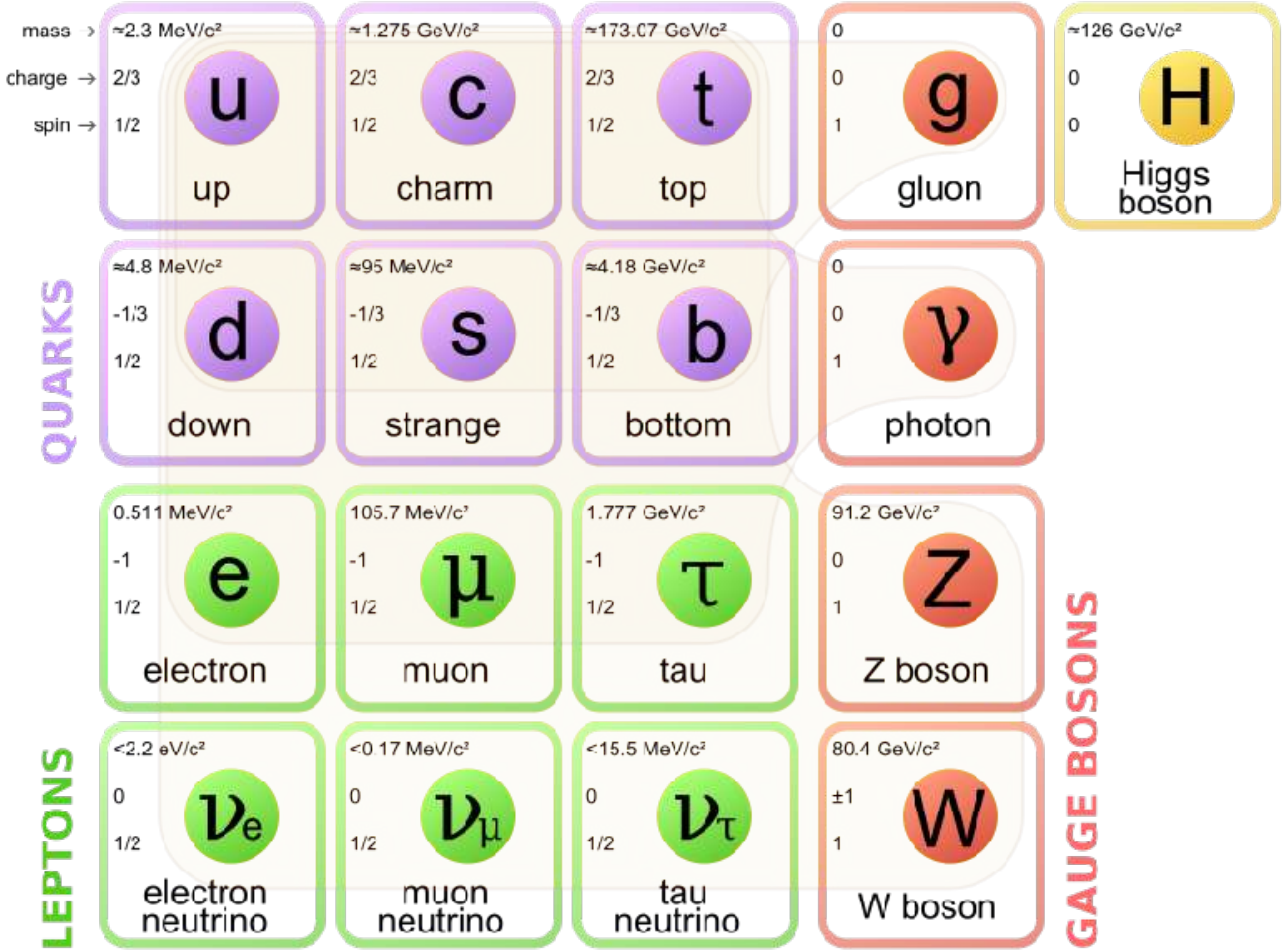
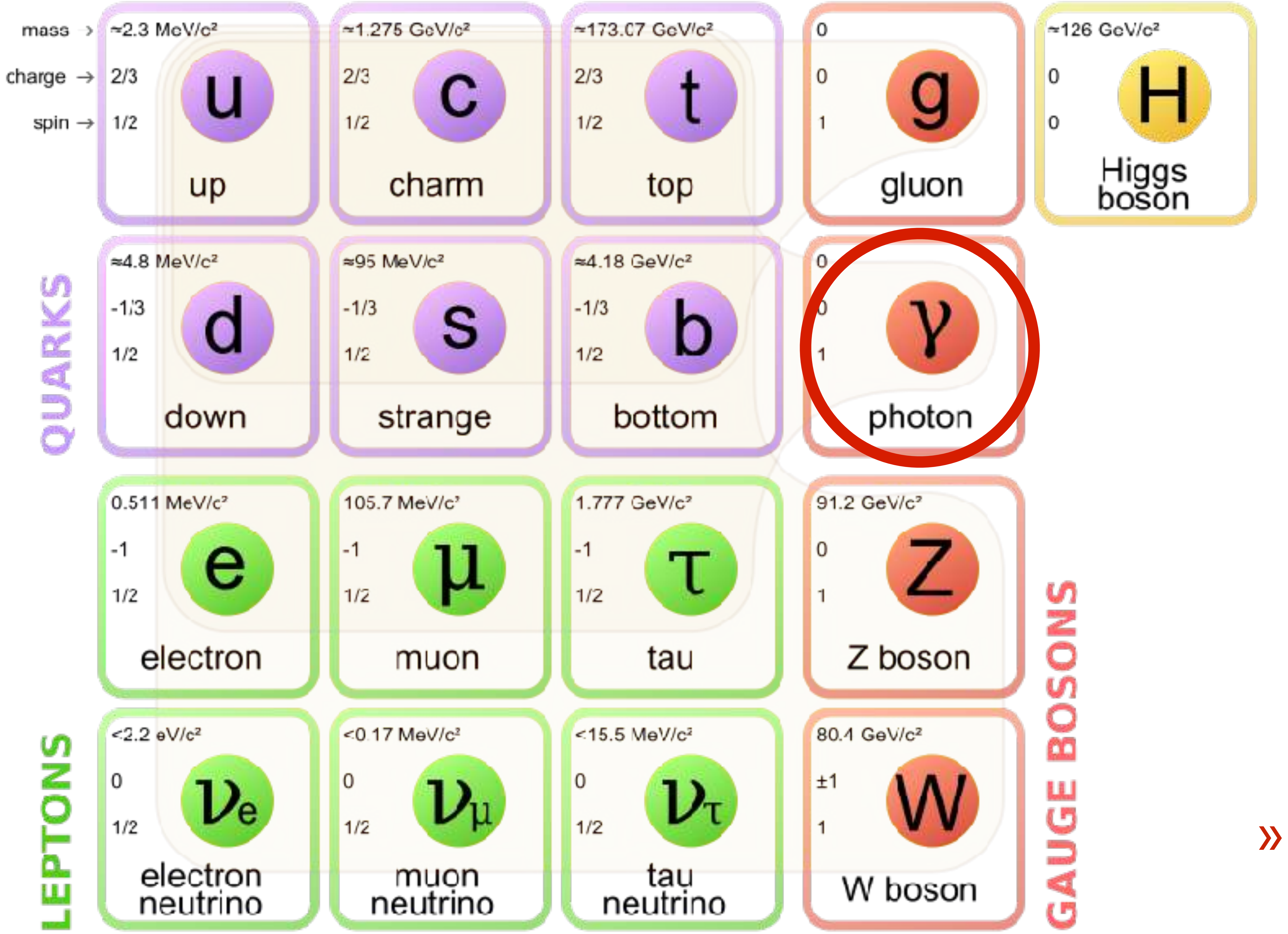
From Structured Photons to Structured Electrons

Présenté par : Ebrahim Karimi | Presented by: Ebrahim Karimi

Elementary particles



Elementary particles



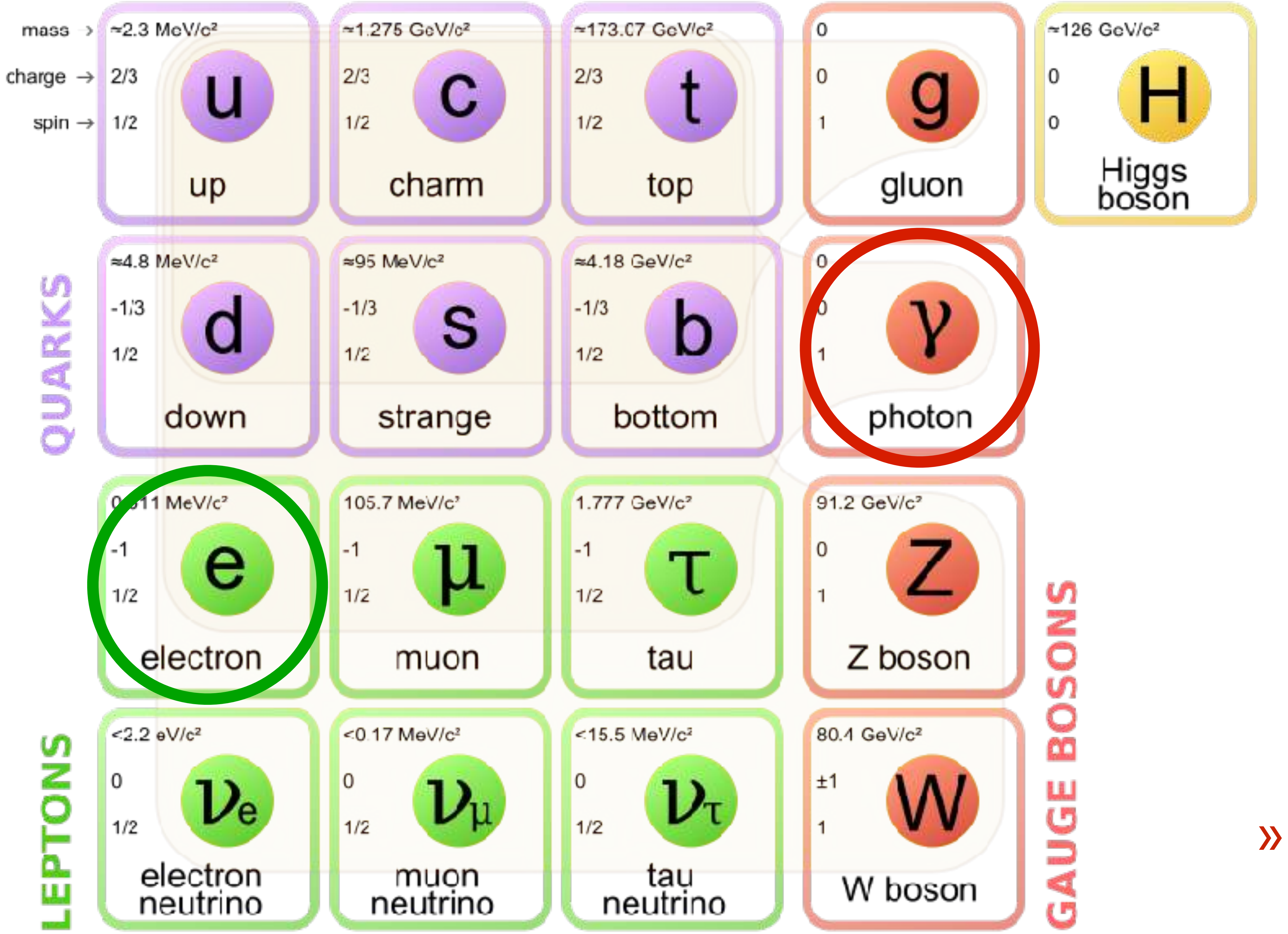
» An elementary particle

$$m_\gamma = 0\ kg$$

$$q_\gamma = 0\ C$$

$$|\mathbf{S}| = 1$$

Elementary particles



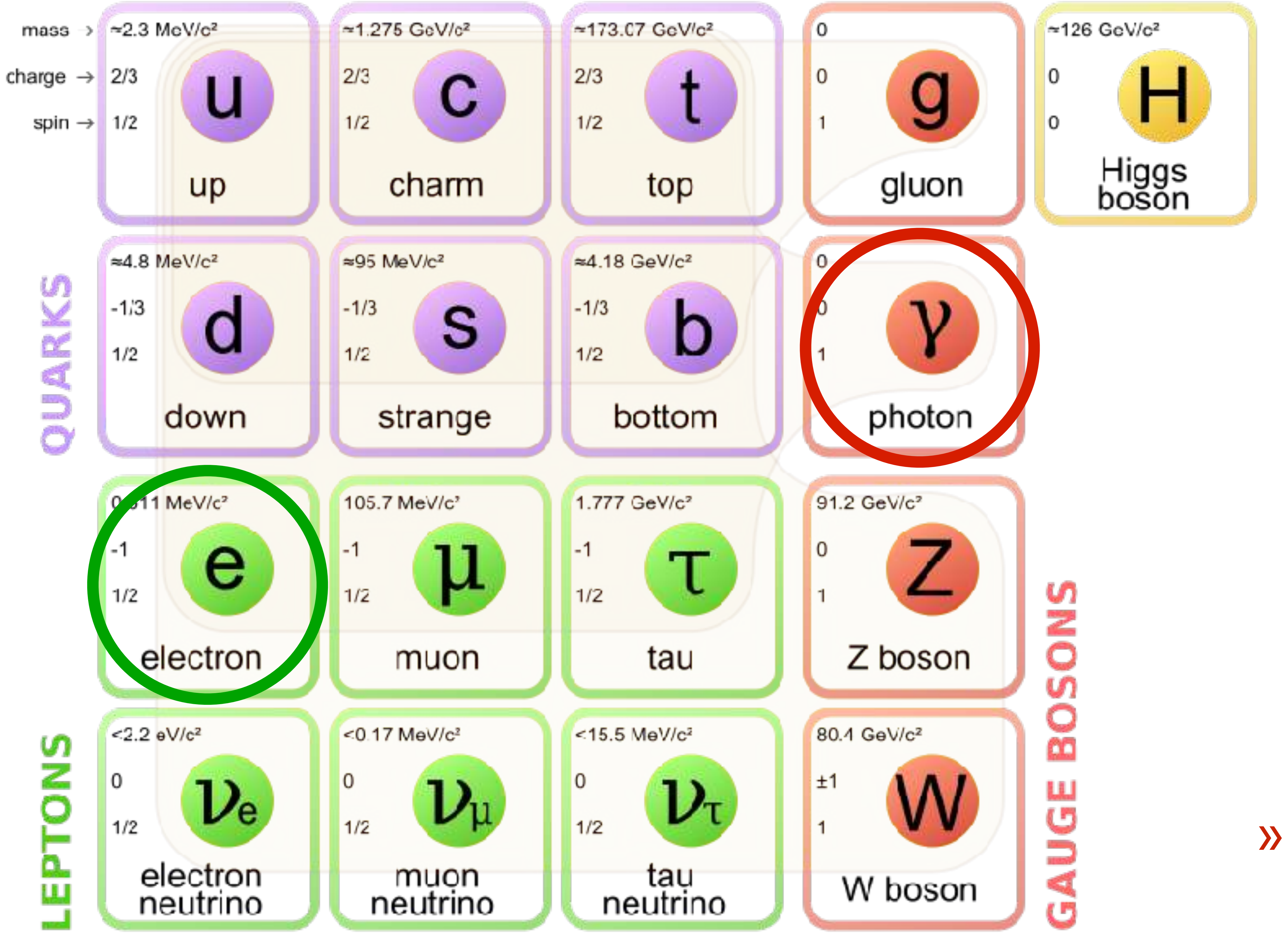
» An elementary particle

$$m_e = 9.10 \times 10^{-31}\, kg$$
$$e = -1.6 \times 10^{-19}\, C$$
$$|\mathbf{S}| = \frac{1}{2}$$

» An elementary particle

$$m_\gamma = 0\ kg$$
$$q_\gamma = 0\ C$$
$$|\mathbf{S}| = 1$$

Elementary particles



Electron
Proton
Photon
Neutron
Boson
…
…
…
Person

» An elementary particle

$$m_e = 9.10 \times 10^{-31}\, kg$$
$$e = -1.6 \times 10^{-19}\, C$$
$$|\mathbf{S}| = \frac{1}{2}$$

» An elementary particle

$$m_\gamma = 0\ kg$$
$$q_\gamma = 0\ C$$
$$|\mathbf{S}| = 1$$

Light: Maxwell's Equations

$$\nabla \cdot \mathbf{D} = \rho$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

Light: Maxwell's Equations

$$\nabla \cdot \mathbf{D} = \rho$$

$$\alpha^{\mu}\partial_{\mu}\mathcal{F}^{i} = 0$$
$$\partial_{i}\mathcal{F}^{i} = 0$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

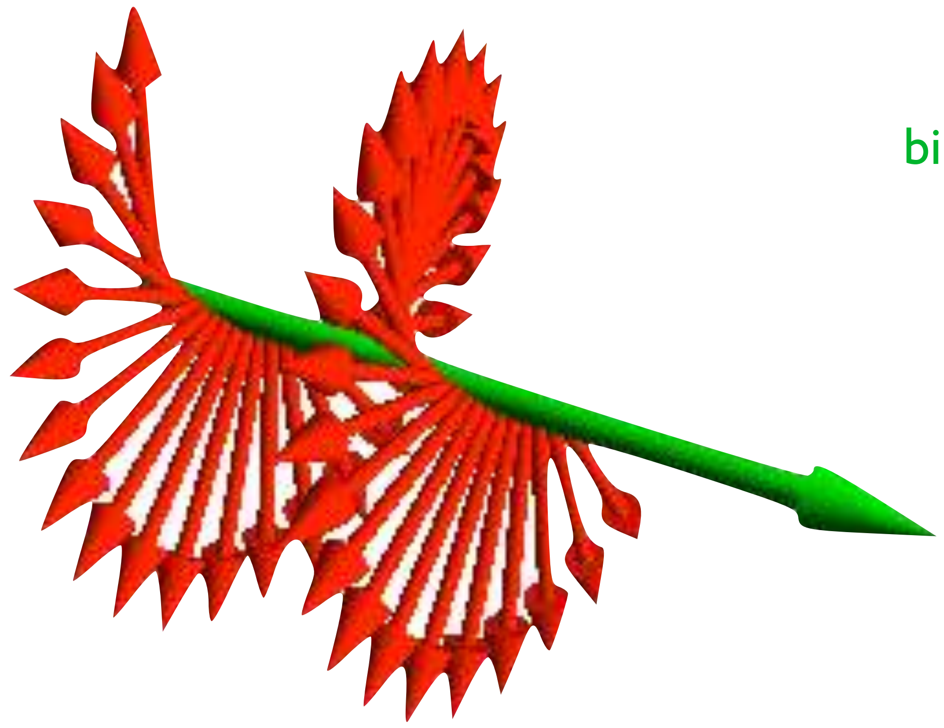
Light: Degrees of Freedom

continuous variable

Linear momentum (k-vector)

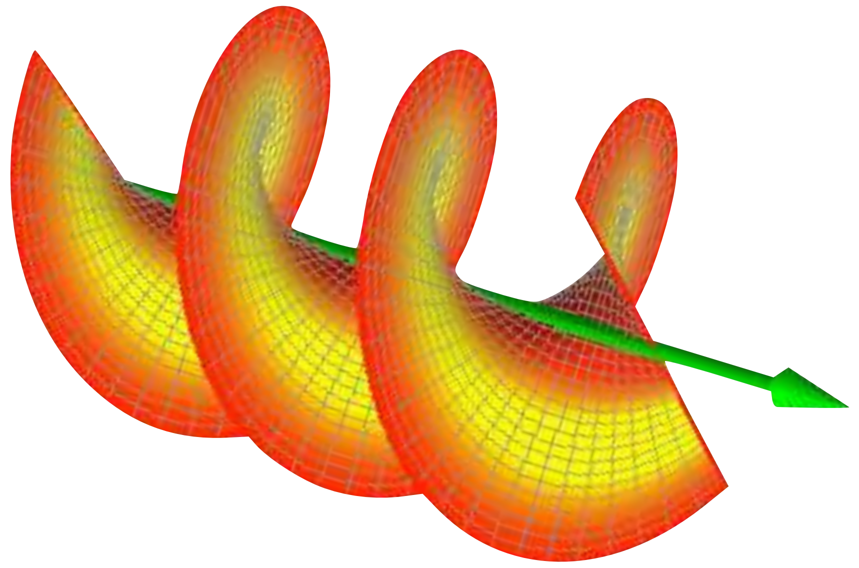
$|\kappa\rangle$

bi-dimensional variable



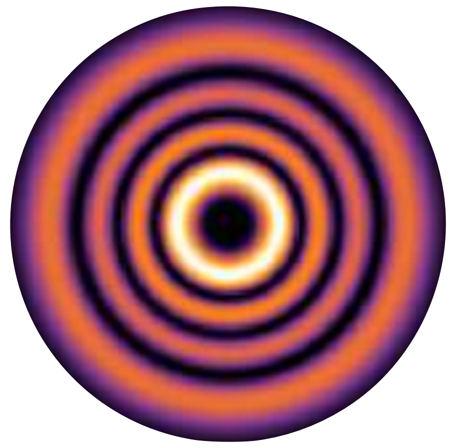
$|\pi\rangle$ Polarisation (Spin)

Orbital angular momentum (OAM)



$|o\rangle$

infinite dimension (discrete)



$|p\rangle$ Radial mode (p number)

infinite dimension (discrete)

E. K. & E Santamato, *Optics Letters* **37**, 2484 (2012).
E. K., et al., *Phys. Rev. A* **89**, 063813 (2014).

H. Rubinsztein-Dunlop *et al.*, Roadmap on structured light, *Journal of Optics* **19**, 013001 (2017).

Structured Photons

$$|\psi\rangle = \sum_{\omega,\sigma,n,p,\ell} c^{\omega,\sigma}_{n,p,\ell}\,|\omega,\sigma,n,p,\ell\rangle$$

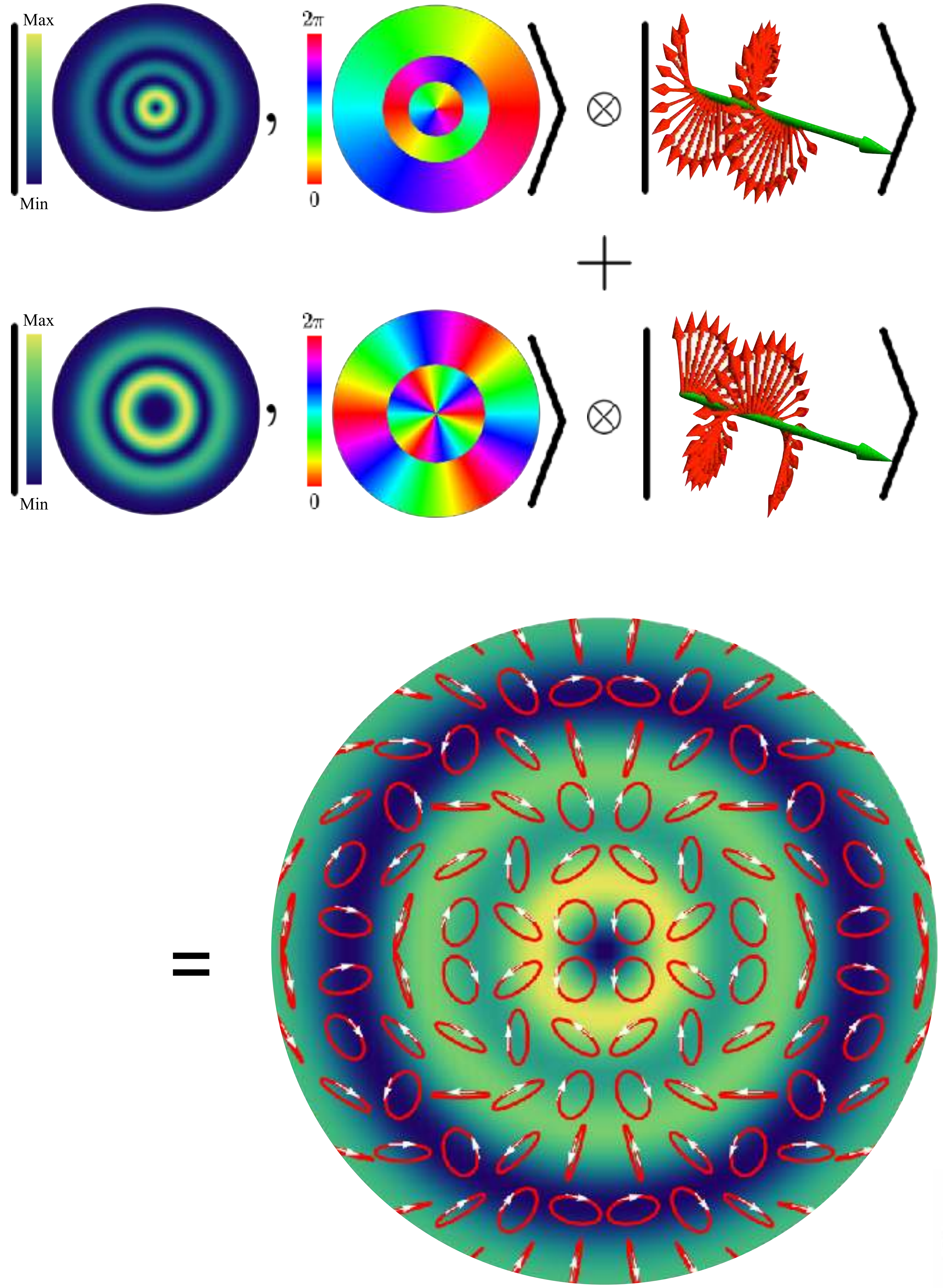
$\omega \in \mathbb{R}$

$\sigma \in \{-1,+1\}$

$n \in \mathbb{Z}^+$

$p \in \mathbb{Z}^+$

$\ell \in \mathbb{Z}$



E. K. & E Santamato, *Optics Letters* **37**, 2484 (2012).
E. K., et al., *Phys. Rev. A* **89**, 063813 (2014).

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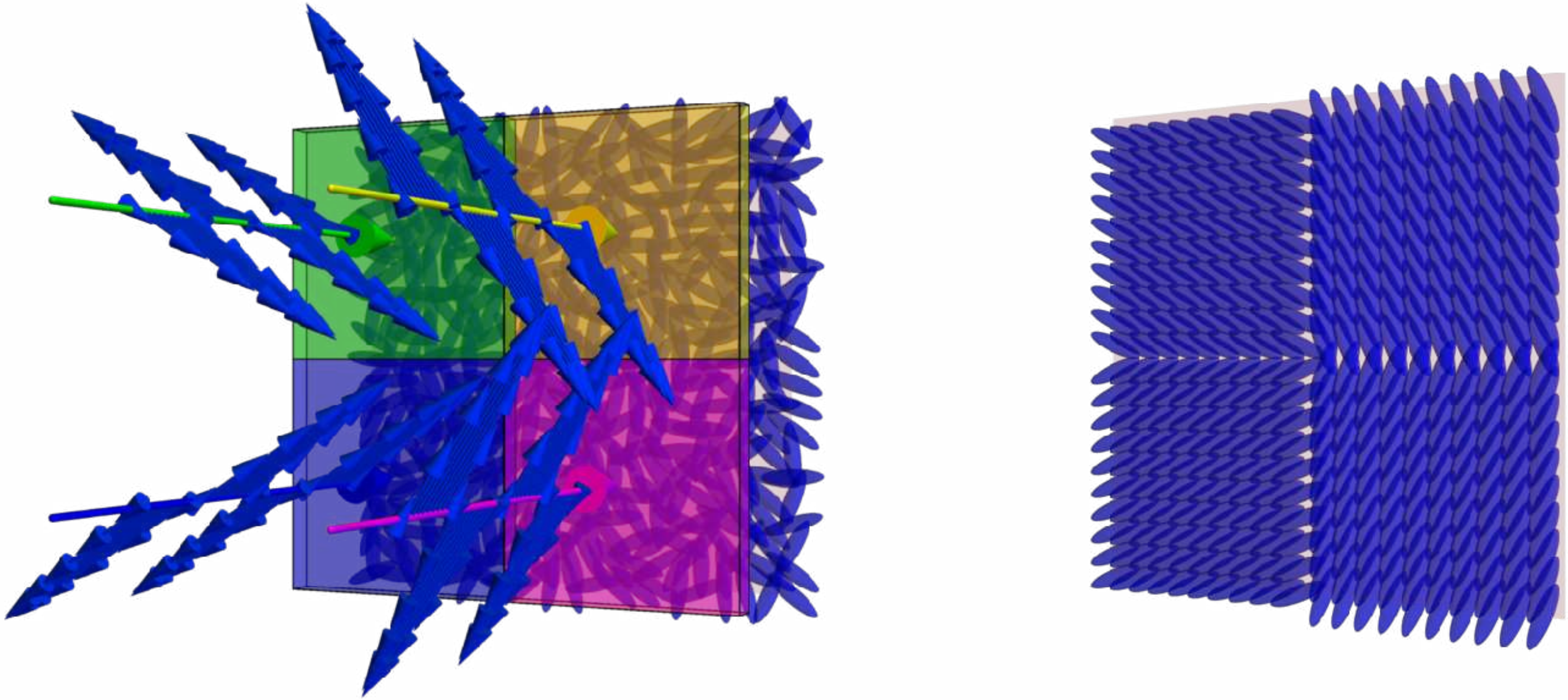
E.K. and R W Boyd, *Science* **350**, 1172 (2015).

Structured Photons

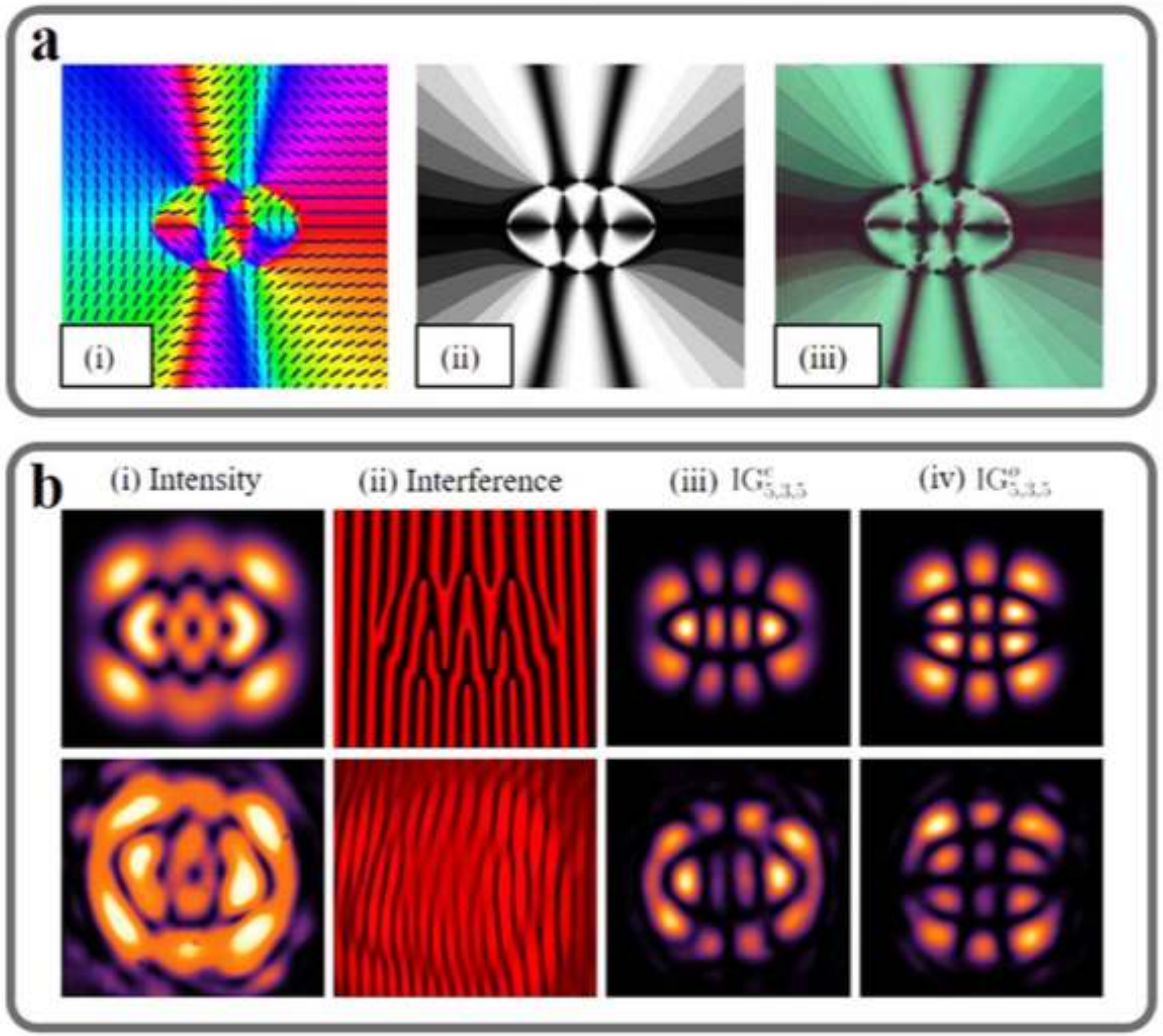
A. Sit, F. Hufnagel, E.K., in Press (2021).

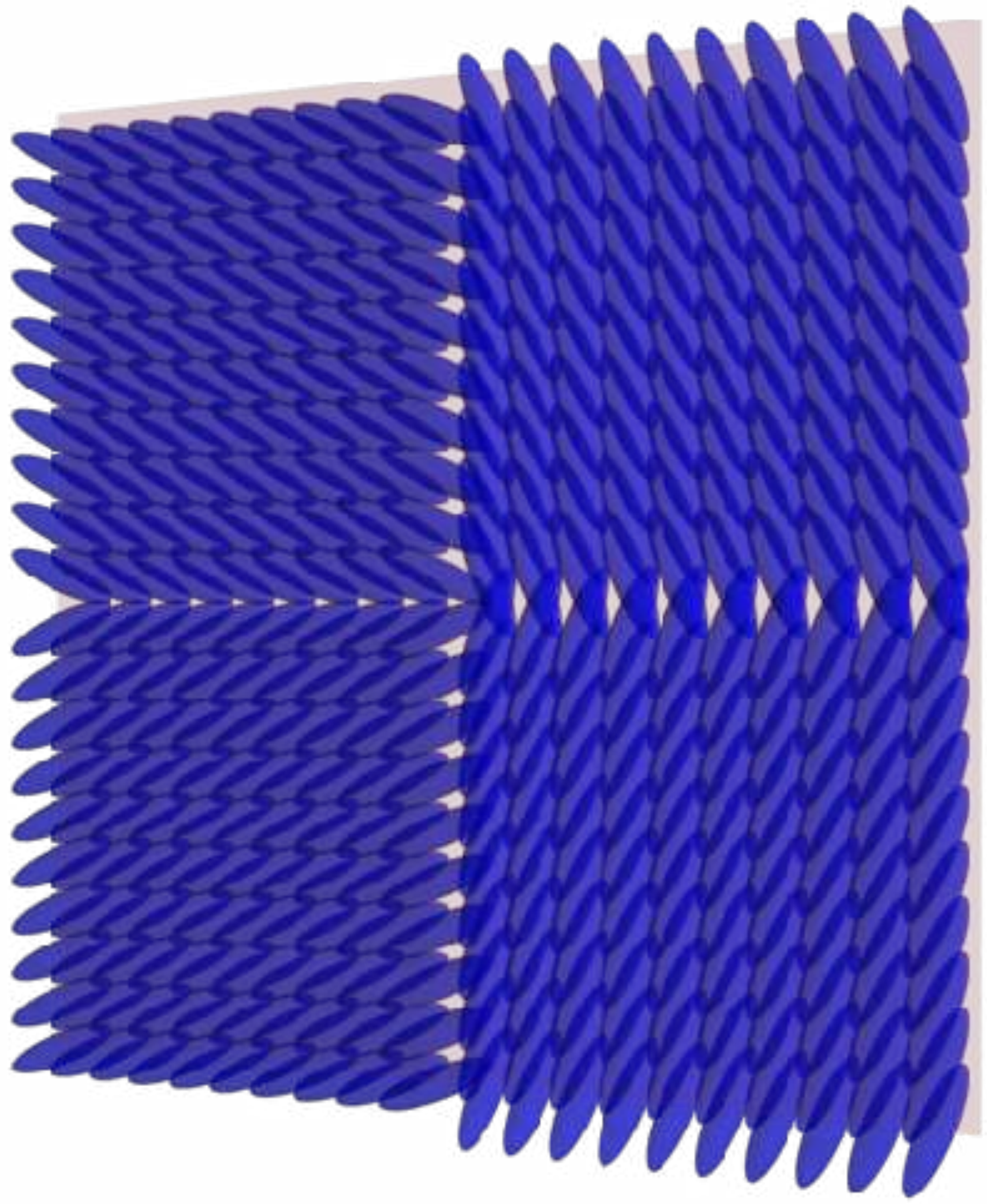
Generation: Liquid Crystal



H Larocque, J Gagnon-Bischoff, F Bouchard, R Fickler, J Upham, R W Boyd & E K, *Journal of Optics* **18**, 124002 (2016)
E Cohen, H Larocque, F Bouchard, F Nejadsattari, Y Gefen & E.K., *Nature Reviews Physics* **1,** 437 (2019).

Generation: Liquid Crystal





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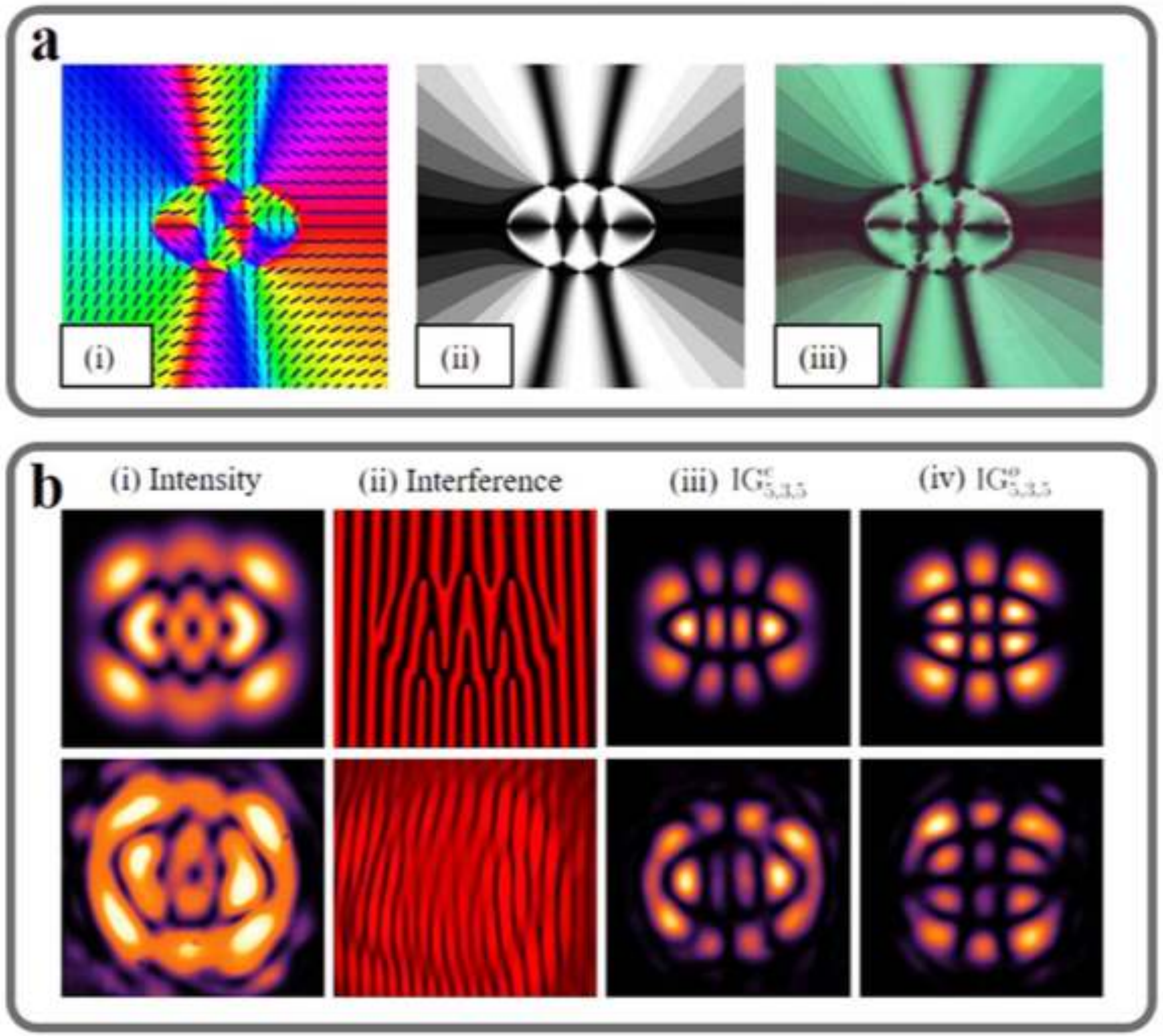

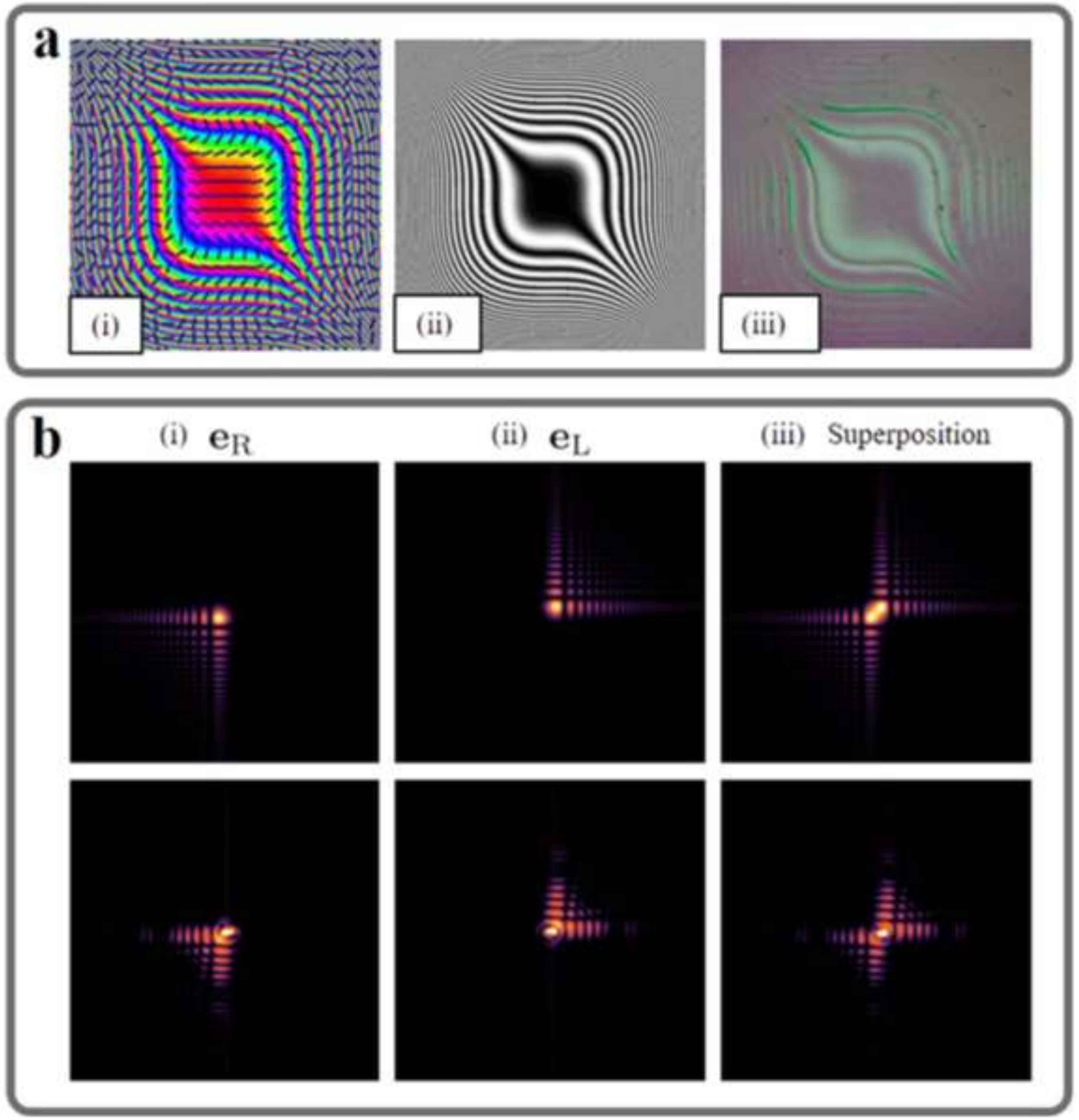

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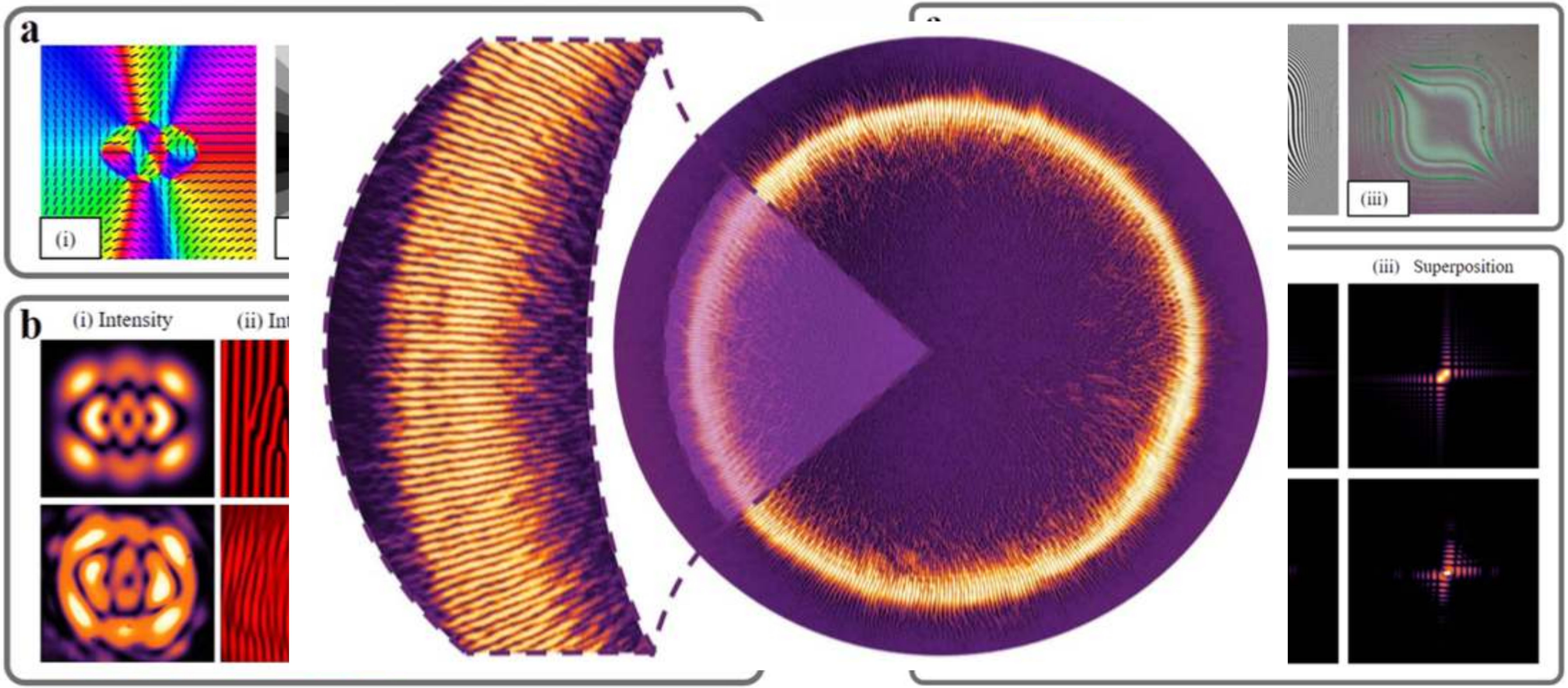

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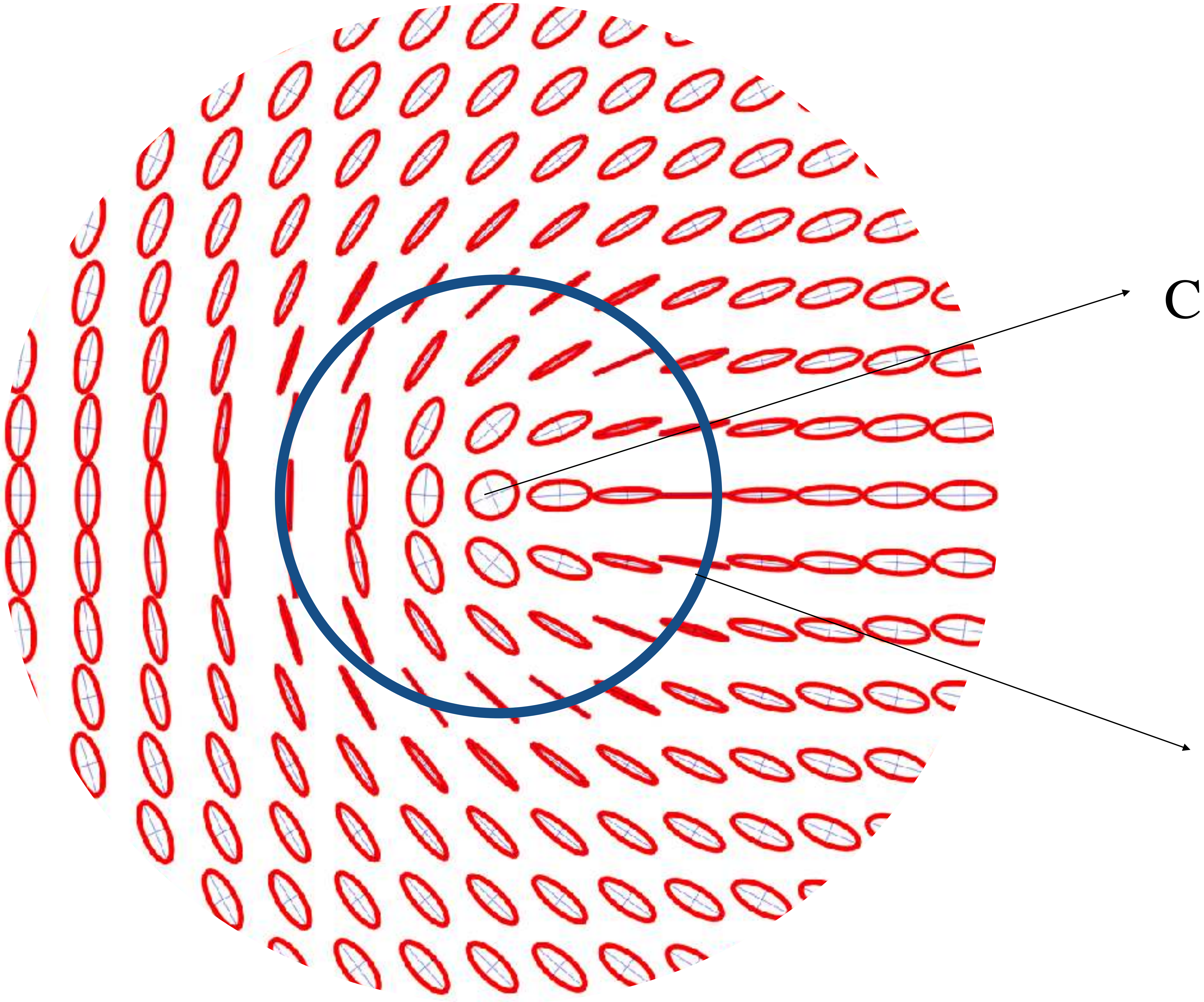
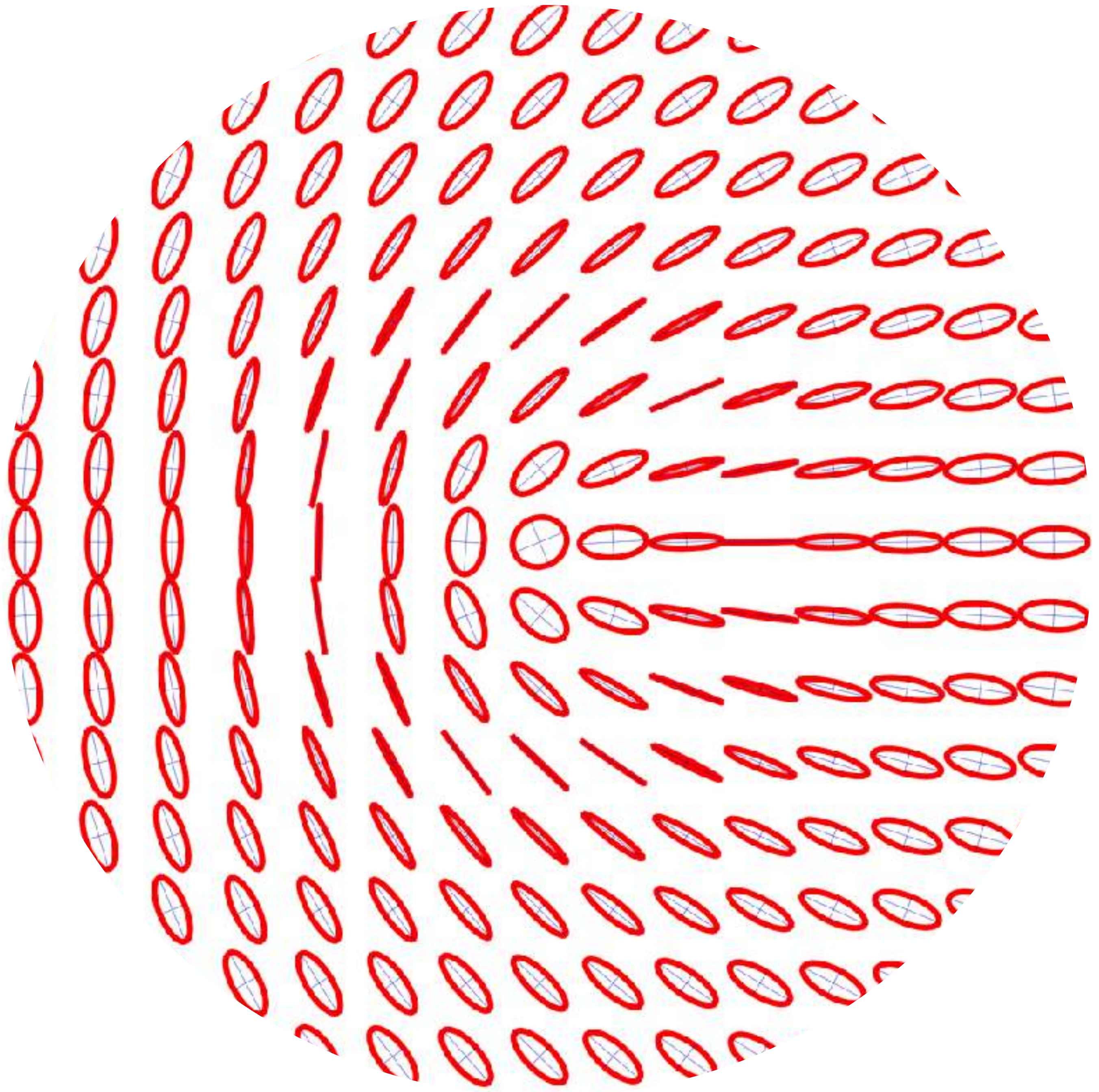
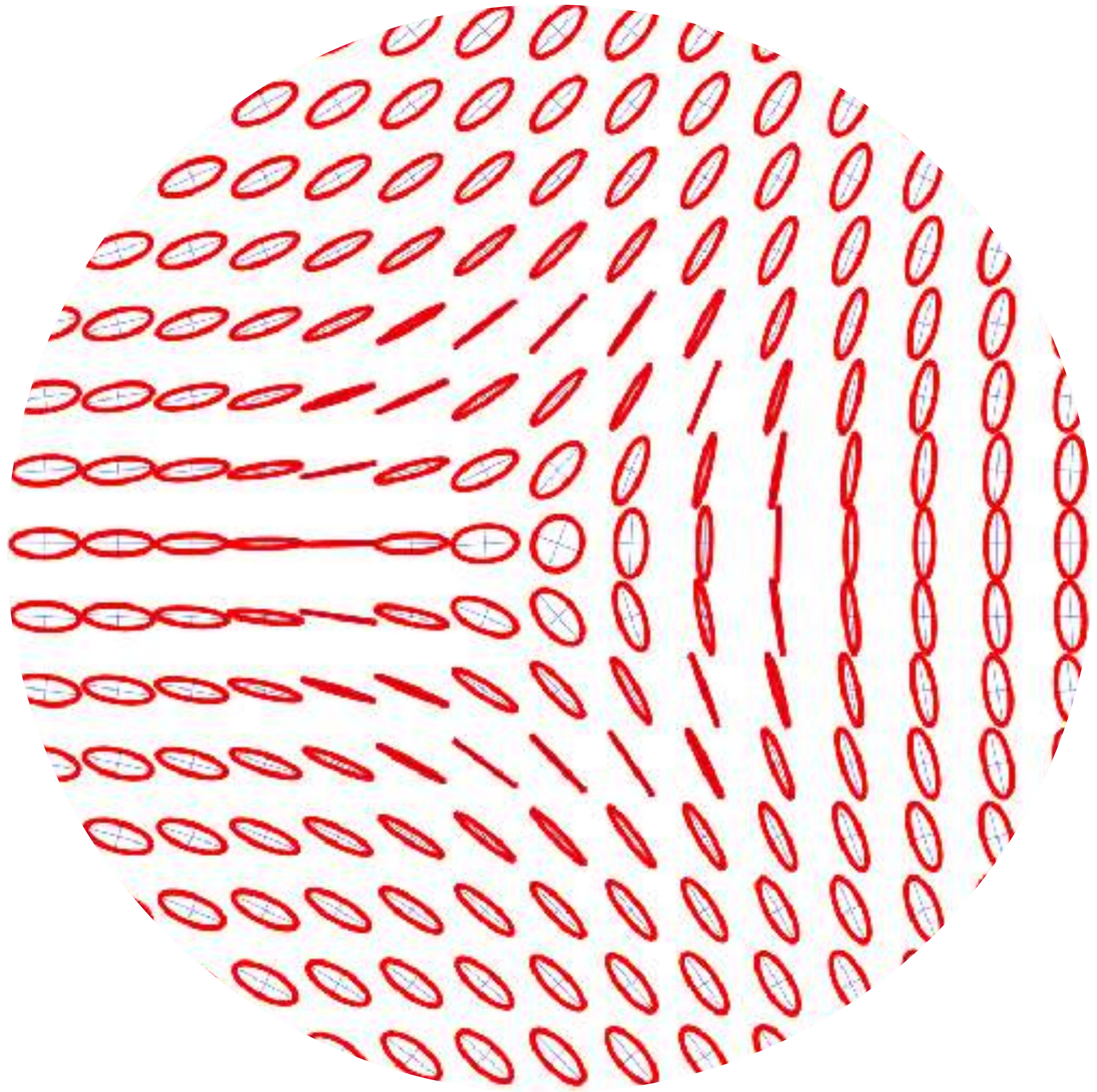
Polarisation topologies: polarisation singularity



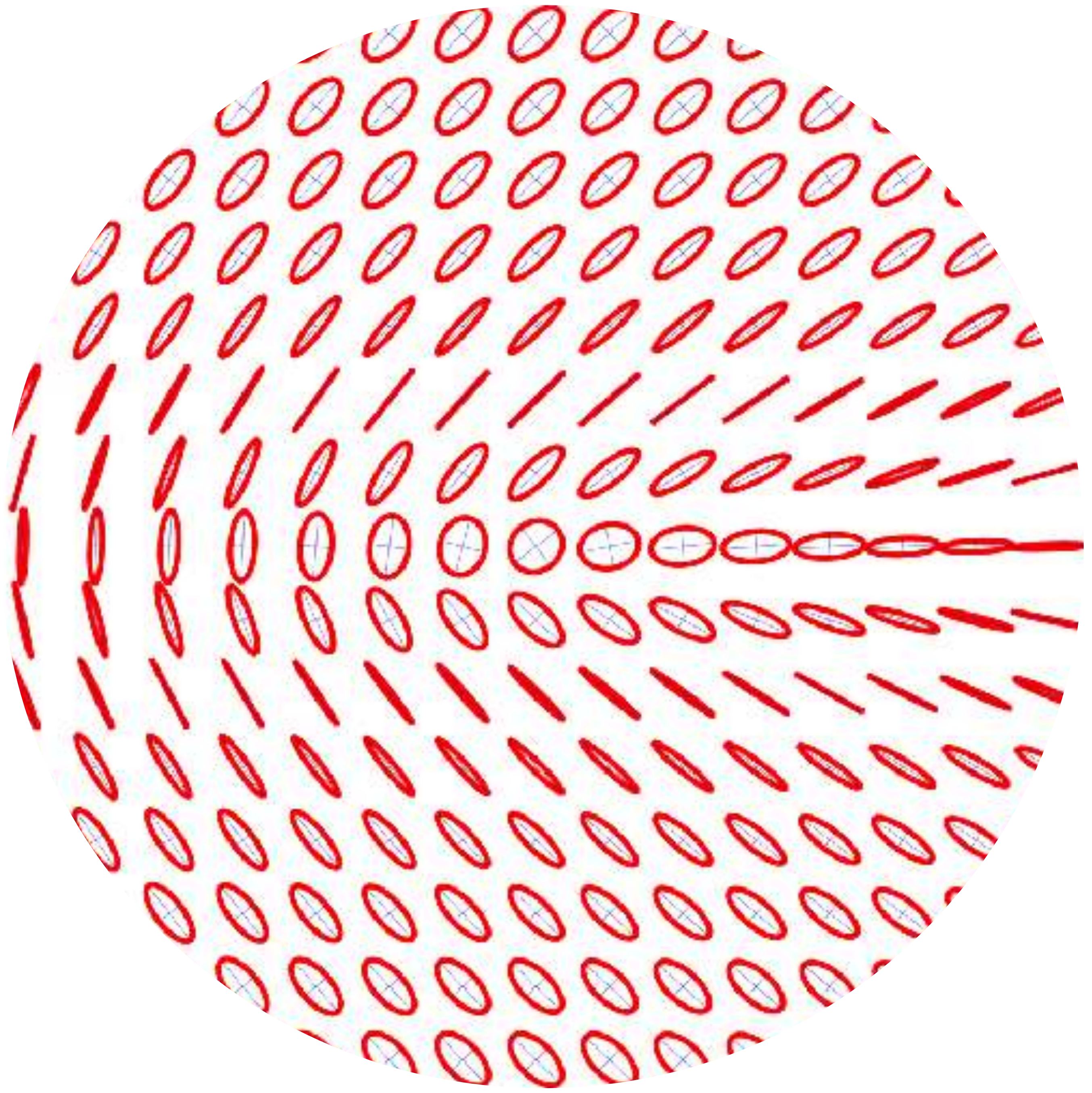
Major polarisation topologies



Lemon



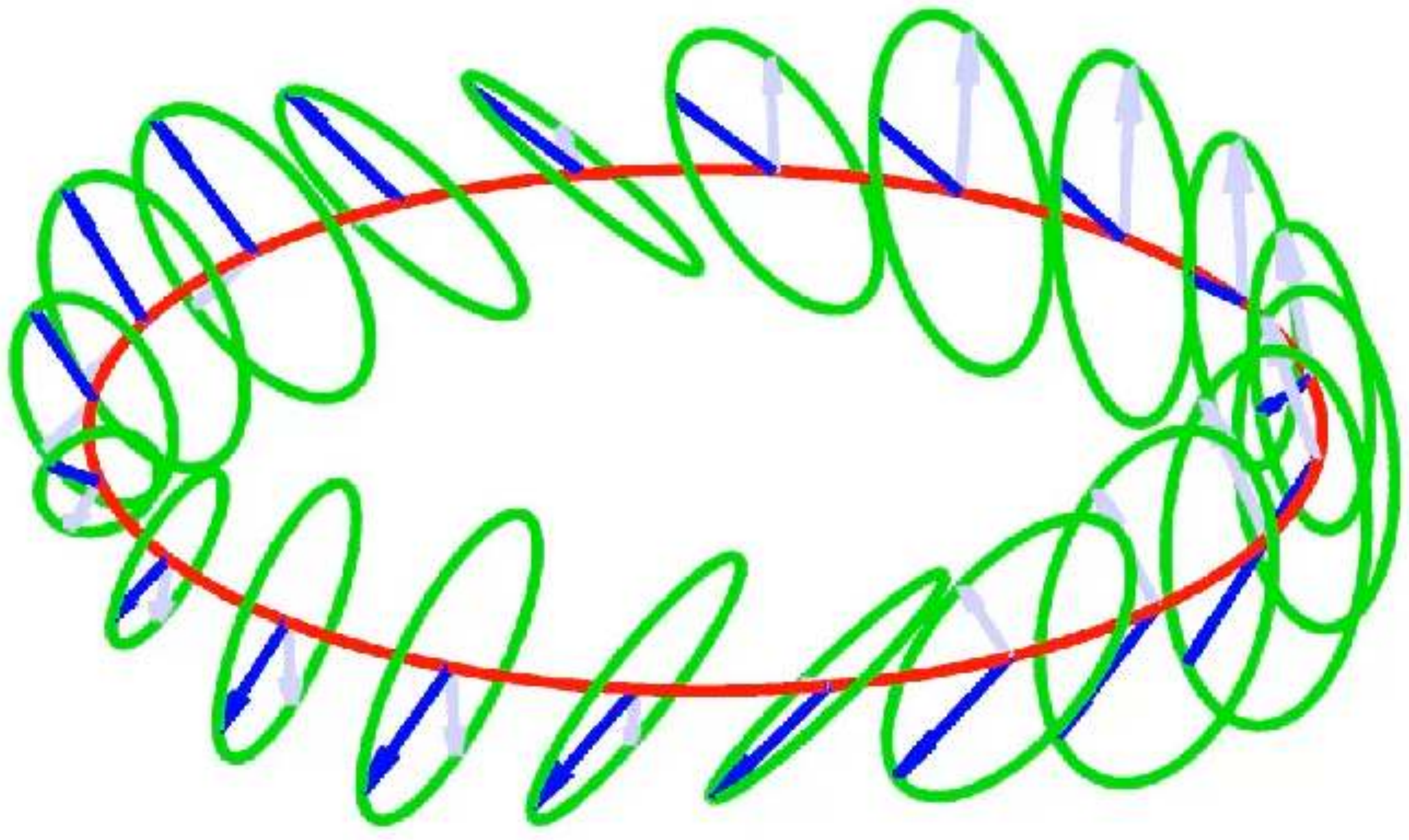
Star



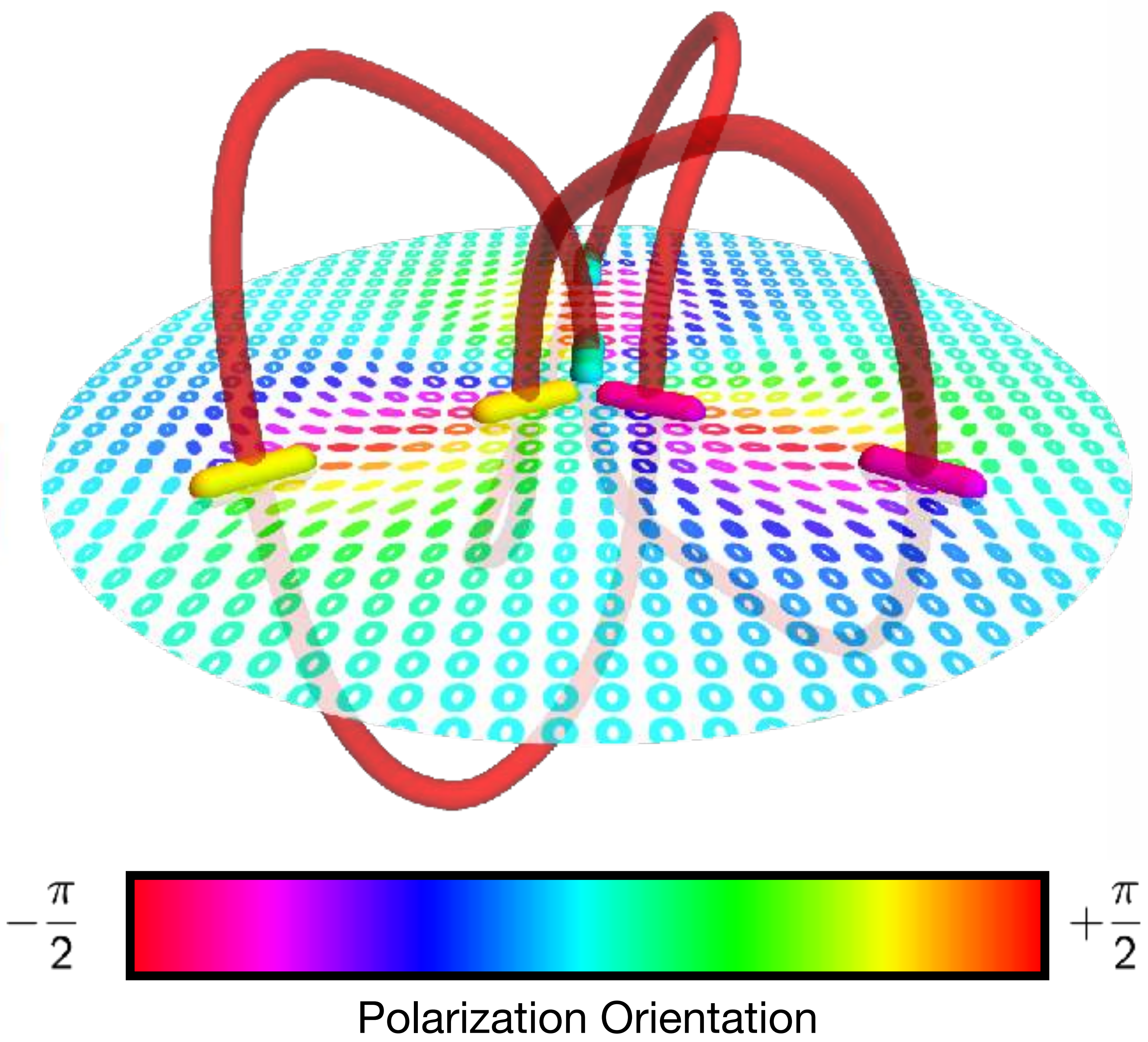
Monstar

3D Polarisation Topologies

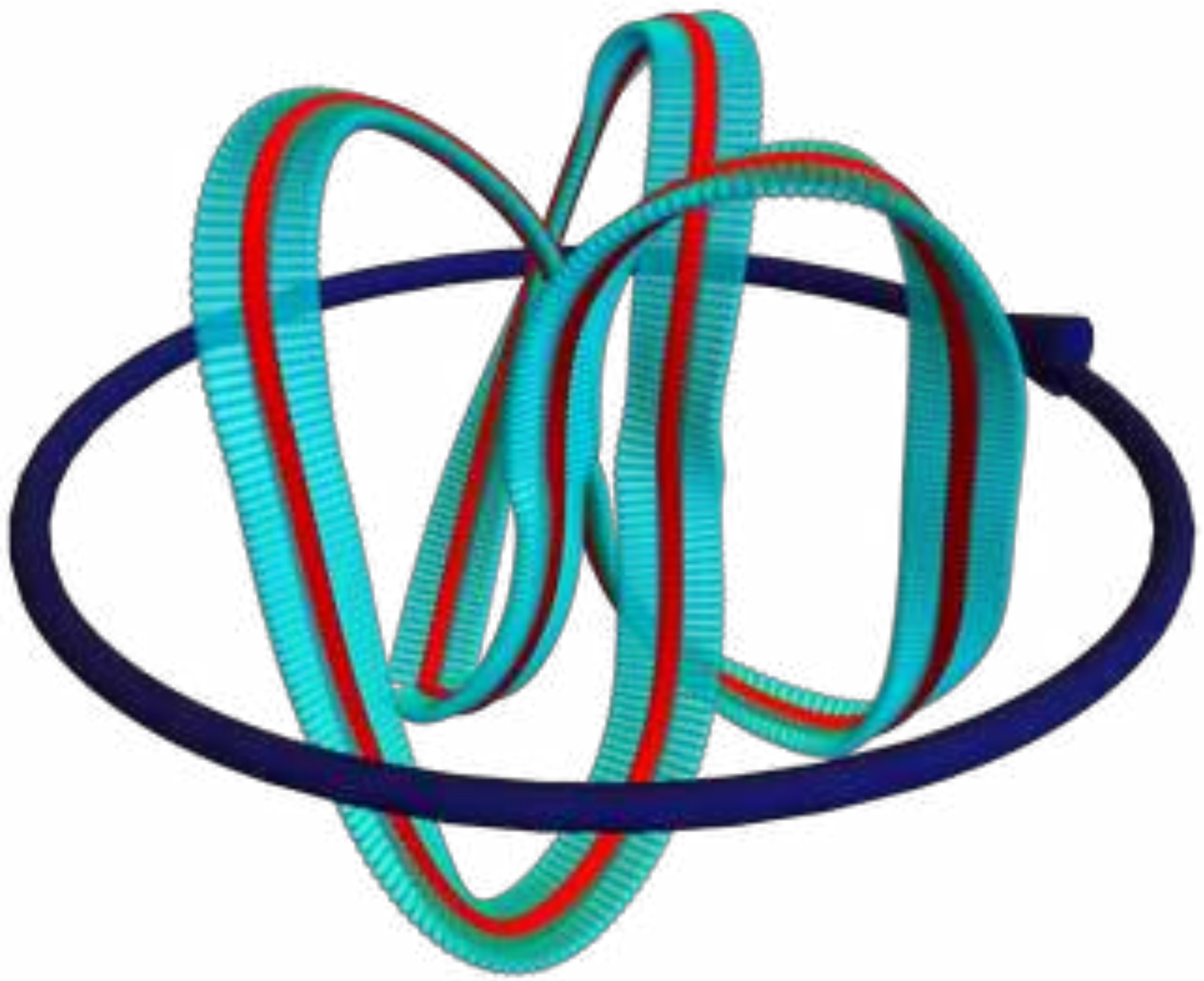
Möbius



Knots



Framed Knots



H Larocque, A D'Errico, M Ferrer, A Carmy, E Cohen & E. K., *Nature Communications* **11**, 5119 (2020).
H Larocque, D Sugic, D Mortimer, A J Taylor, R Fickler, R W Boyd, M R Dennis & E. K. *Nature Physics* **14**, 1079 (2018).
T Bauer, P Banzer, E. K., S Orlov, A Rubano, L Marrucci, E Santamato, R W Boyd, G Leuchs, *Science* **29**, 1260635 (2015).

3D Polarisation Topologies

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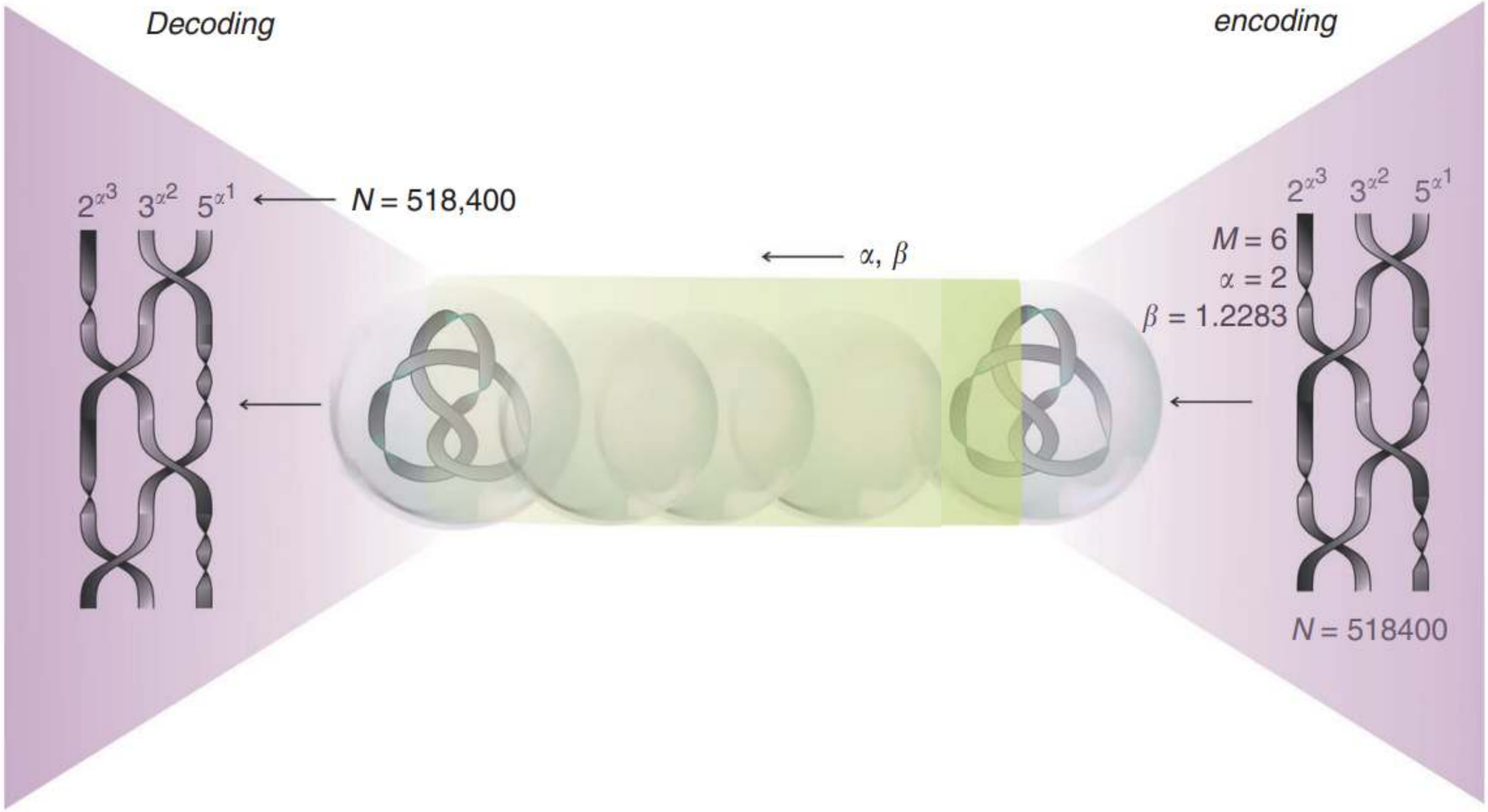
Framed-Knot as information carrier

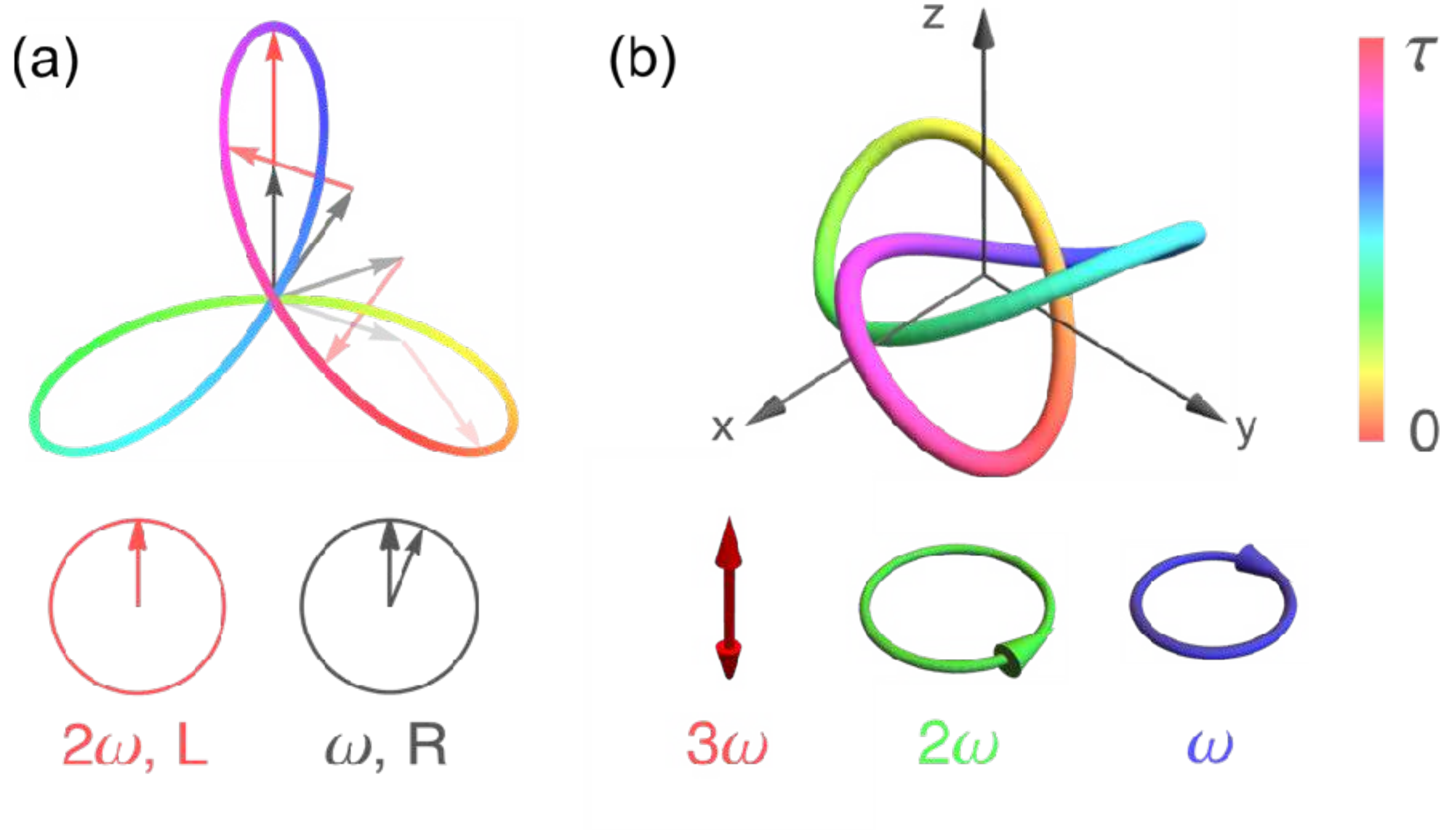
Encode a large integer N in prime numbers as follows

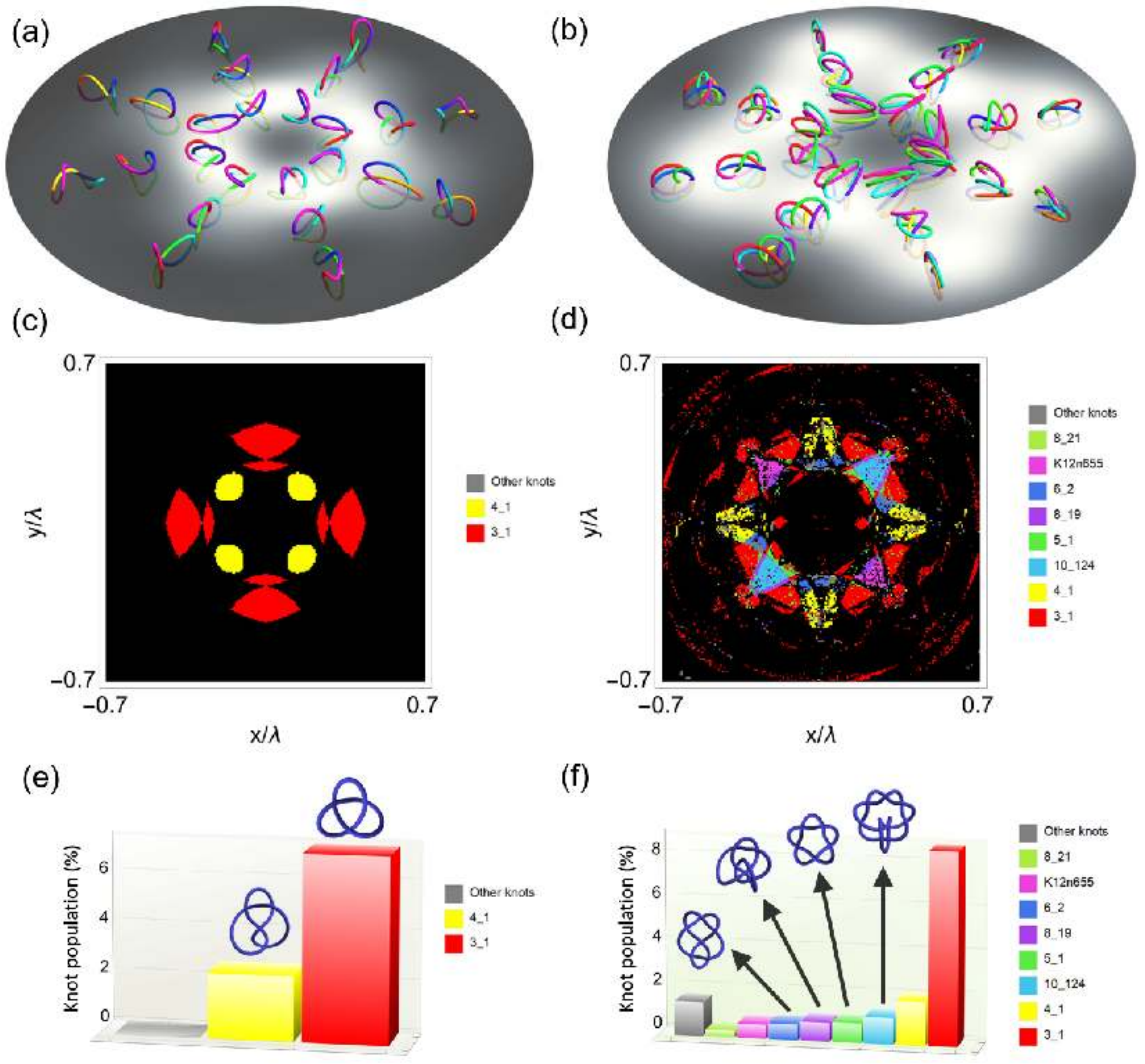
- Assign to each strand a prime number p_k
- In each strand the number of half twists is d_k (if there are no twists d_k = -∞)
- Choose a positive number α (to be shared with the receiver)
- The integer N is given by $N = \Pi_{k=1}^{n} p_k^{(\alpha)_k^d}$



H. Larocque, A. D'Errico, M. Ferrer, A. Carmy, E Cohen & E. K., *Nature Communications* **11**, 5119 (2020).

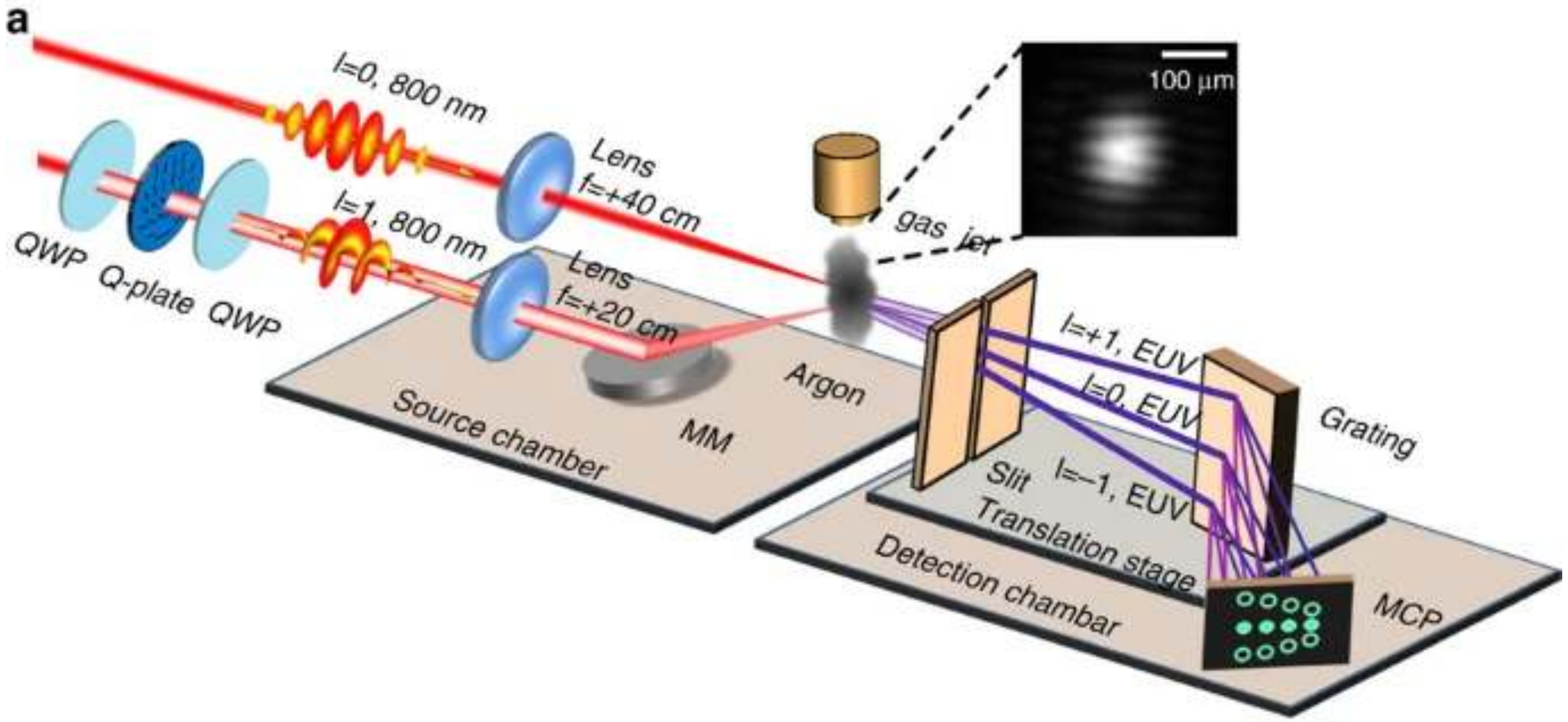
Novel Topologies: Polychromatic structured Light

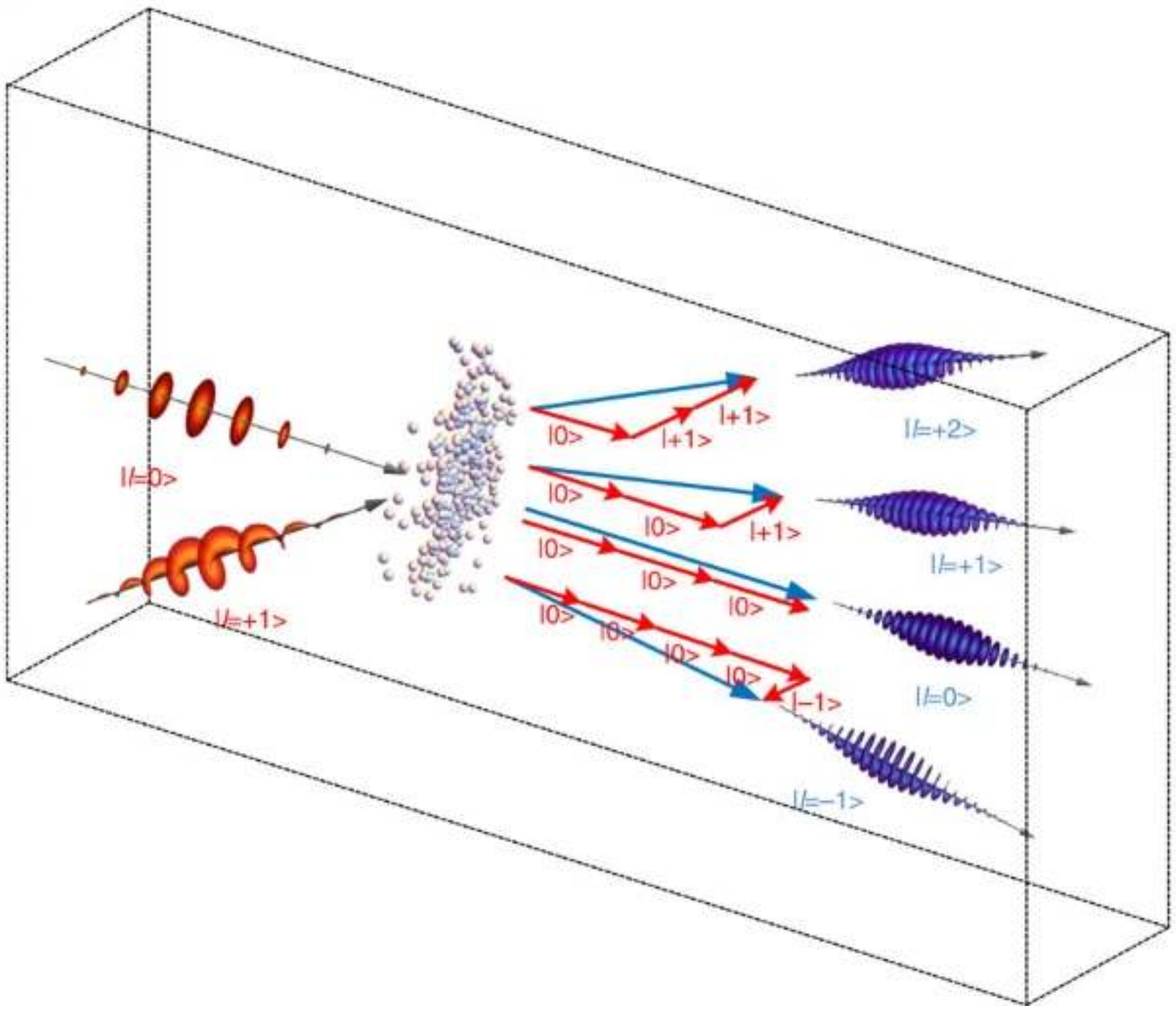




M Ferrer, A D'Errico, A Sit & E. K., *arXiv:2103.06958*.

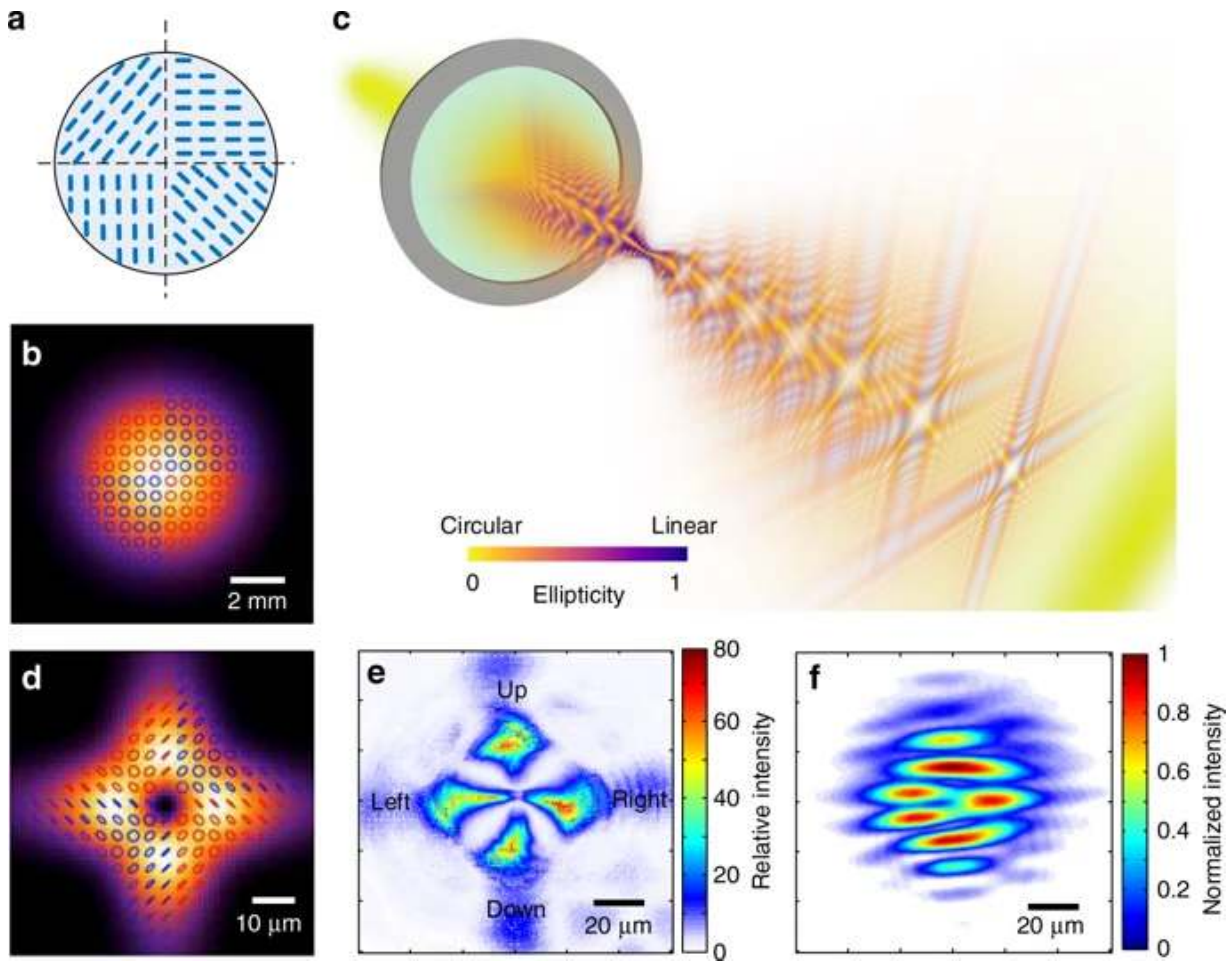
Structured Light at XUV regime

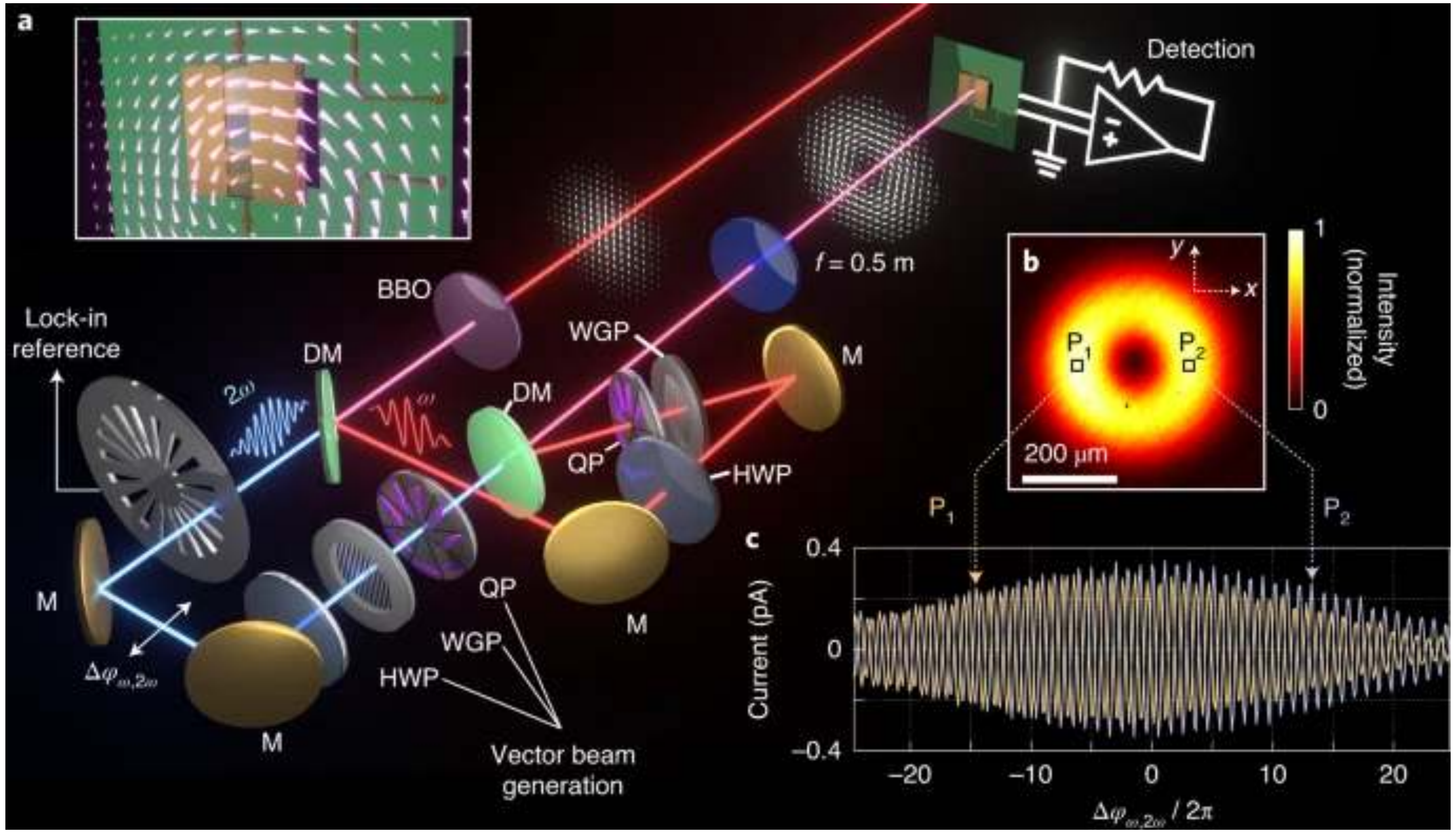




F Kong, C Zhang, F Bouchard, Z Li, G G Brown, D H Ko, T J Hammond, L Arissian, R W Boyd, E.K. & P B Corkum, *Nature Communications* **8**, 14970 (2017).

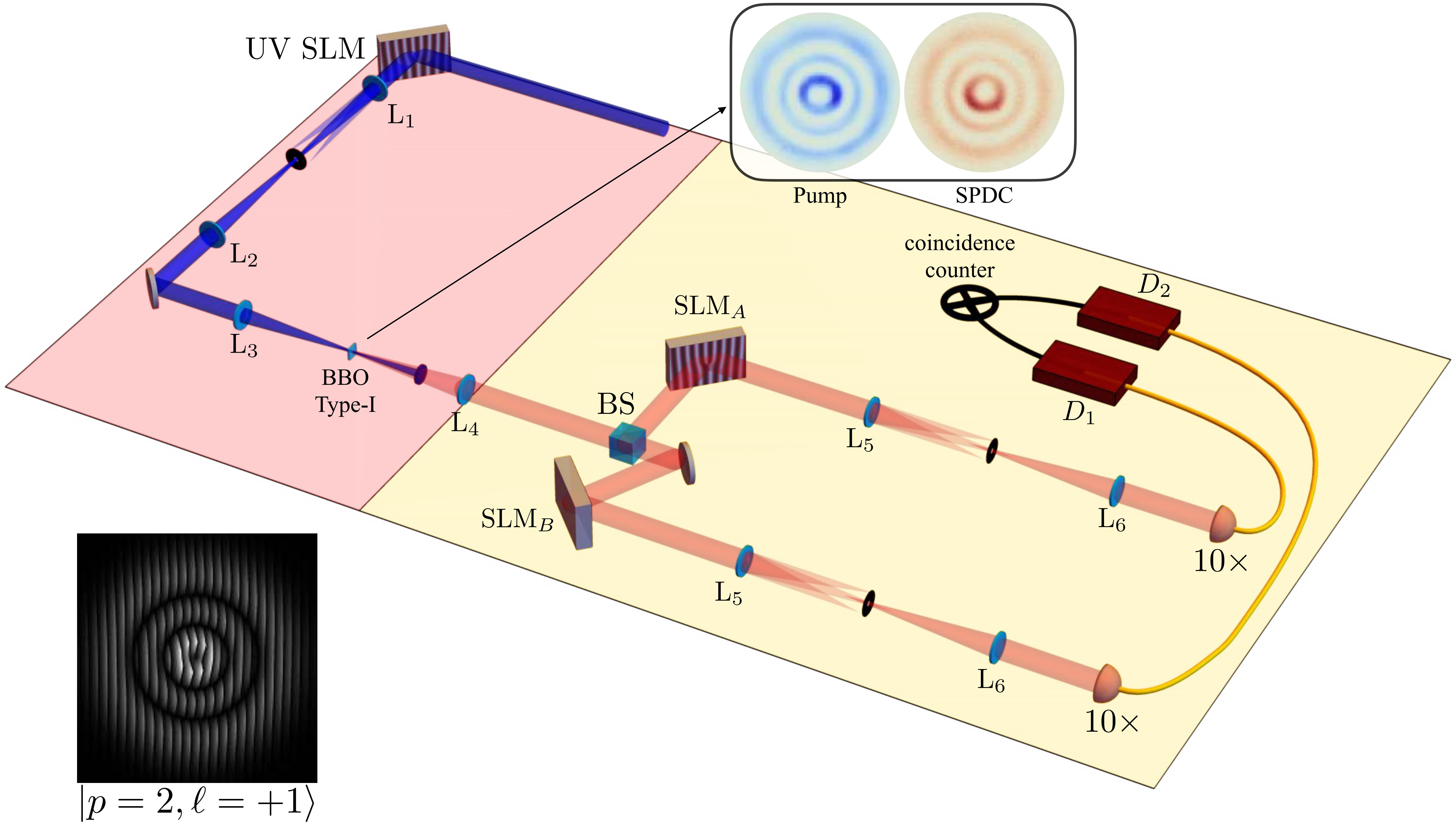
Structured Light at XUV regime

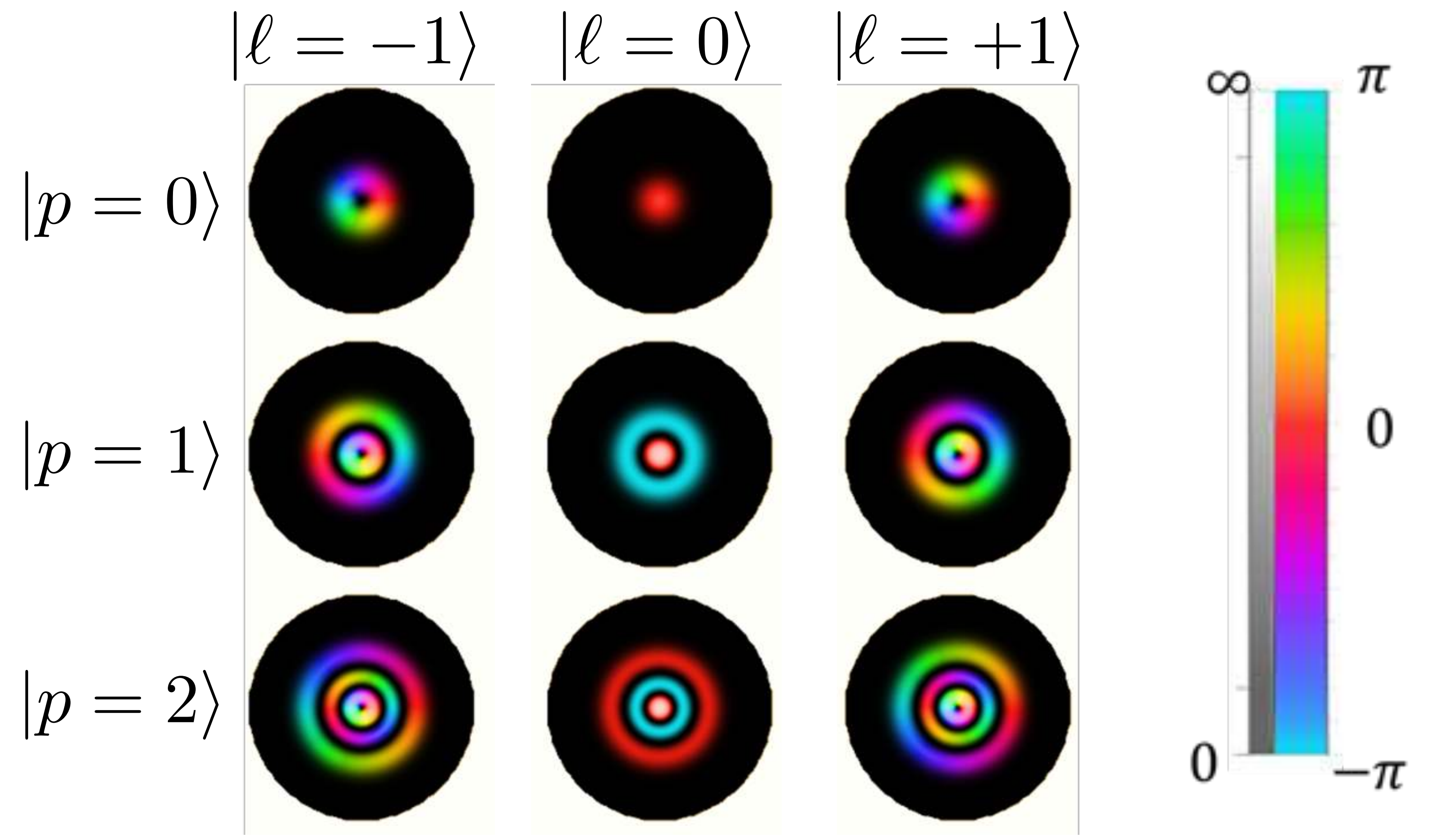


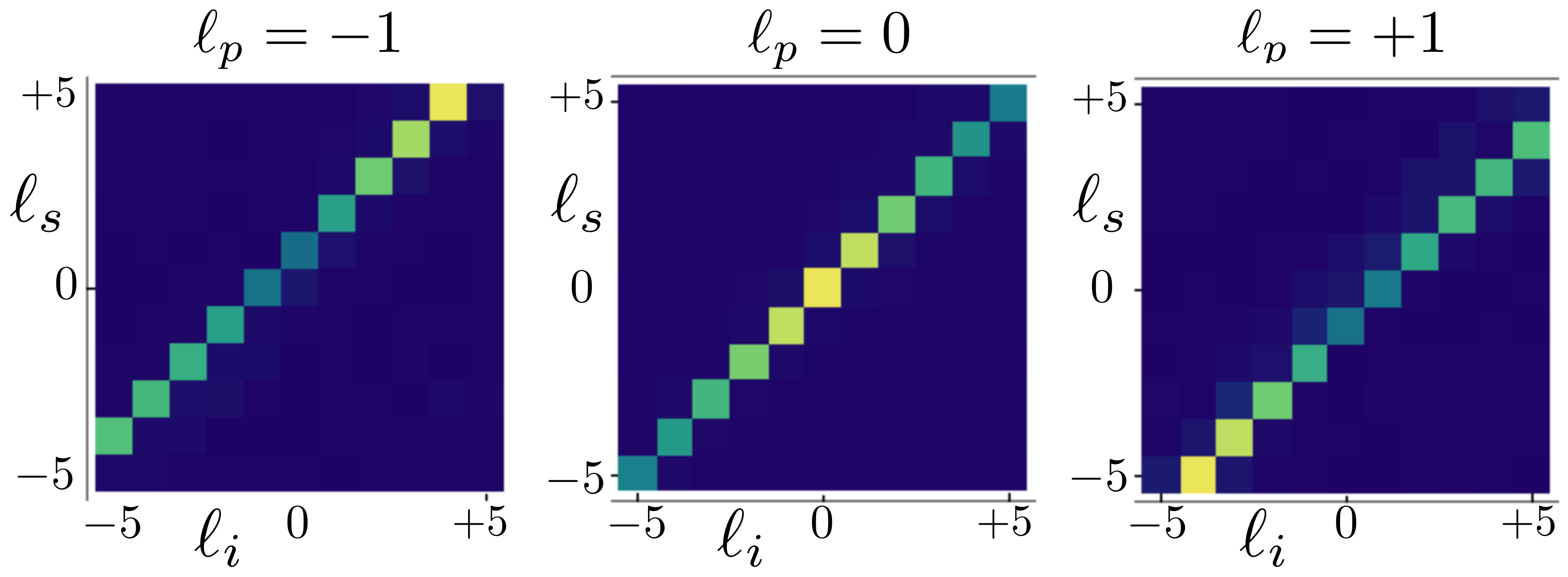


F Kong, C. Zhang, H. Larocque, Z. Li, F. Bouchard, D. H. Ko, G. G. Brown, A. Korobenko, T. J. Hammond, Robert W. Boyd, E. K. & P. B. Corkum, *Nature Communications* **10**, 2020 (2019)
S Sederberg, F Kong, F Hufnagel, C Zhang, E. K. & P B. Corkum, *Nature Photonics* **14**, 680 (2020).

High-dimensional Entangled States

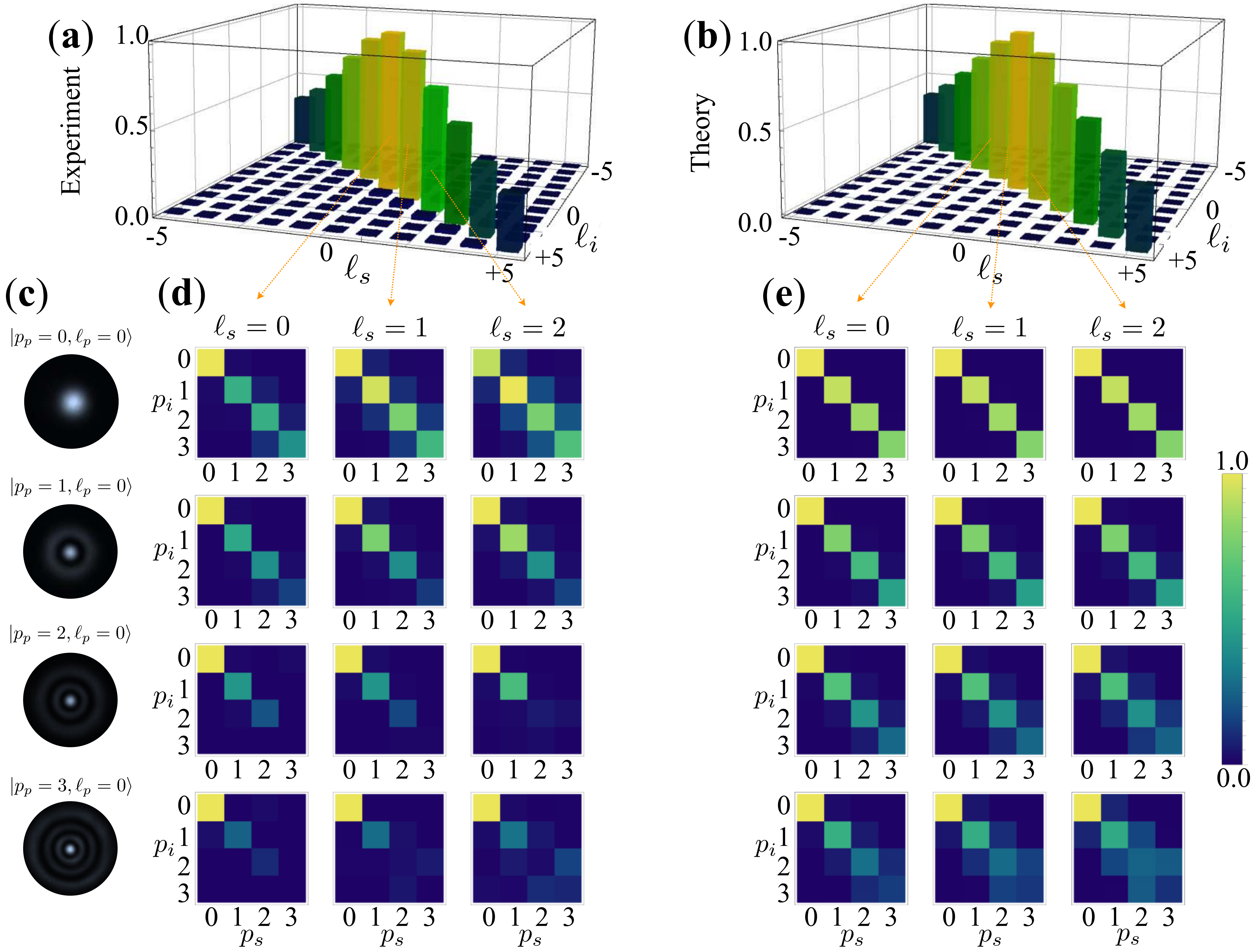


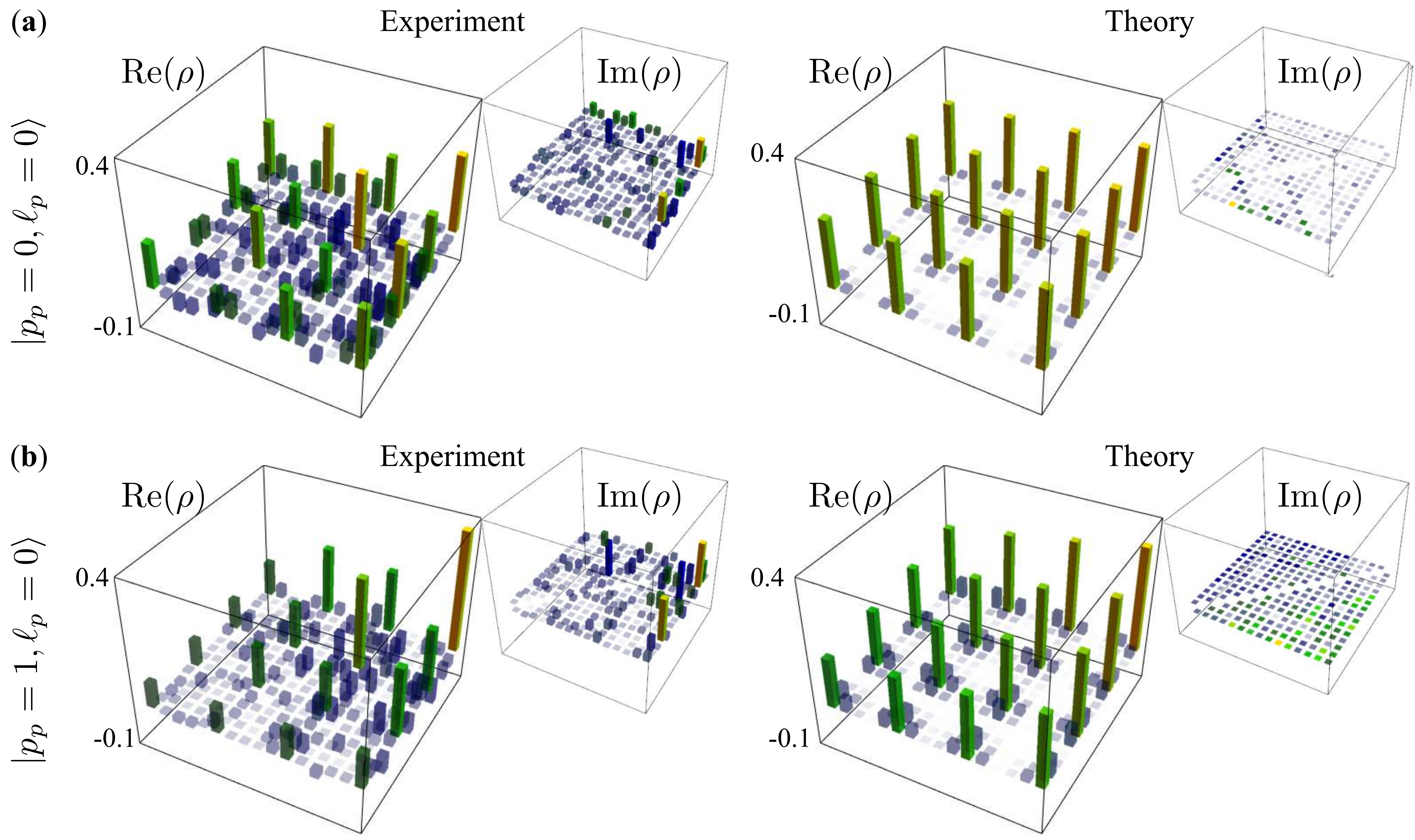




A. D'Ericco, F. Hufnagel, F Miatto, M Rezaee & E.K. *in press, Optics Letters,* (2021).

High-dimensional Entangled States





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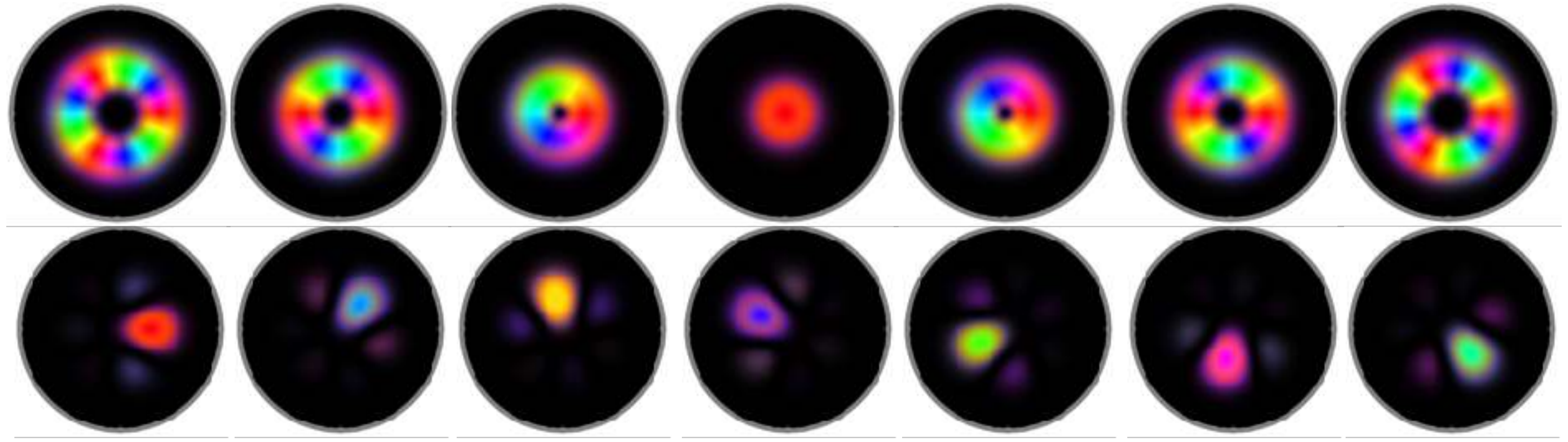
Application in Quantum Communication

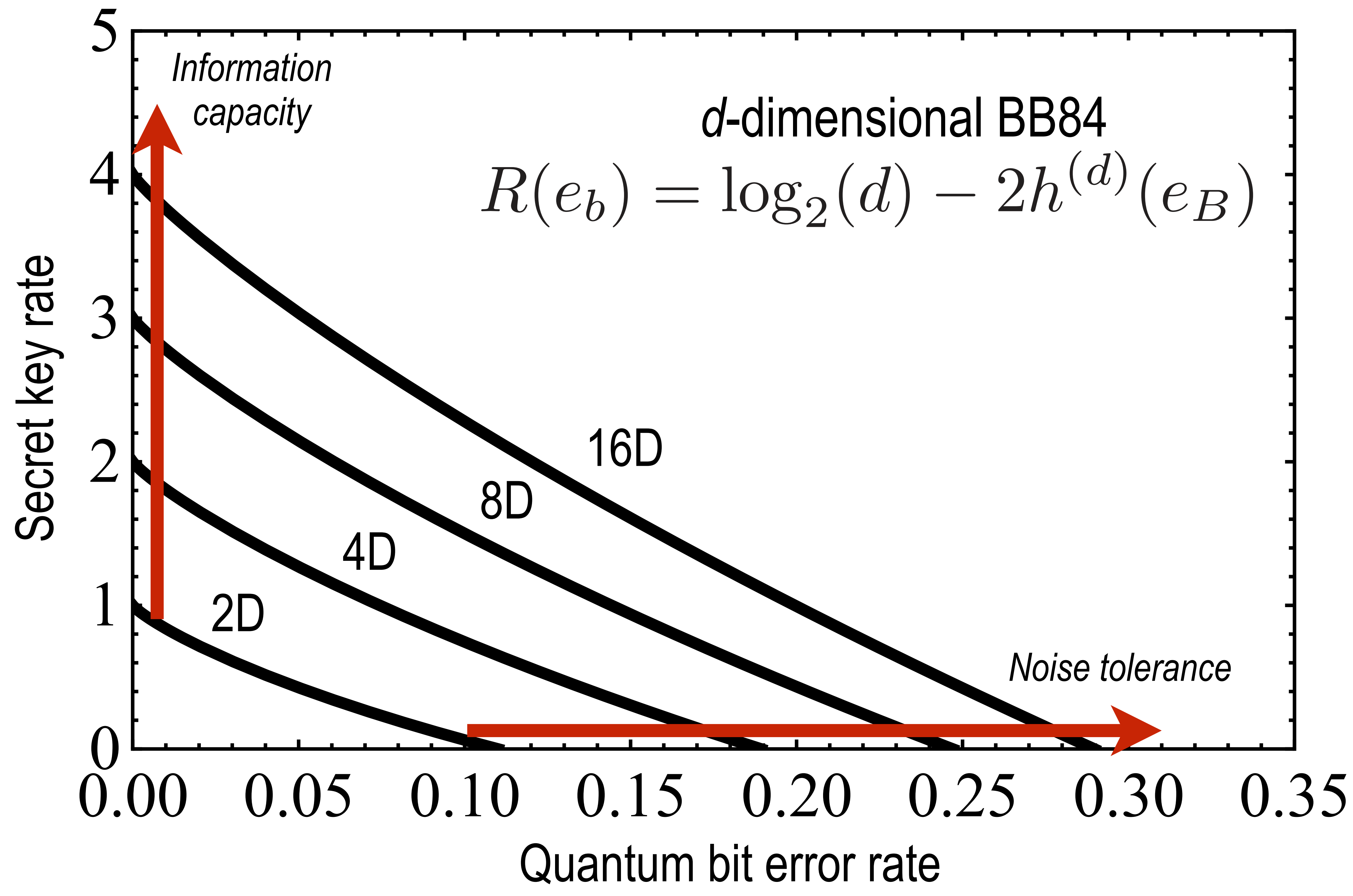
Application in High-Dimensional Quantum Key Distribution

$\{|\psi\rangle_1\}$

$\{|\psi\rangle_2\}$

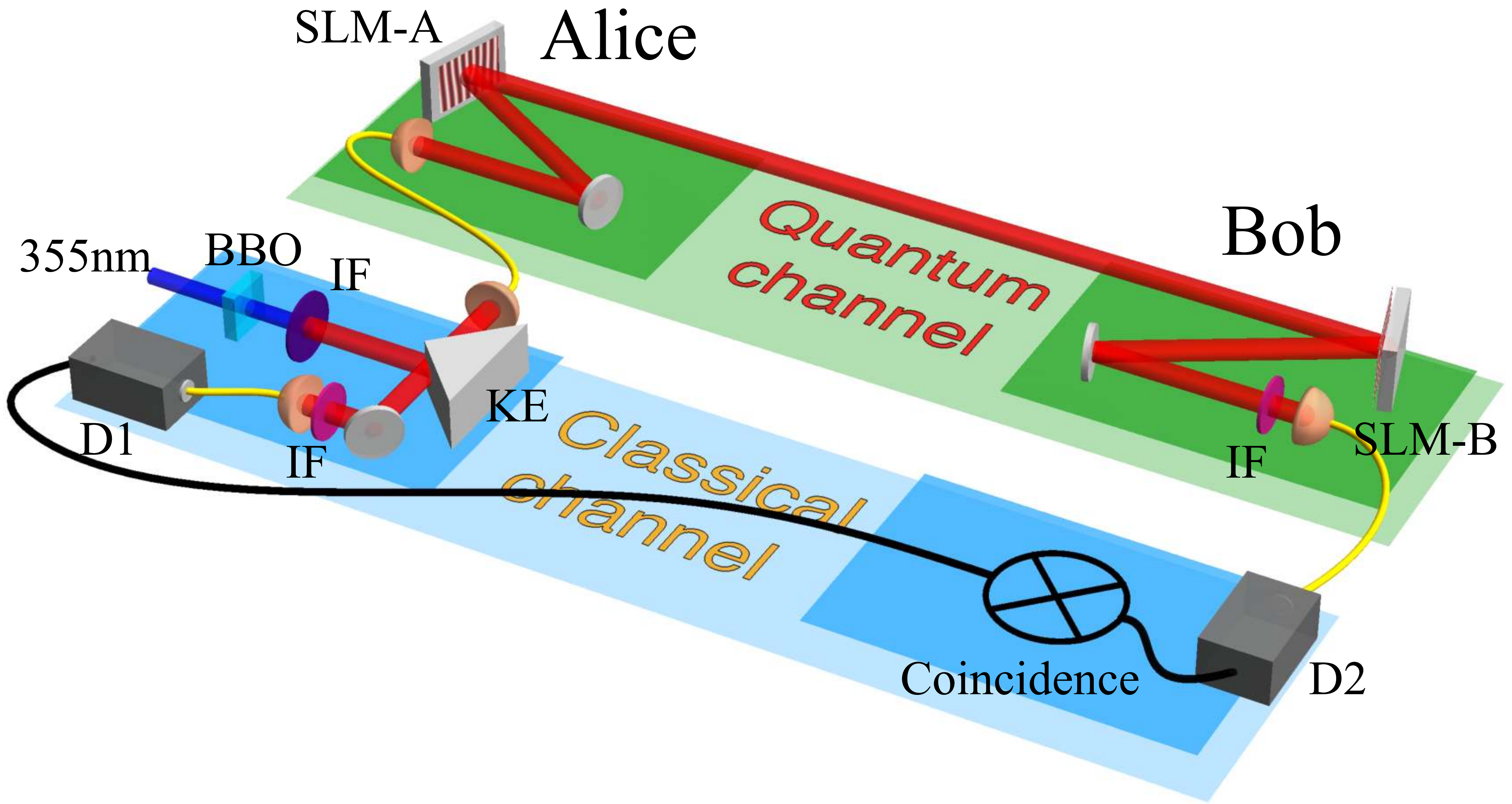


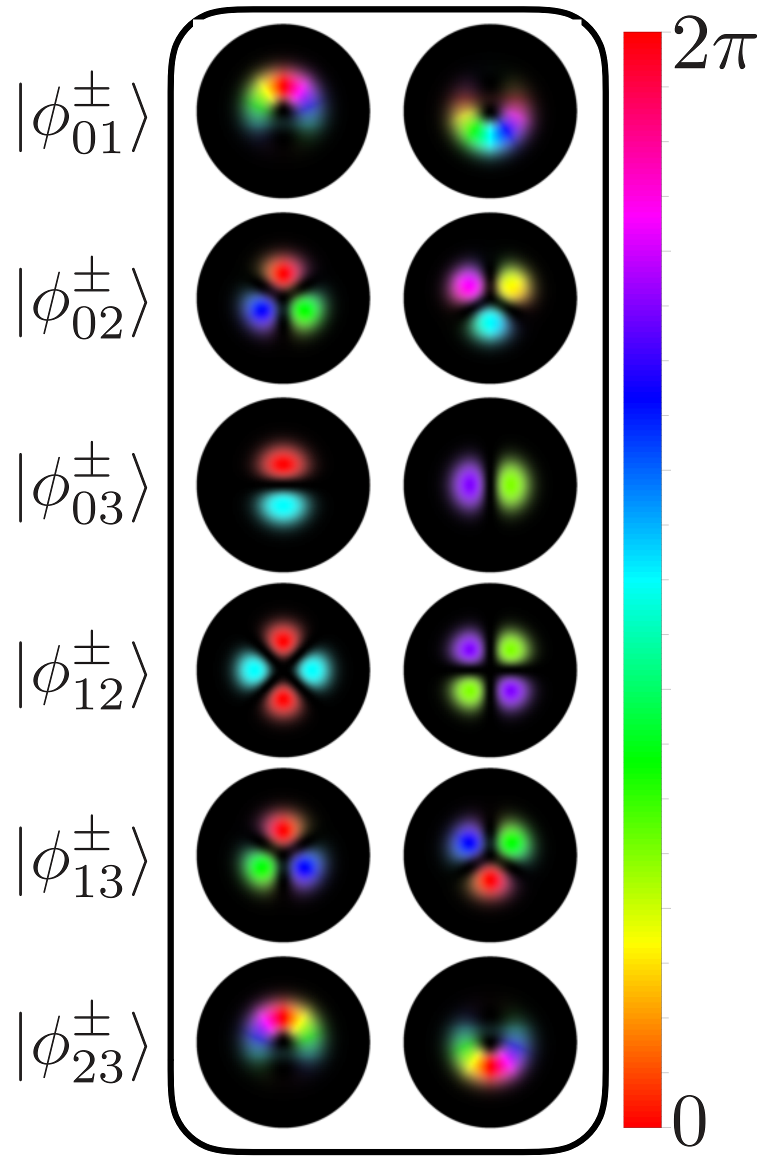
$\{|\psi\rangle_i\}$



F Bouchard, K Heshami, D England, R Fickler, R W Boyd, B-G Englert, L L Sánchez-Soto & E.K., *Quantum* **2**, 111 (2018).

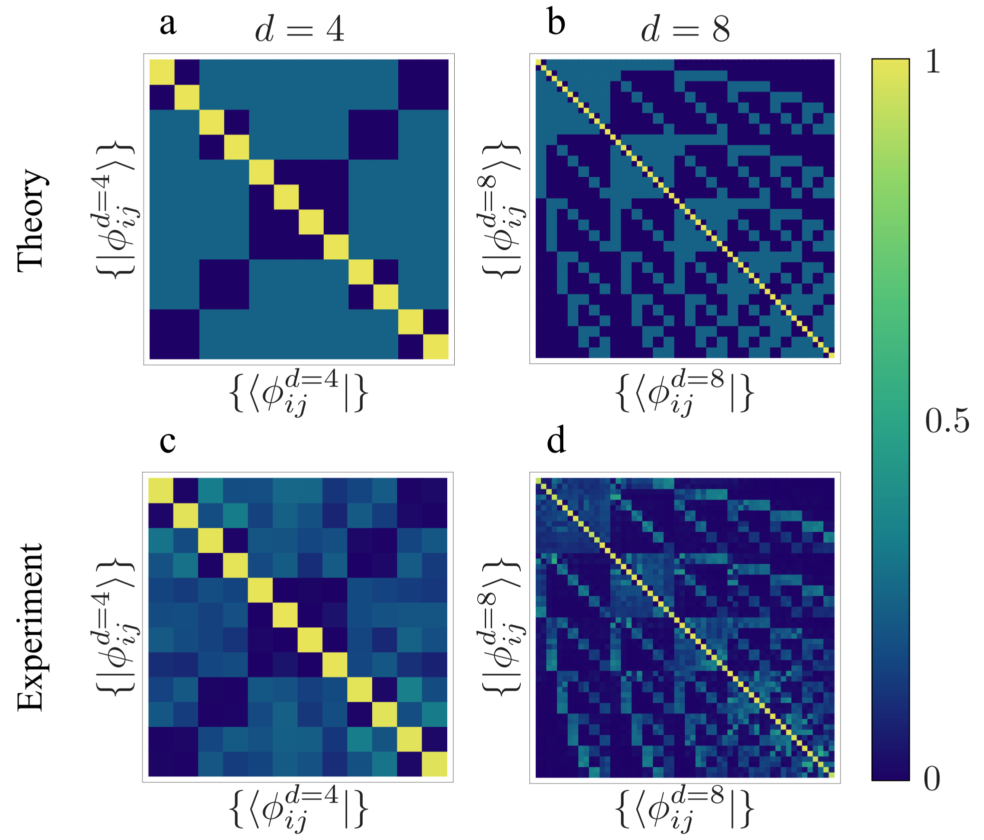
Quantum Key Distribution: Survey and Comparison





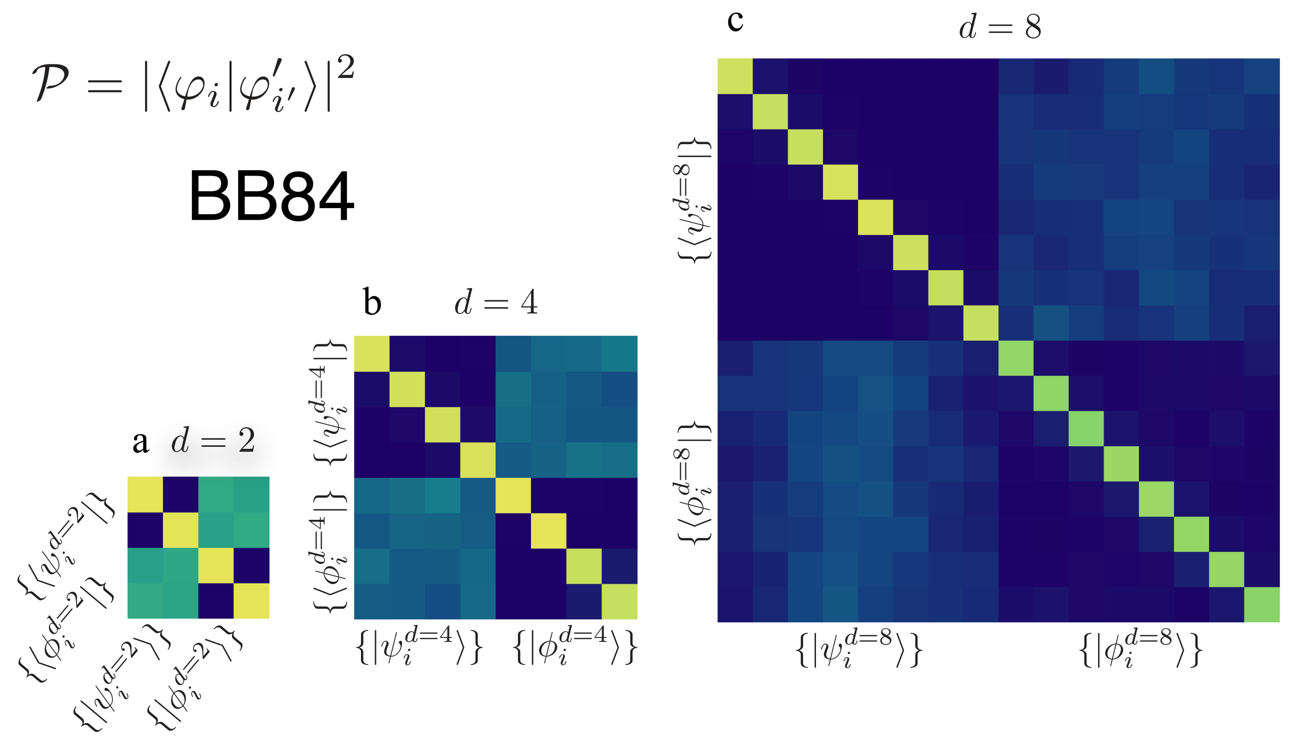
Protocol	d	$e_b^{\max}$	$e_b^{\exp}$	$R(0)$	$R^{\exp}$	Sifting	$R^{\exp}\times$ Sifting
Chau15	4	50 %	0.778 %	1	0.8170	1/6	0.1362
	8	50 %	3.11 %	1	0.8172	1/28	0.0292
BB84	2	11.00 %	0.628 %	1	0.8901	1/2 - 1*	0.4451 - 0.8901
	4	18.93 %	3.51 %	2	1.4500	1/2 - 1*	0.7250 - 1.4500
	8	24.70 %	10.9 %	3	1.3942	1/2 - 1*	0.6971 - 1.3942
MUB	2	12.62 %	0.923 %	1	0.8727	1/3 - 1*	0.2909 - 0.8727
	4	23.17 %	3.87 %	2	1.5316	1/5 - 1*	0.3063 - 1.5316
Singapore	2	38.93 %	1.23 %	0.4	0.374**	1	0.374**

Chau15

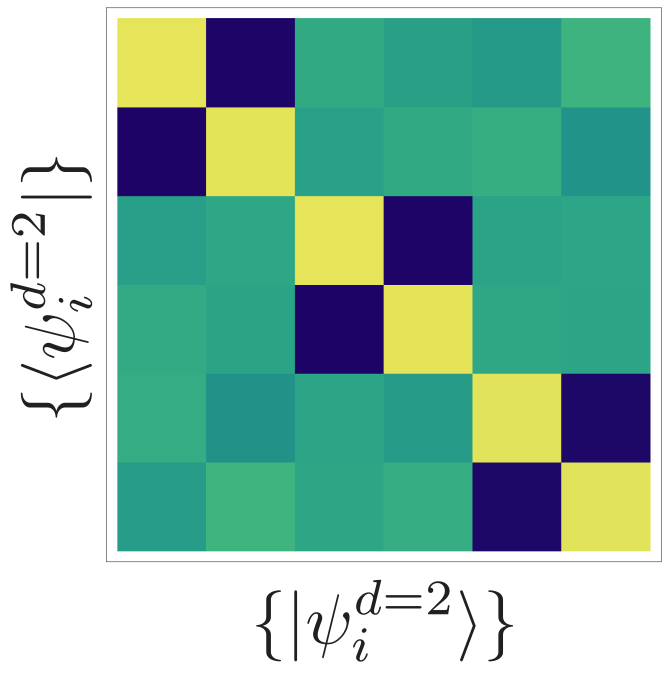


$$\mathcal{P} = |\langle\varphi_i|\varphi'_{i'}\rangle|^2$$

BB84



MUB



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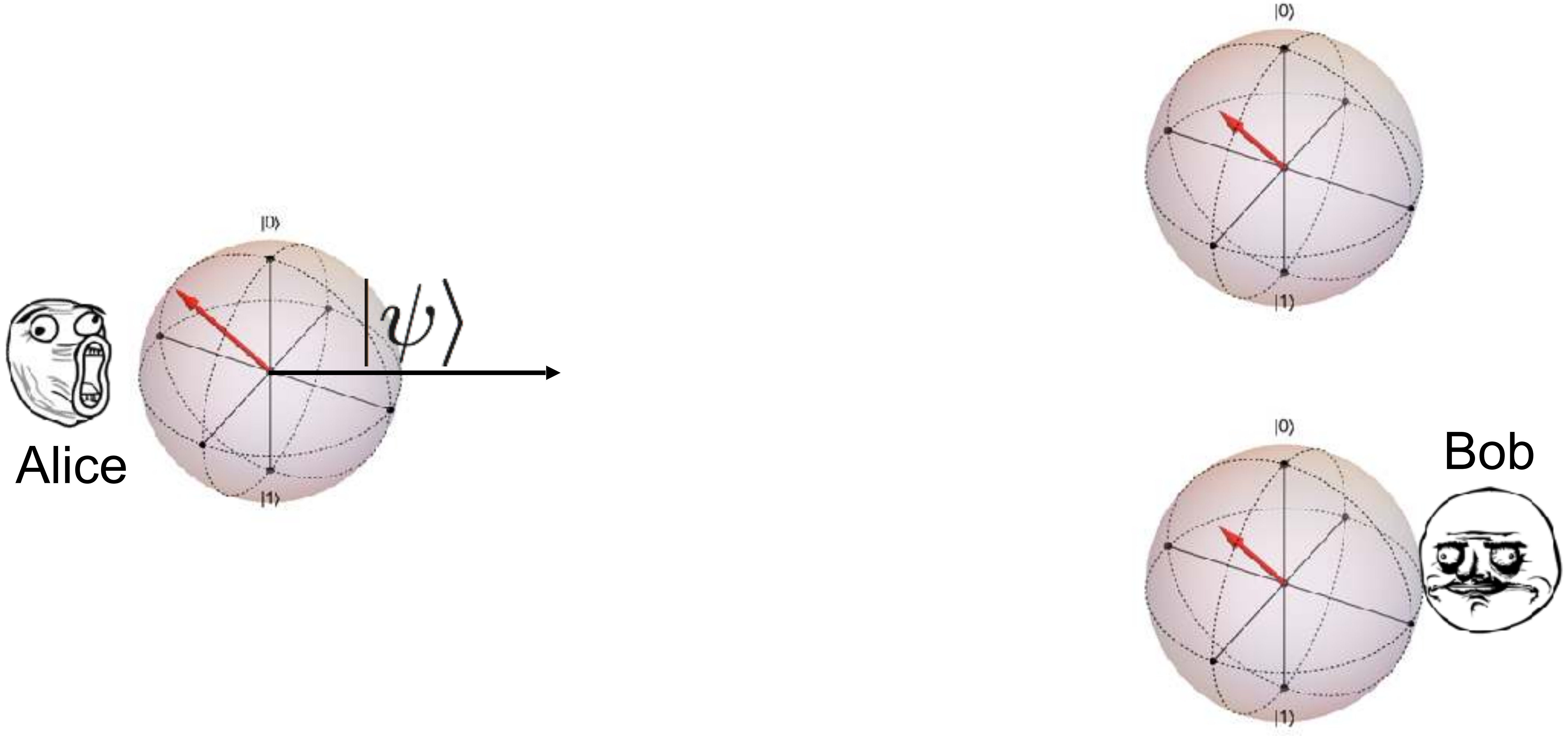
High-Dimensional Quantum Key Distribution: Security threshold



F. Bouchard, R. Fickler, R. W. Boyd, and E. K., *Science Advances* **3**, e1601915 (2017)

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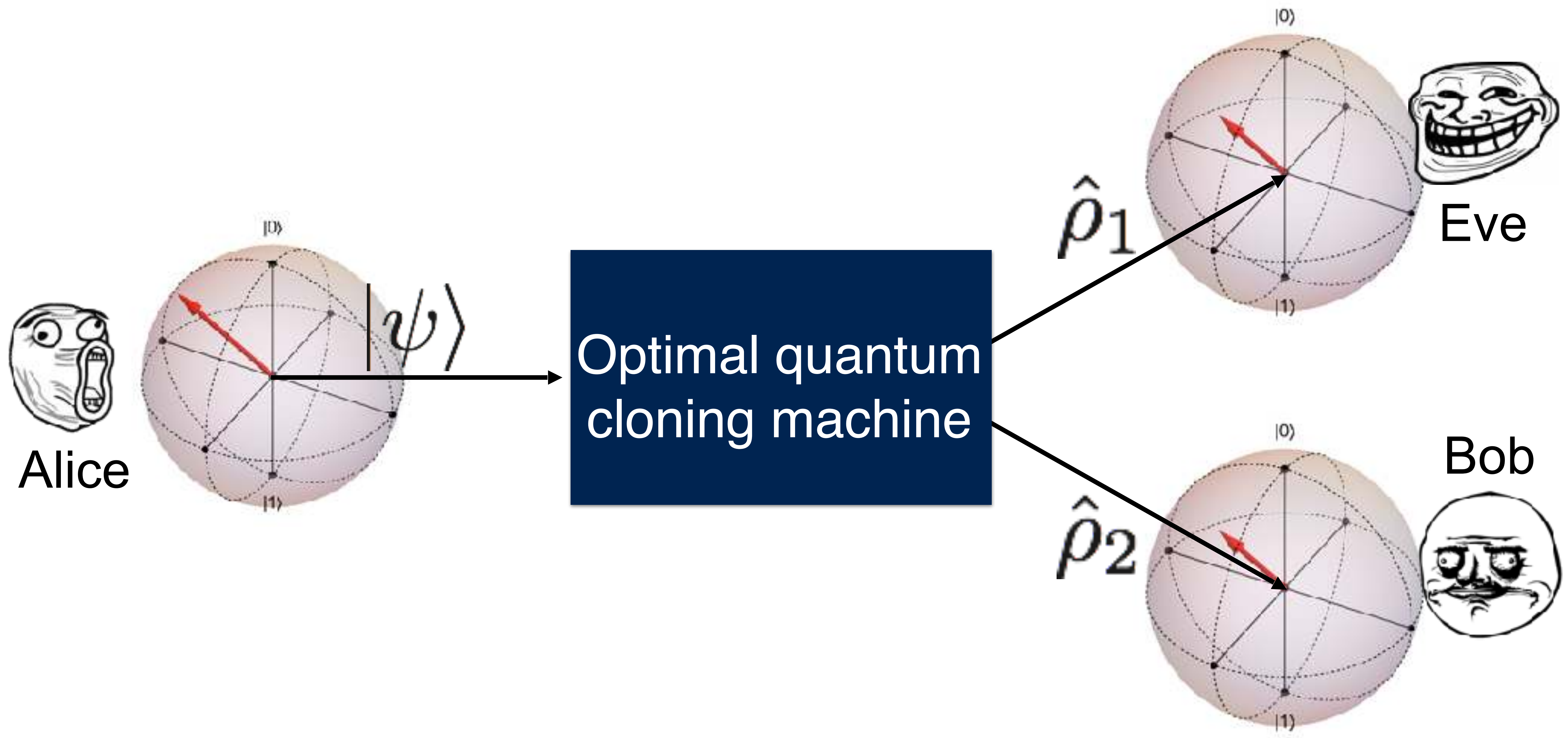

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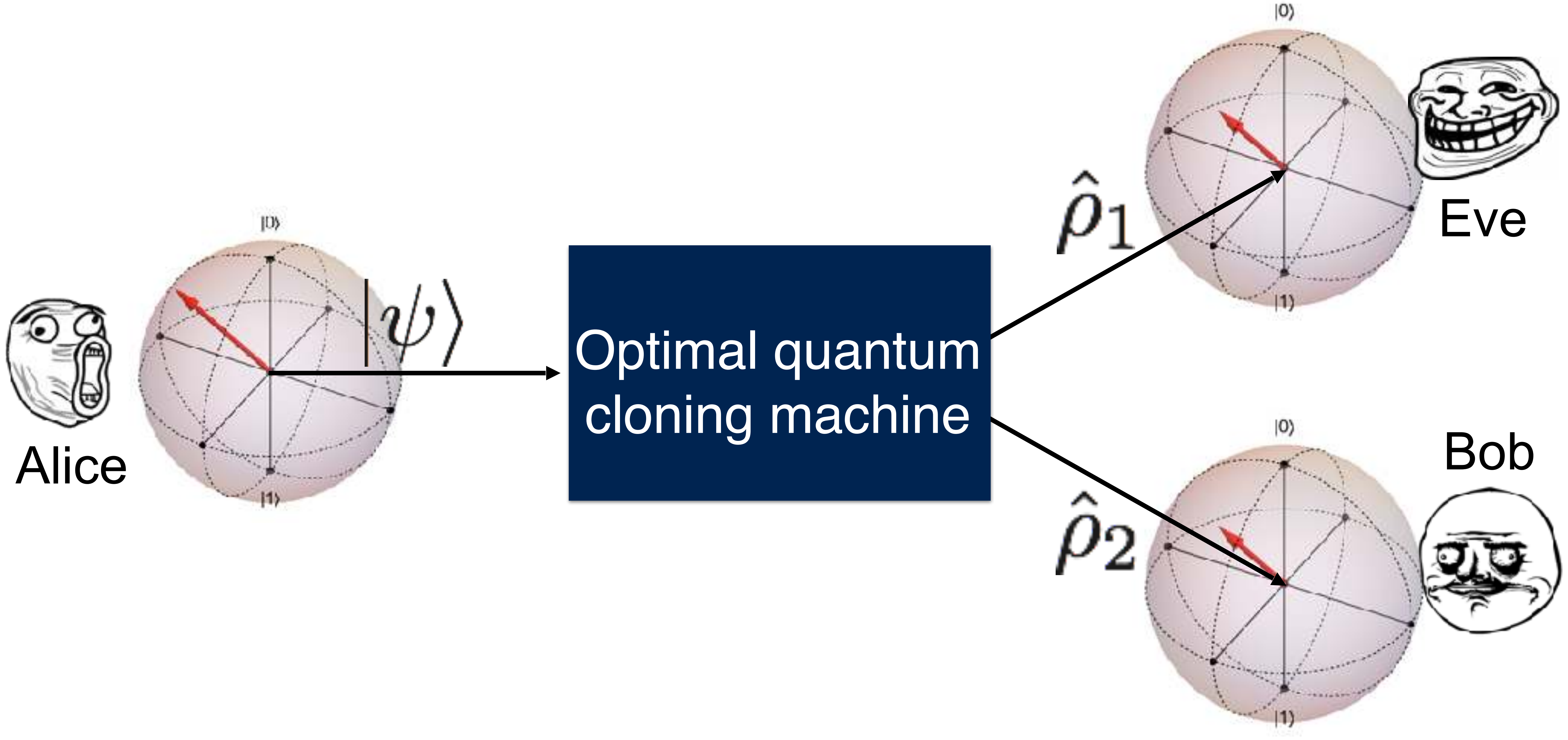
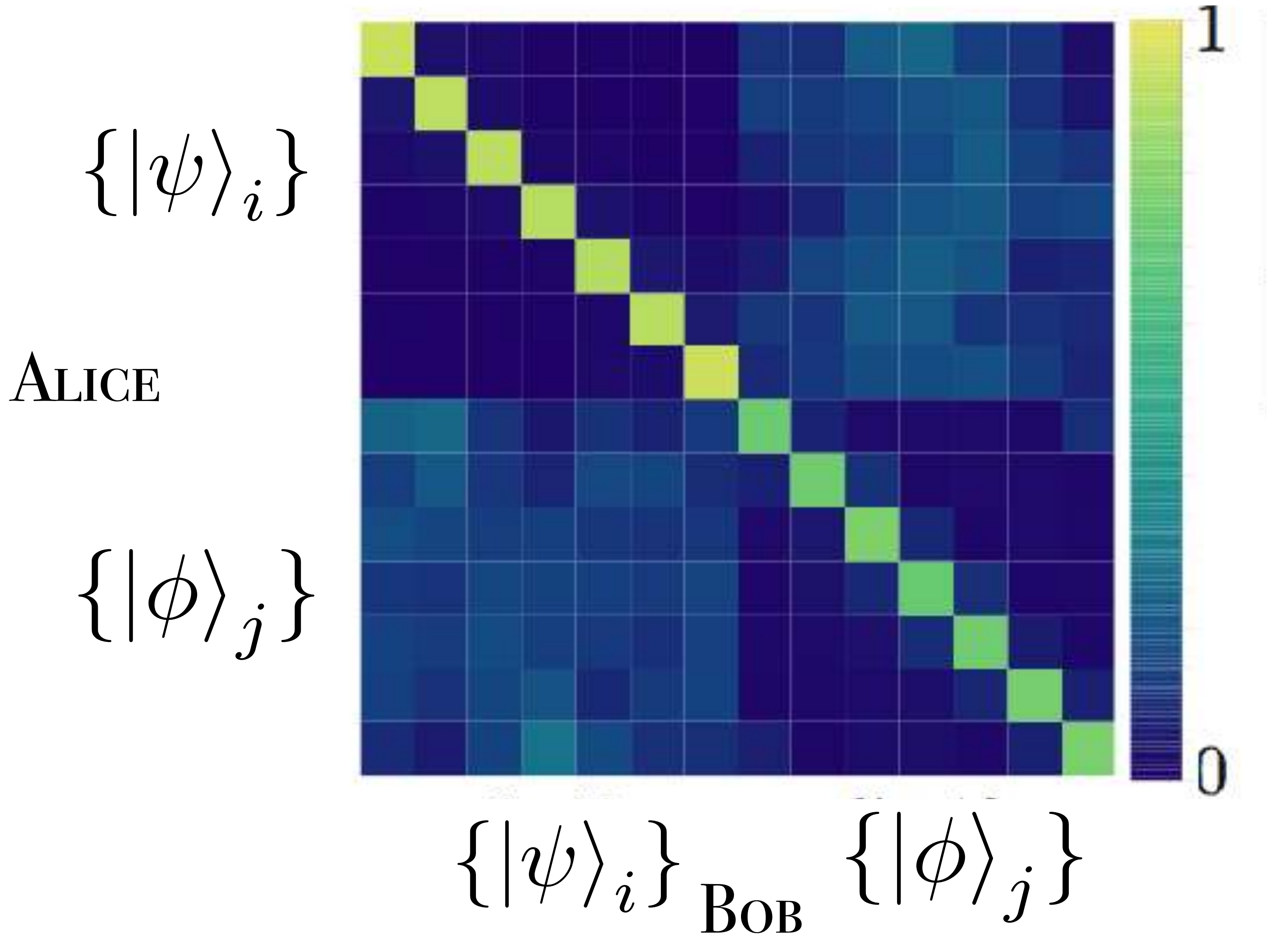
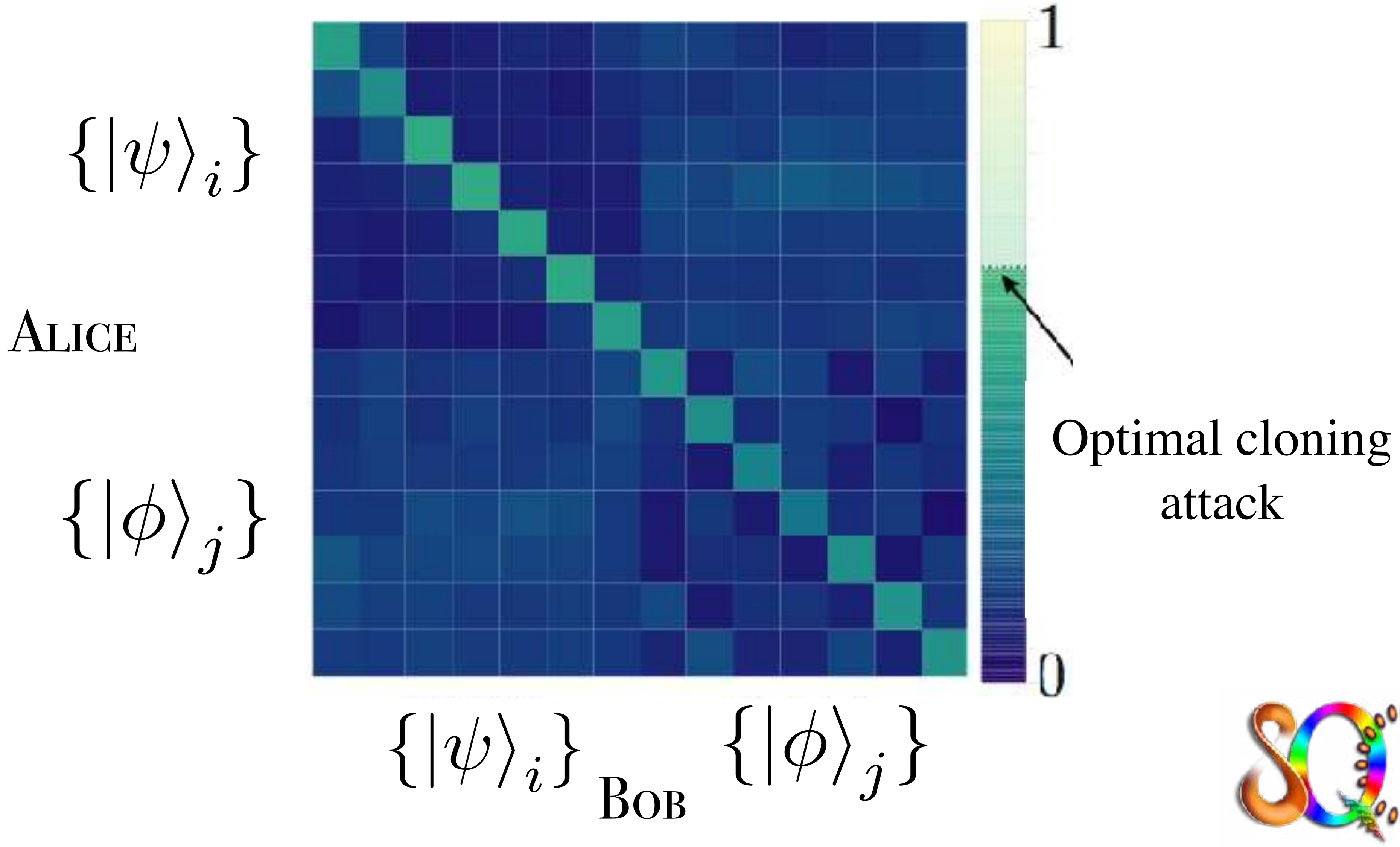


Optimal quantum cloning machine





Optimal cloning attack

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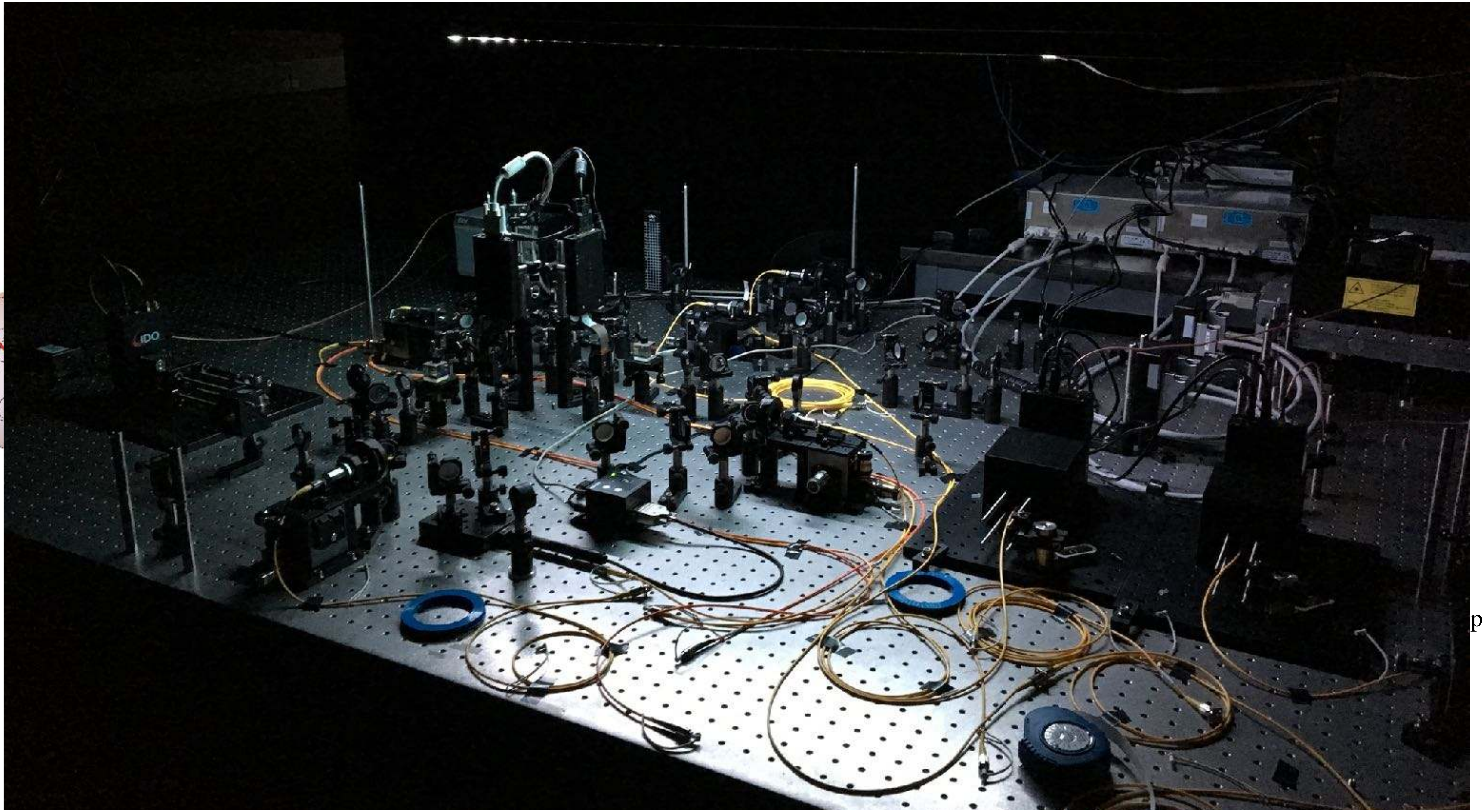
High-Dimensional Quantum Key Distribution: Security threshold

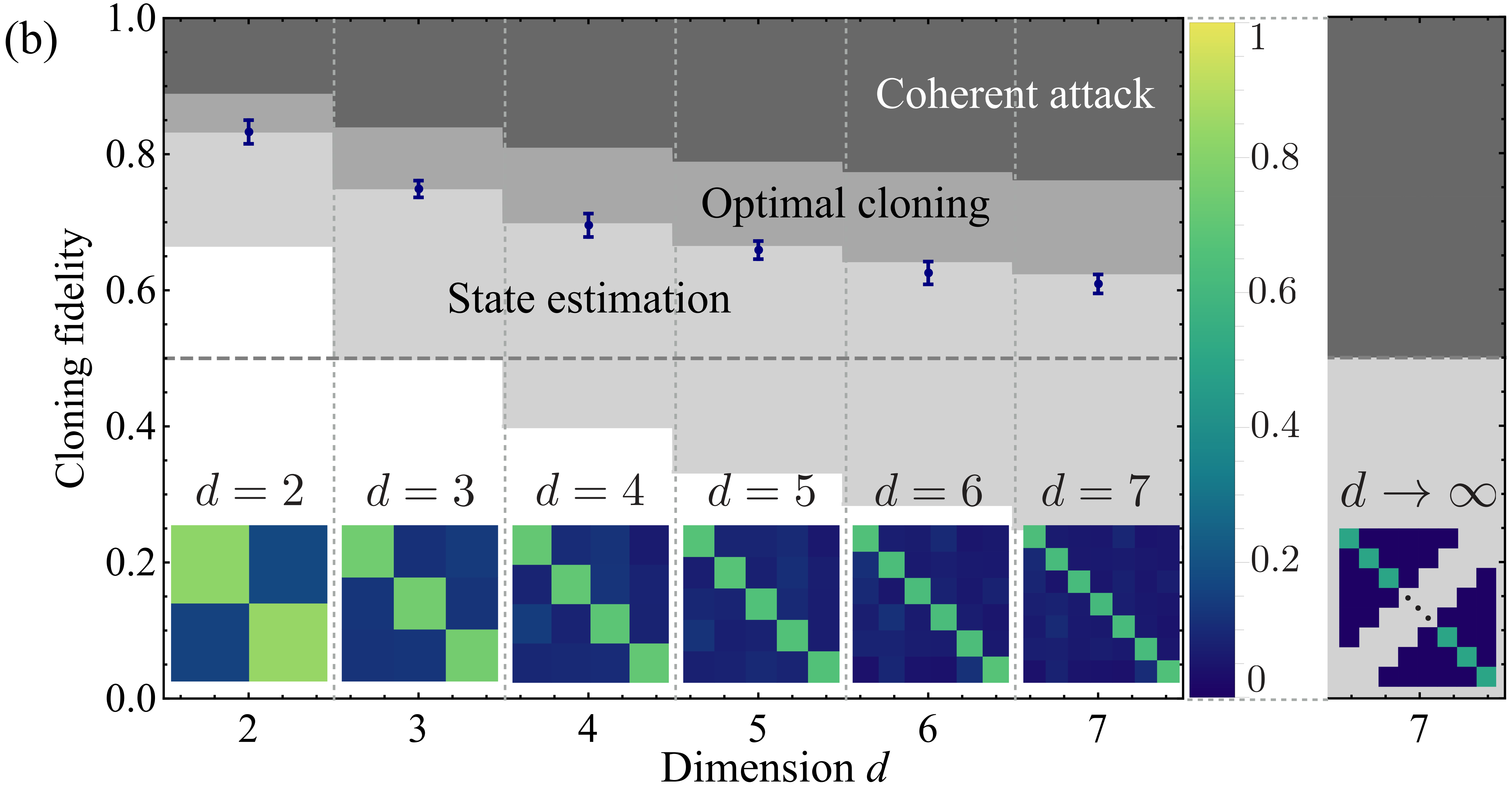


ptimal cloning
attack

F. Bouchard, R. Fickler, R. W. Boyd, and E. K., *Science Advances* **3**, e1601915 (2017)

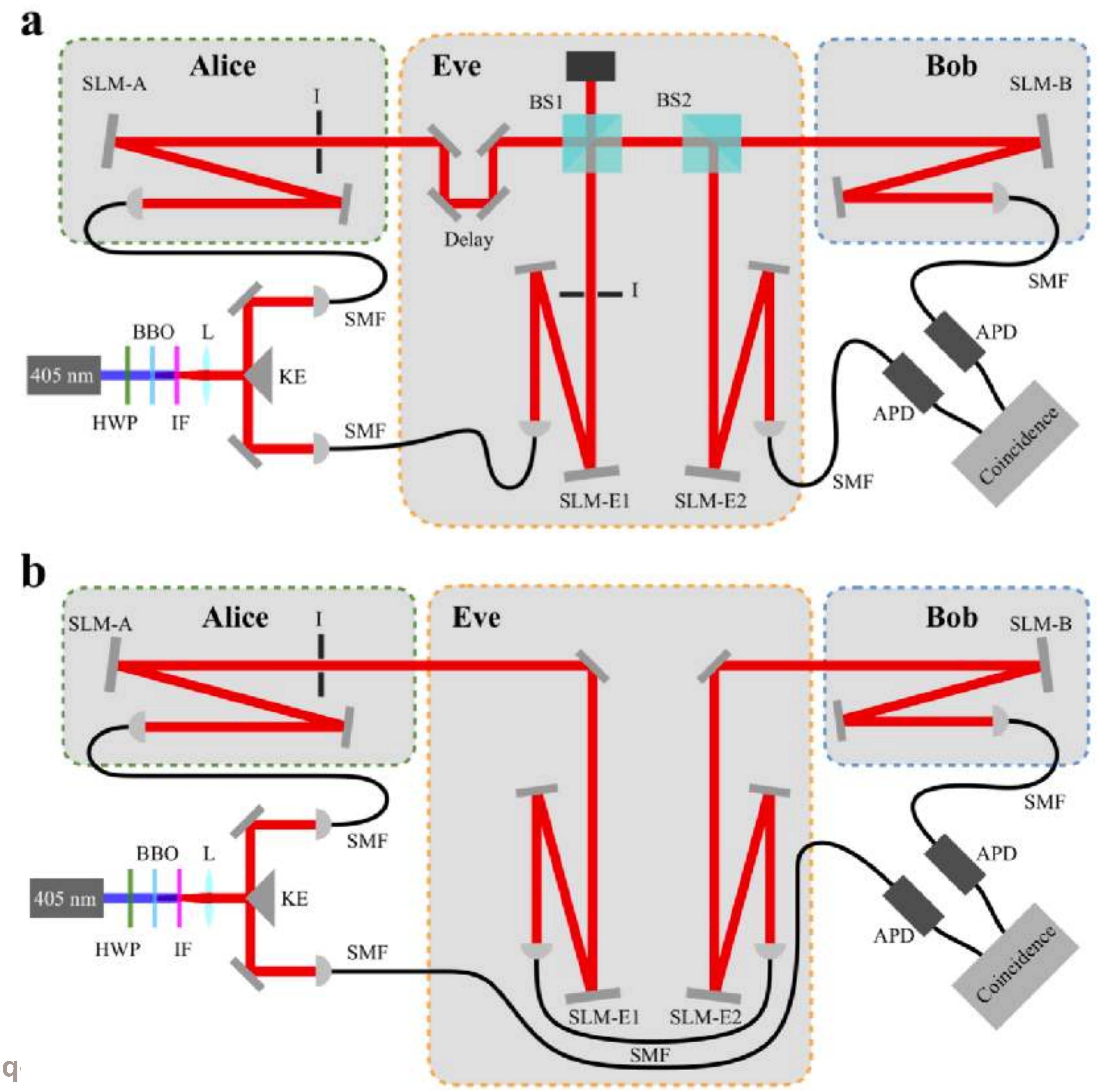
High-Dimensional Quantum Key Distribution: Security threshold

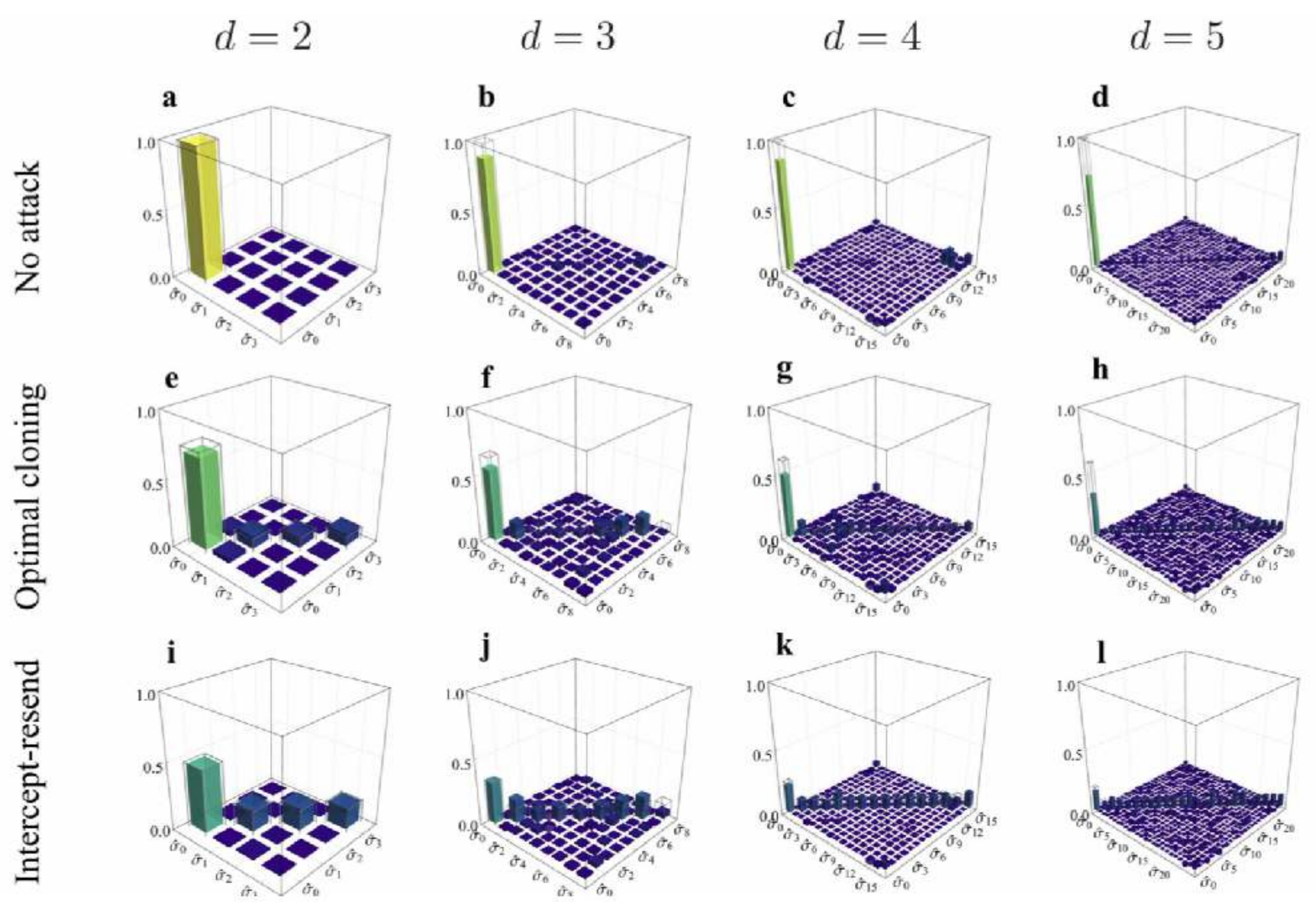
Dimension	$d = 2$	$d = 3$	$d = 4$	$d = 5$	$d = 6$	$d = 7$	$d \to \infty$
Theory	0.833	0.75	0.7	0.667	0.643	0.625	0.5
Experimental	0.82 ± 0.01	0.75 ± 0.01	0.70 ± 0.02	0.66 ± 0.01	0.64 ± 0.02	0.62 ± 0.02	
	0.84 ± 0.02	0.75 ± 0.01	0.70 ± 0.01	0.67 ± 0.01	0.62 ± 0.01	0.61 ± 0.01	
		0.75 ± 0.01	0.68 ± 0.01	0.65 ± 0.08	0.62 ± 0.01	0.61 ± 0.01	
			0.70 ± 0.02	0.66 ± 0.01	0.62 ± 0.01	0.60 ± 0.01	
				0.65 ± 0.02	0.62 ± 0.01	0.61 ± 0.01	
					0.63 ± 0.02	0.60 ± 0.01	
						0.62 ± 0.02	
Average	0.83 ± 0.02	0.75 ± 0.01	0.70 ± 0.02	0.66 ± 0.01	0.63 ± 0.02	0.61 ± 0.01	



F. Bouchard, R. Fickler, R. W. Boyd, and E. K., *Science Advances* **3**, e1601915 (2017)

Quantum Key Distribution: Process Matrix and Detecting Eavesdropper





F Bouchard, F Hufnagel, DKoutný, A Abbas, A Sit, K Heshami, R Fickler & E.K., *Quantum* **3**, 138 (2019).

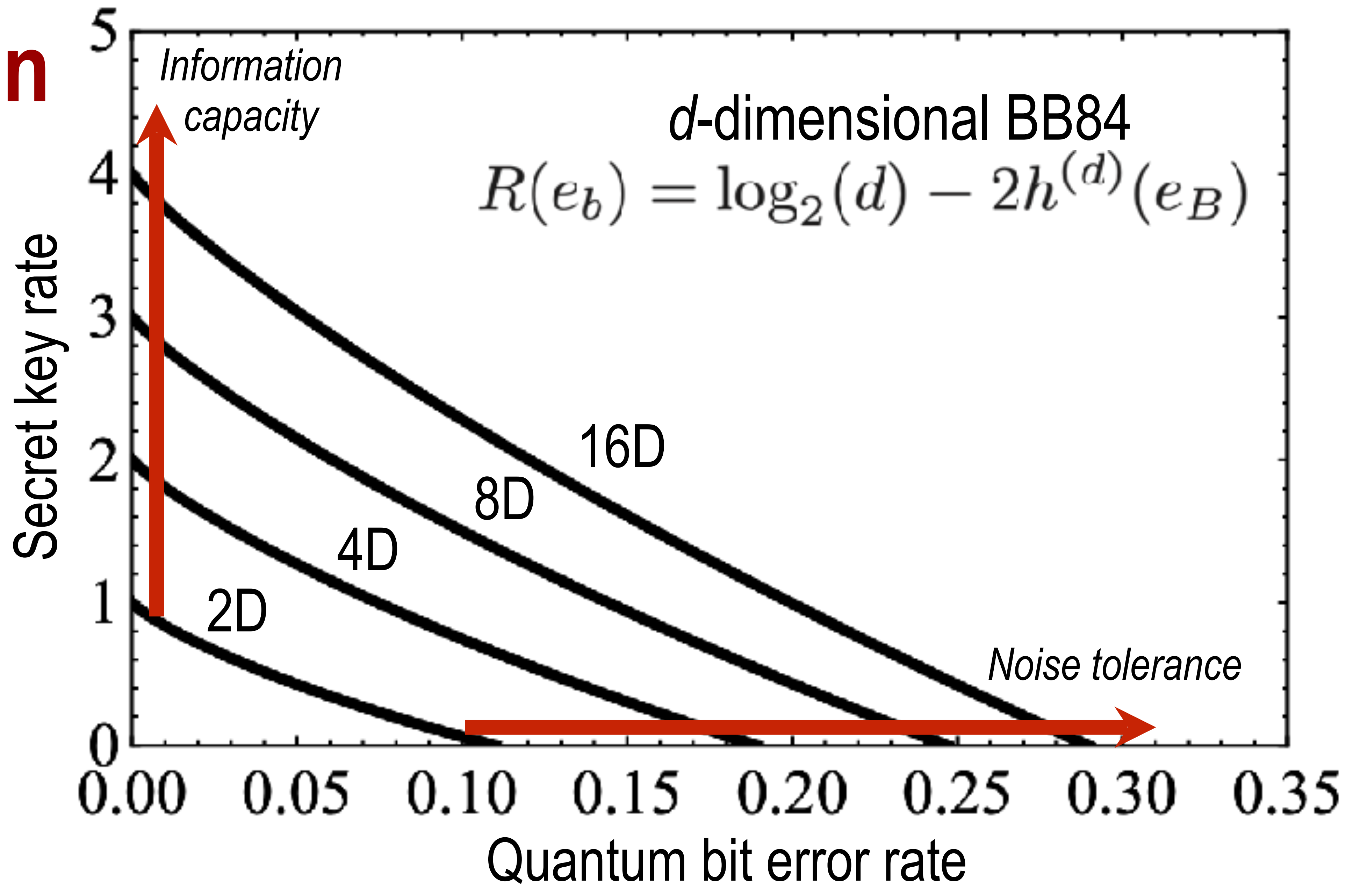
Structured Photons: Applications in Secure Communication

Structured Photons:

More information per carrier

They are robust in a noisier channel

$\{|\psi\rangle_i\}$



F Bouchard, K Heshami, D England, R Fickler, R W Boyd, B-G Englert, L L Sánchez-Soto & E.K., *Quantum* **2**, 111 (2018).

Structured Photons: Applications in Secure Communication

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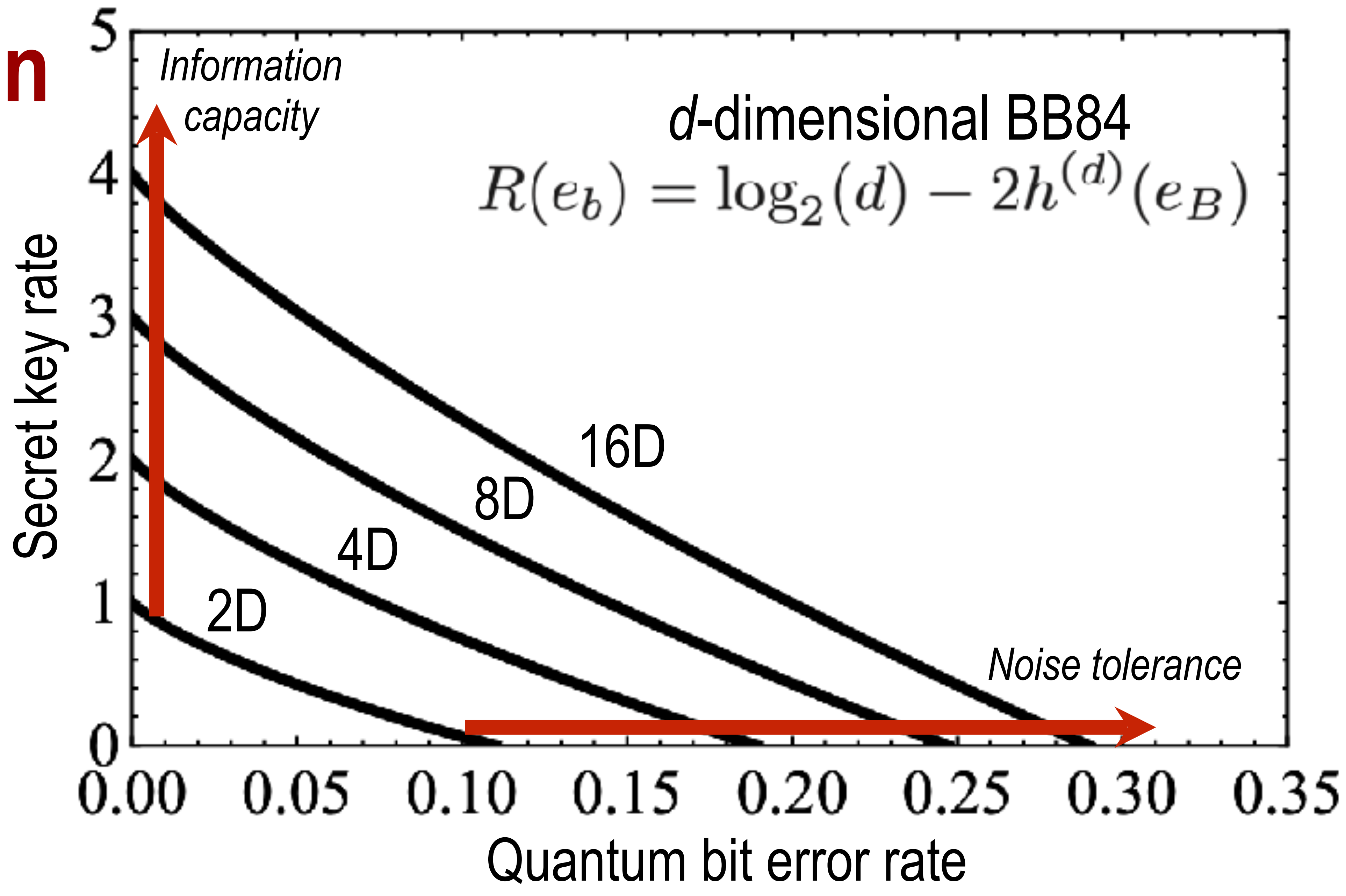
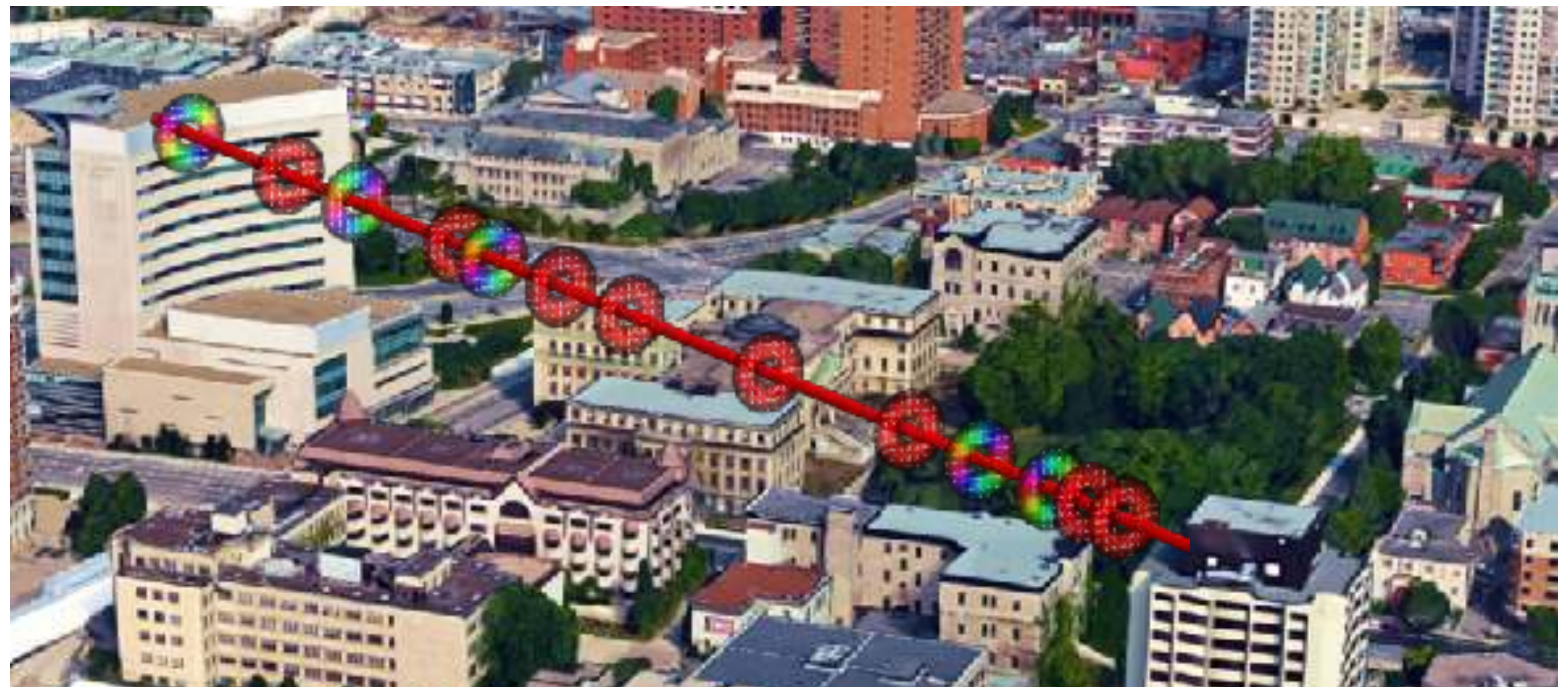
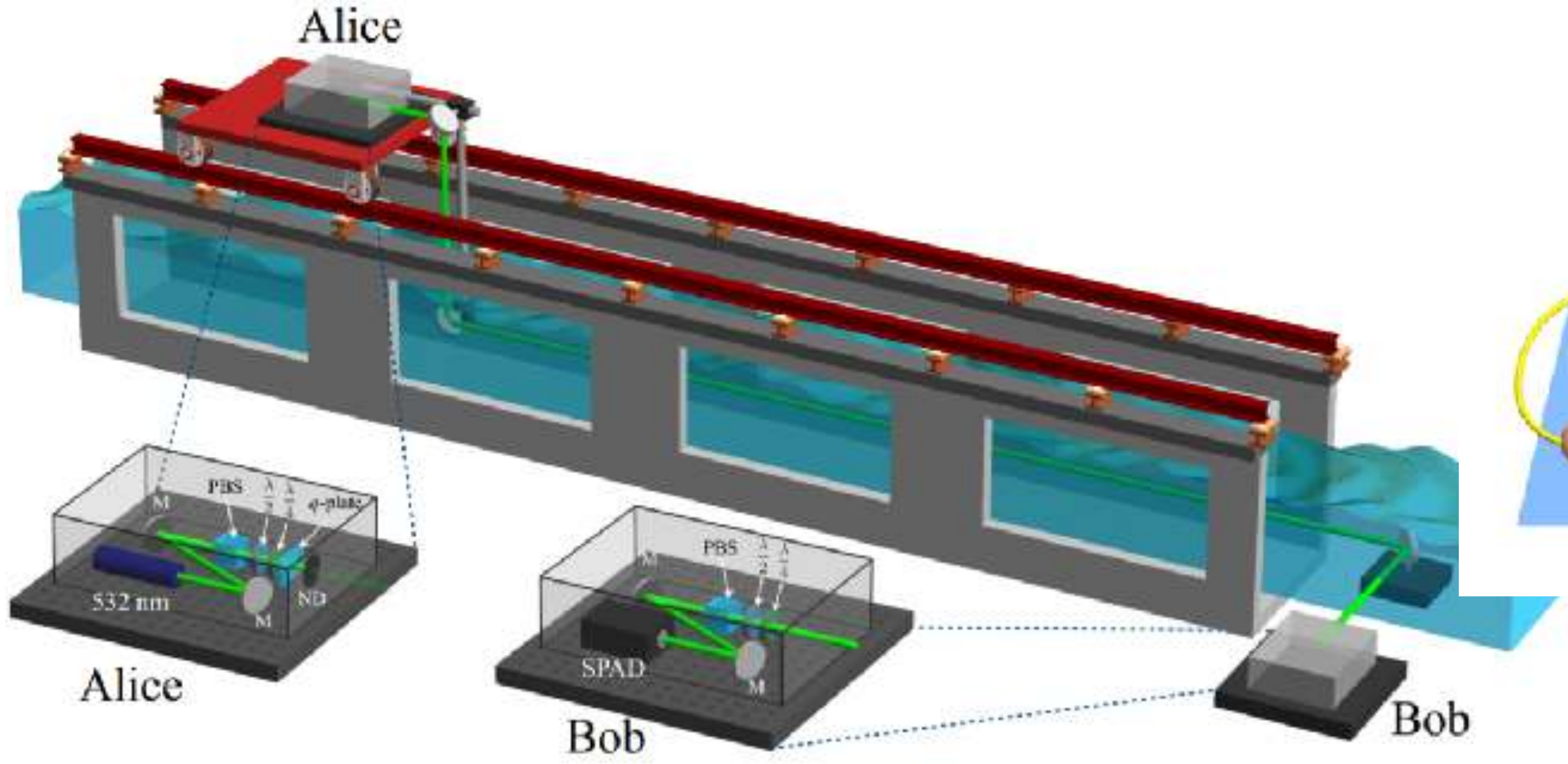
$\{|\psi\rangle_i\}$





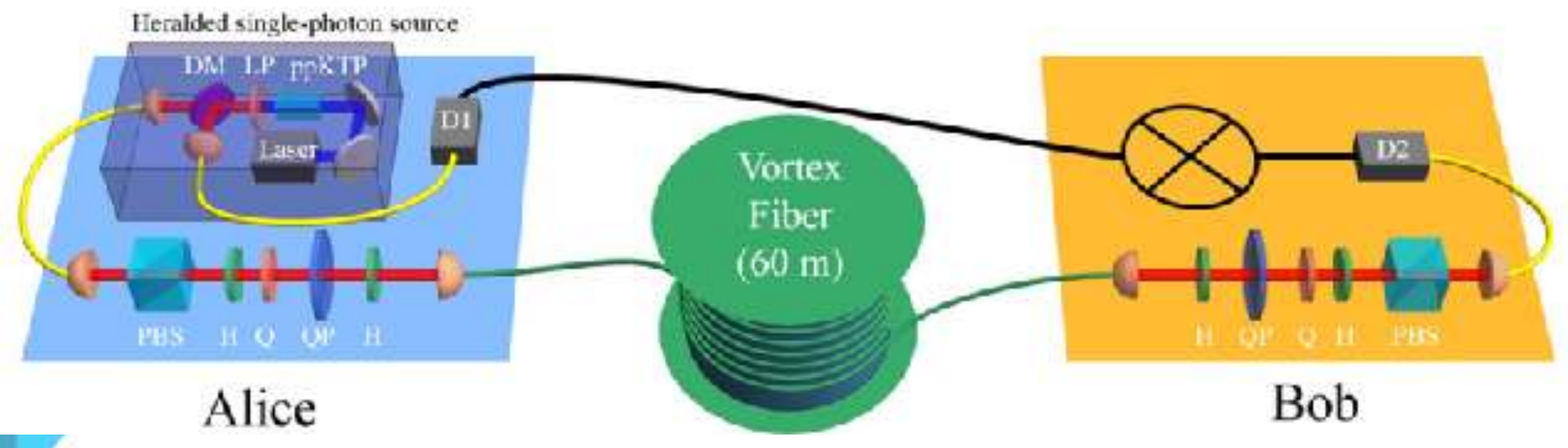
Free-space channel

A. Sit, F. Bouchard, R. Fickler, J. Gagnon-Bischoff, H. Larocque, K. Heshami, D. Elser, C. Peuntinger, K. Günthner, B. Heim, C. Marquardt, G. Leuchs, R. W. Boyd & E. K., *Optica* **4**, 1006 (2017).



Underwater channel

F. Bouchard, A. Sit, F. Hufnagel, A Abbas, Y. Zhang, K. Heshami, R. Fickler, C. Marquardt, G. Leuchs, R. W. Boyd & E.K., Optics Express **26**, 22563 (2018).



Fibre channel

A Sit, R Fickler, F Alsaiari, F Bouchard, H Larocque, P Gregg, L Yan, R W Boyd, S Ramachandran & E.K., *Optics Letters* **43**, 4108 (2018).

F Bouchard, K Heshami, D England, R Fickler, R W Boyd, B-G Englert, L L Sánchez-Soto & E.K., *Quantum* **2**, 111 (2018).

NRC-uOttawa 5.4 km free-space link

A deck was designed with a cut-out allowing for an optical table to be isolated from the deck.

The shed of 11' by 8' can hold the optical table and all lab equipment while providing enough space for team members to work both inside and outside of the shed for alignment.

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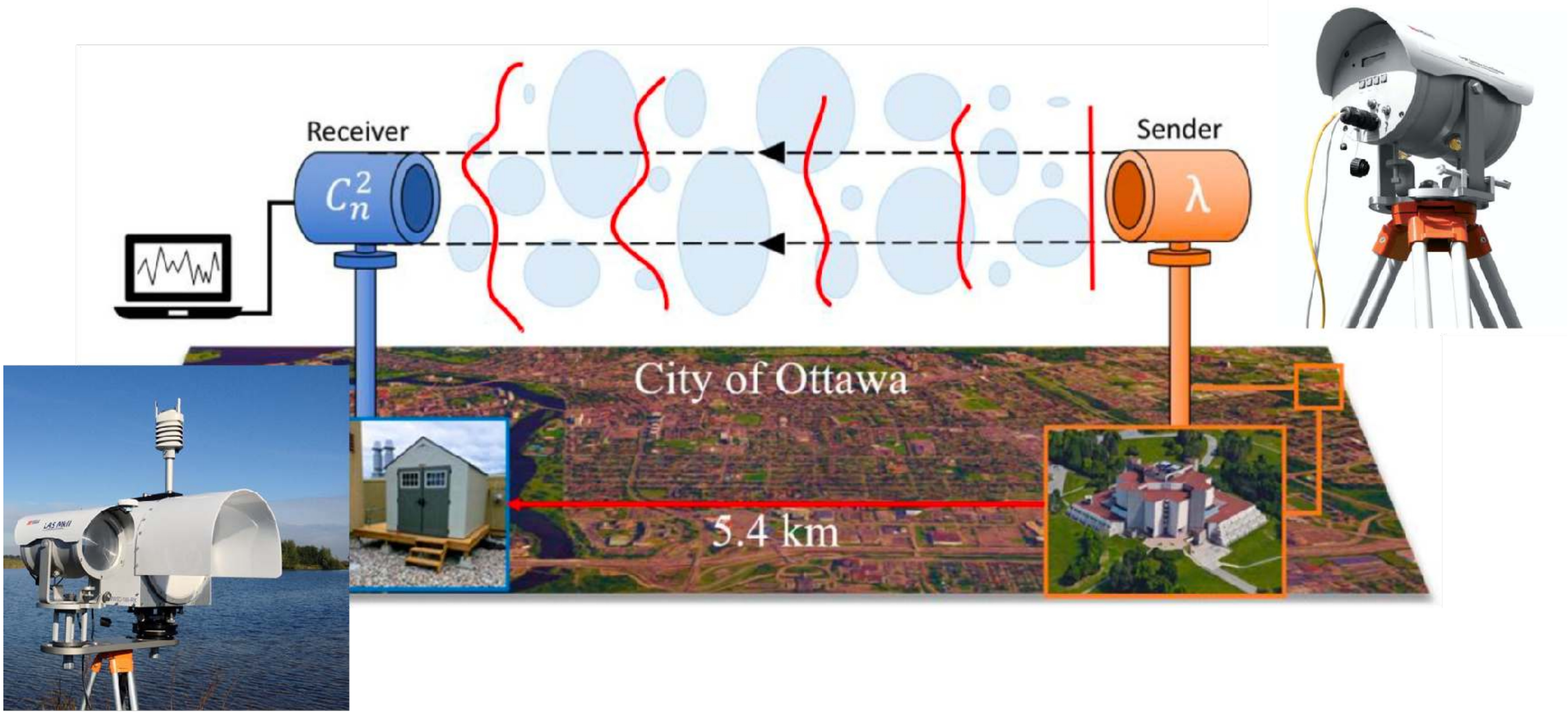
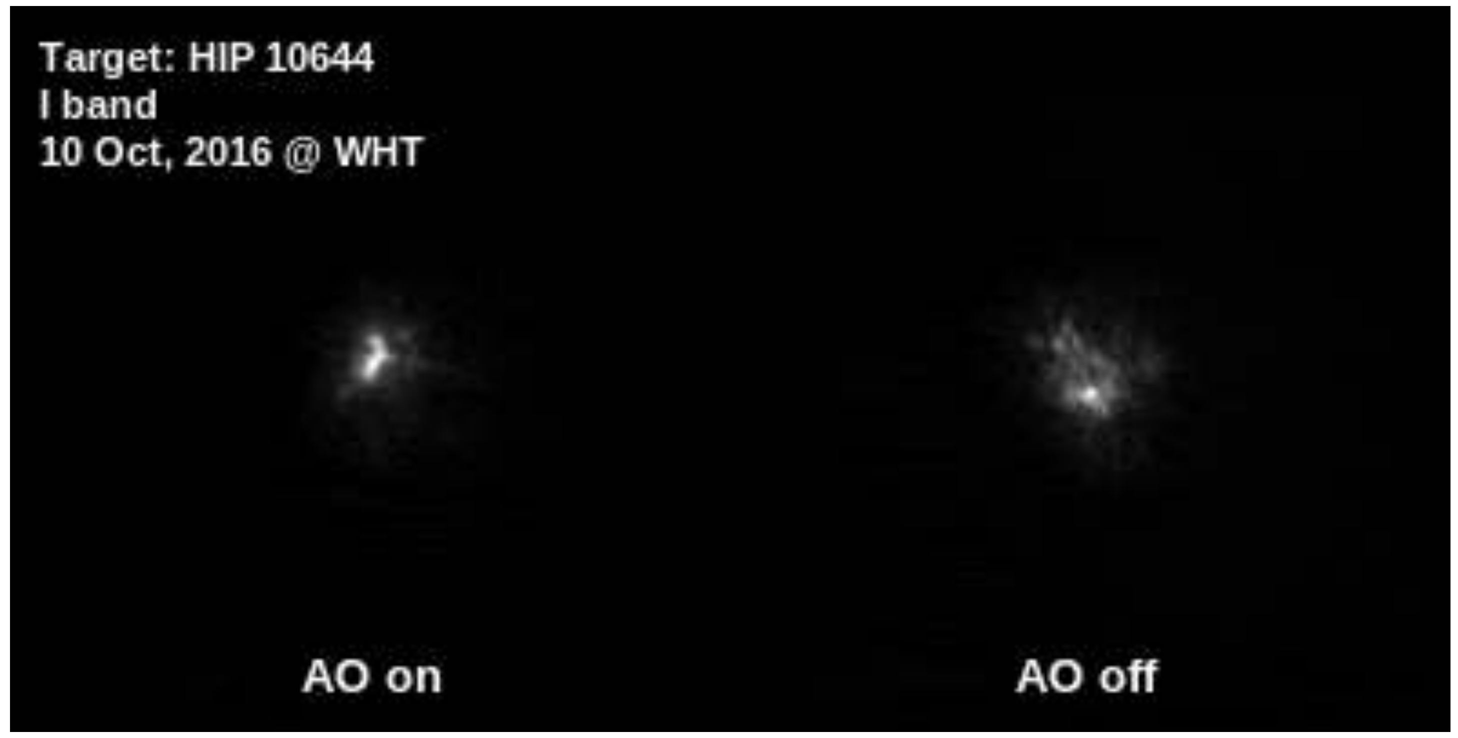
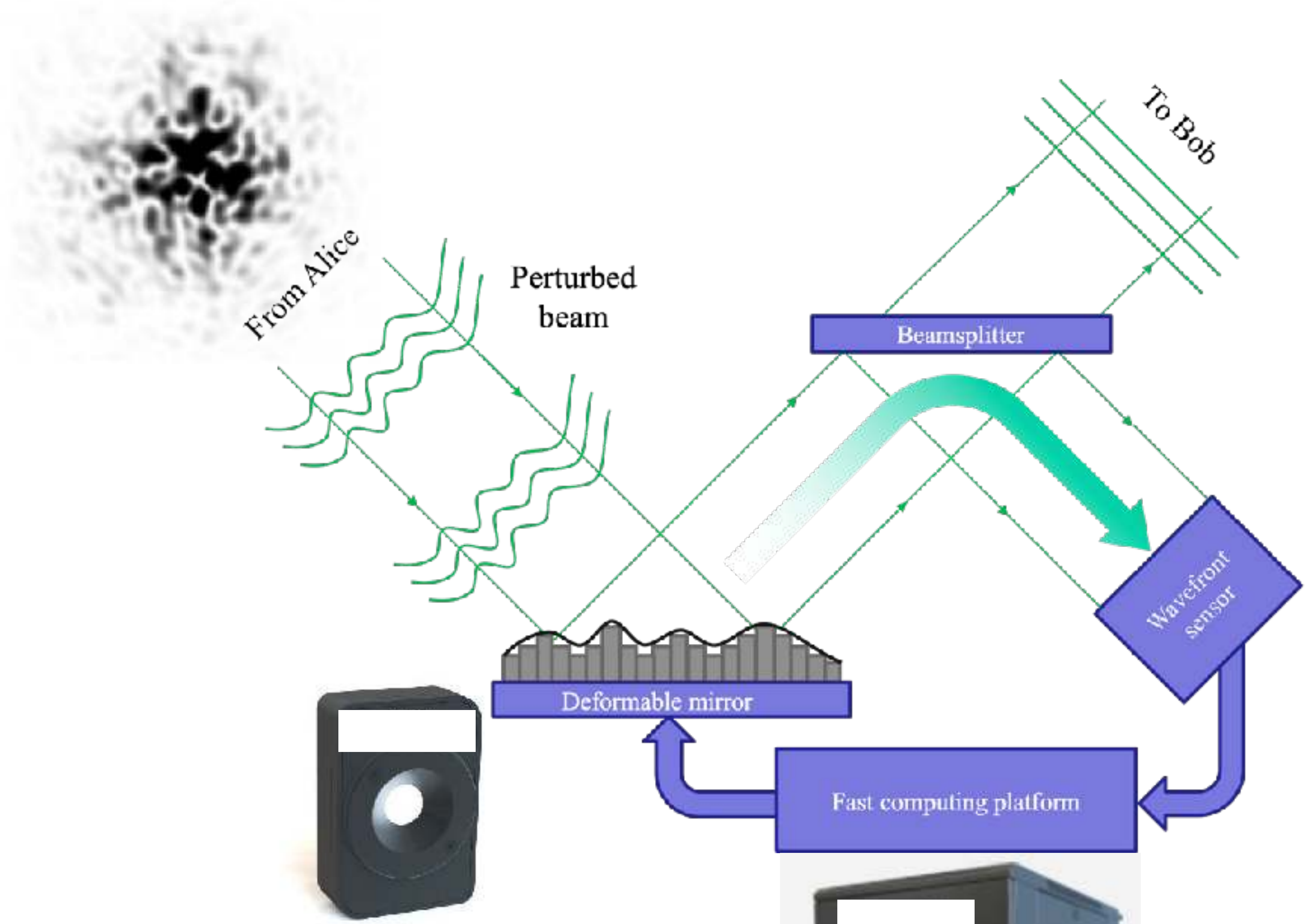
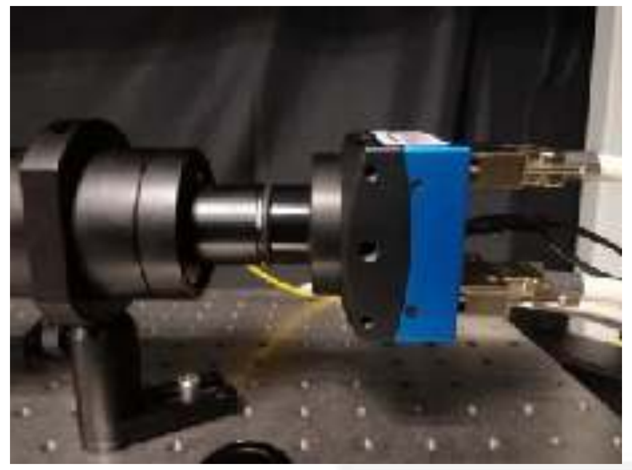

Receiver
C_n^2
Sender
λ
City of Ottawa
5.4 km
LAS MkII

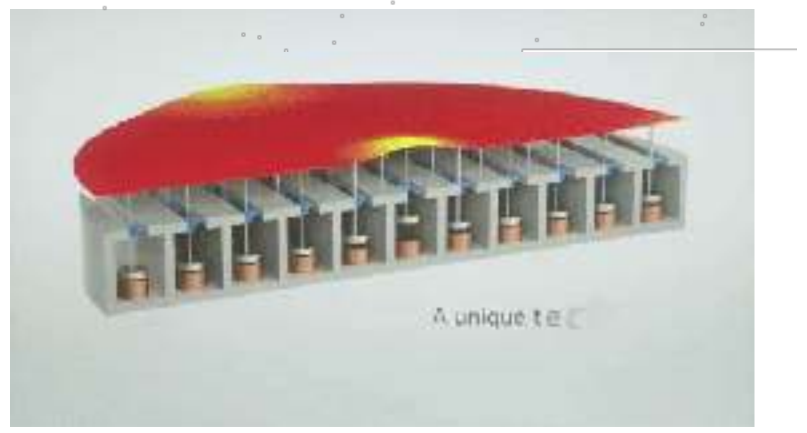

Receiver
C_n^2
Sender
λ
City of Ottawa
5.4 km
LAS MkII

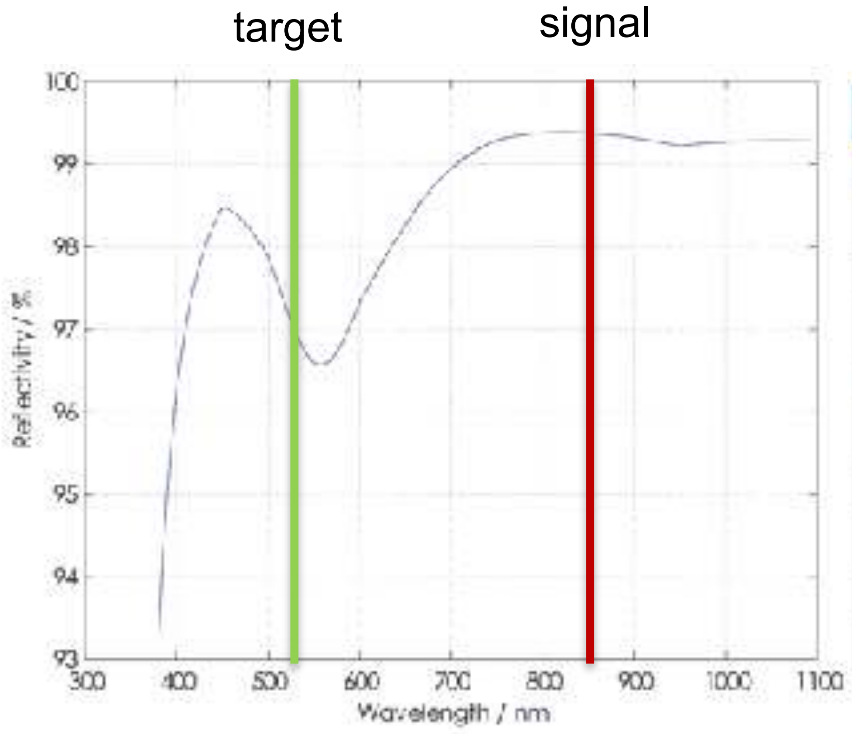
Adaptive Optics System

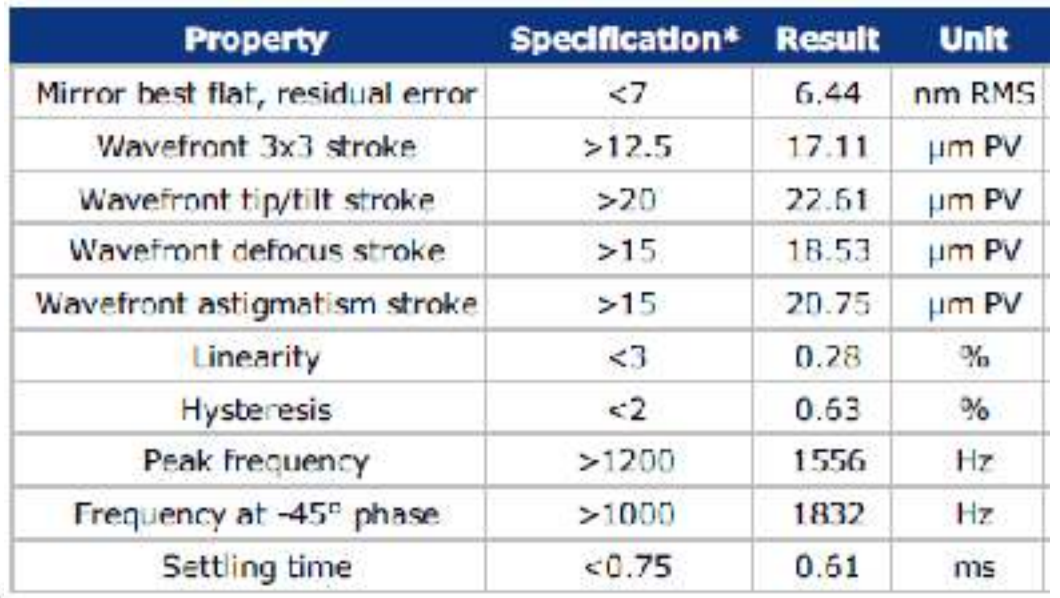






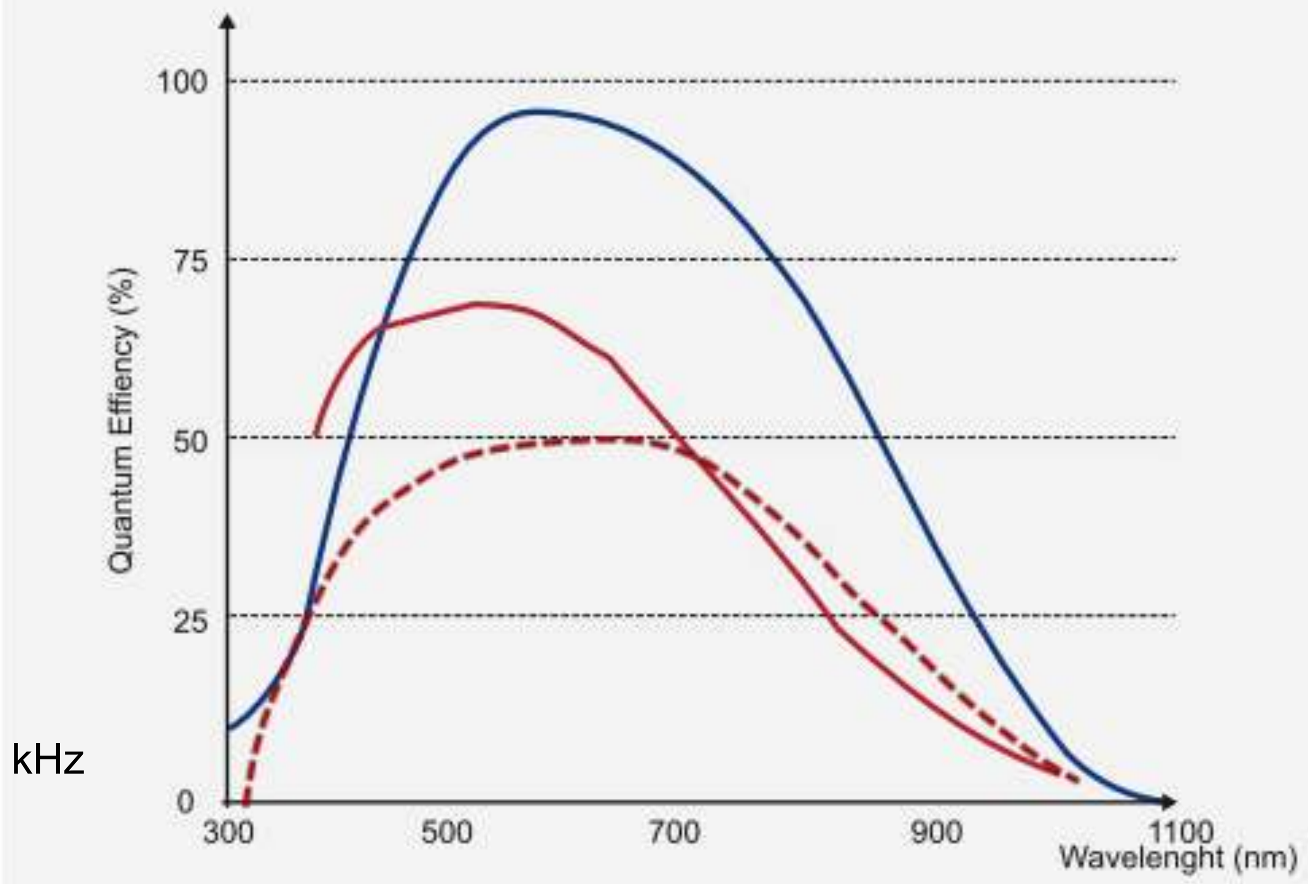






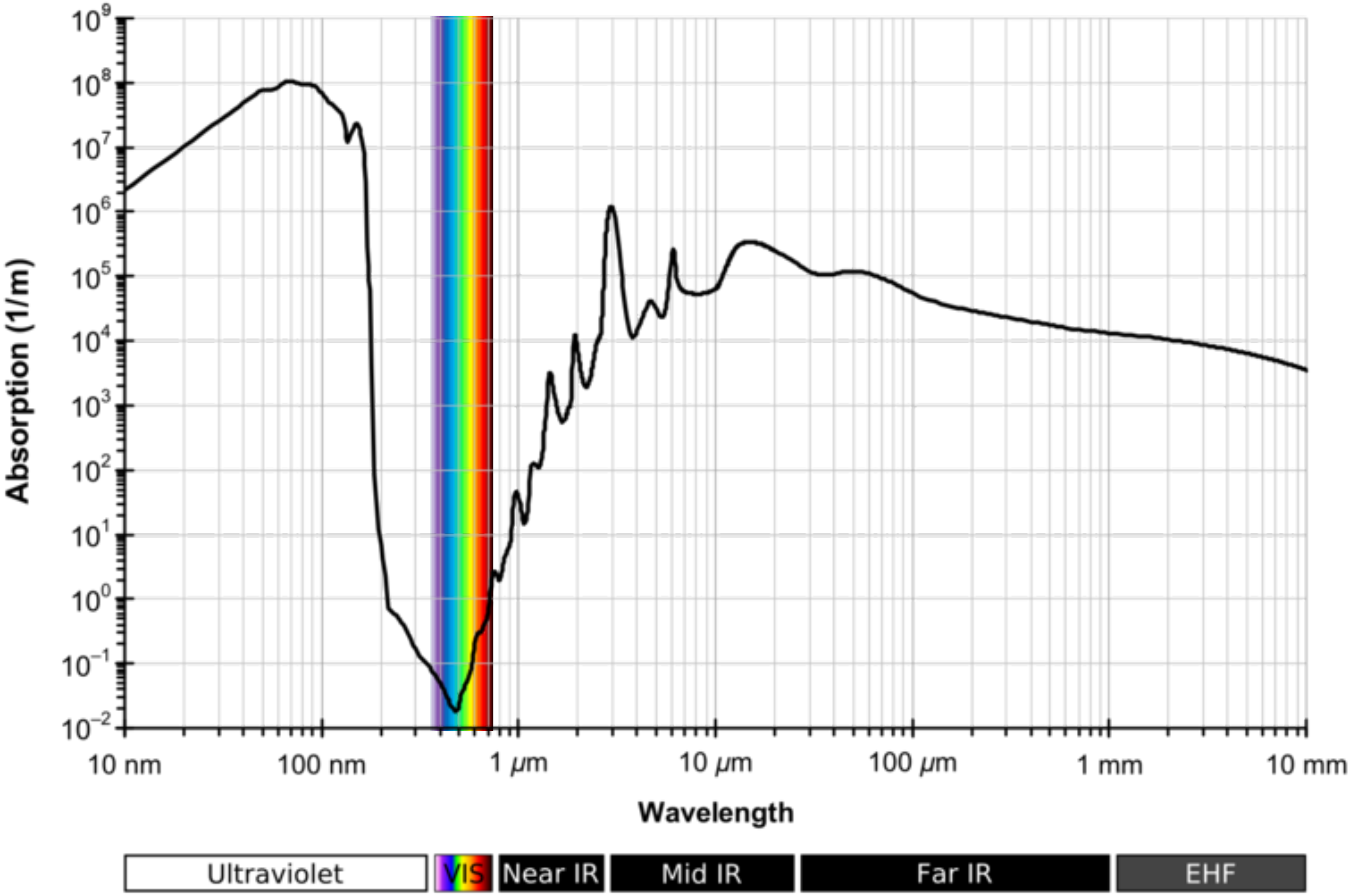
Property	Specification*	Result	Unit
Mirror best flat, residual error	<7	6.44	nm RMS
Wavefront 3x3 stroke	>12.5	17.11	µm PV
Wavefront tip/tilt stroke	>20	22.61	µm PV
Wavefront defocus stroke	>15	18.53	µm PV
Wavefront astigmatism stroke	>15	20.75	µm PV
Linearity	<3	0.28	%
Hysteresis	<2	0.63	%
Peak frequency	>1200	1556	Hz
Frequency at -45° phase	>1000	1832	Hz
Settling time	<0.75	0.61	ms

- up to 5 kHz framerate, average 2 kHz
- 91 µs total latency
- 335 Hz rejection bandwidth



Typical Quantum Efficiency of **SH-EMCCD** (in blue), **SH-CMOS** (in red) and **SH-CMOS *fast*** (in dash red)

Other channels: water

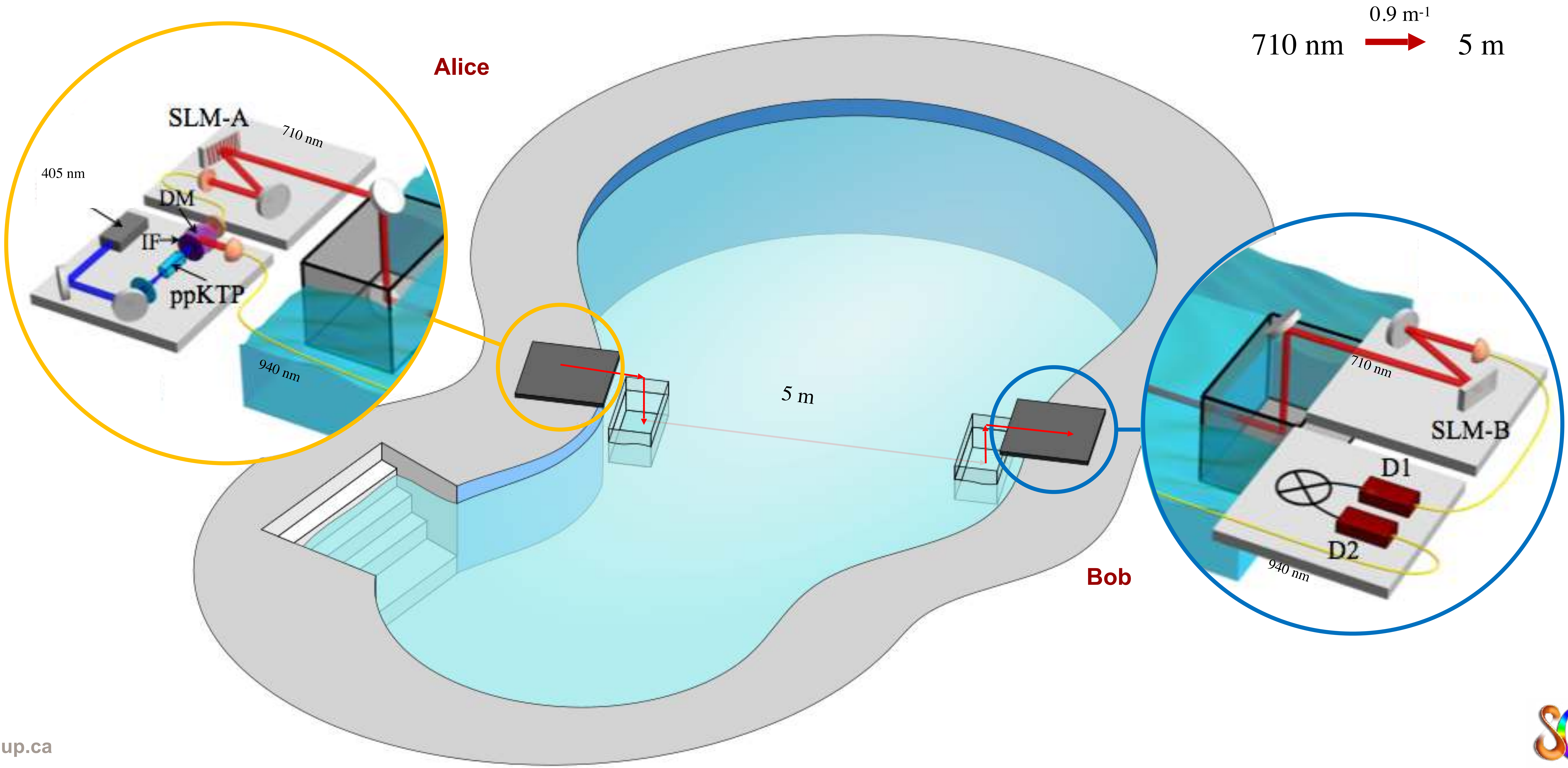


Beer's Law $$L = -\frac{1}{\alpha}\ln\left(\frac{I}{I_0}\right)$$

1550 nm	17000 m^{-1}	300 μm
810 nm	2 m^{-1}	2 m
633 nm	0.3 m^{-1}	15 m
532 nm	0.06 m^{-1}	75 m
420 nm	0.02 m^{-1}	230 m

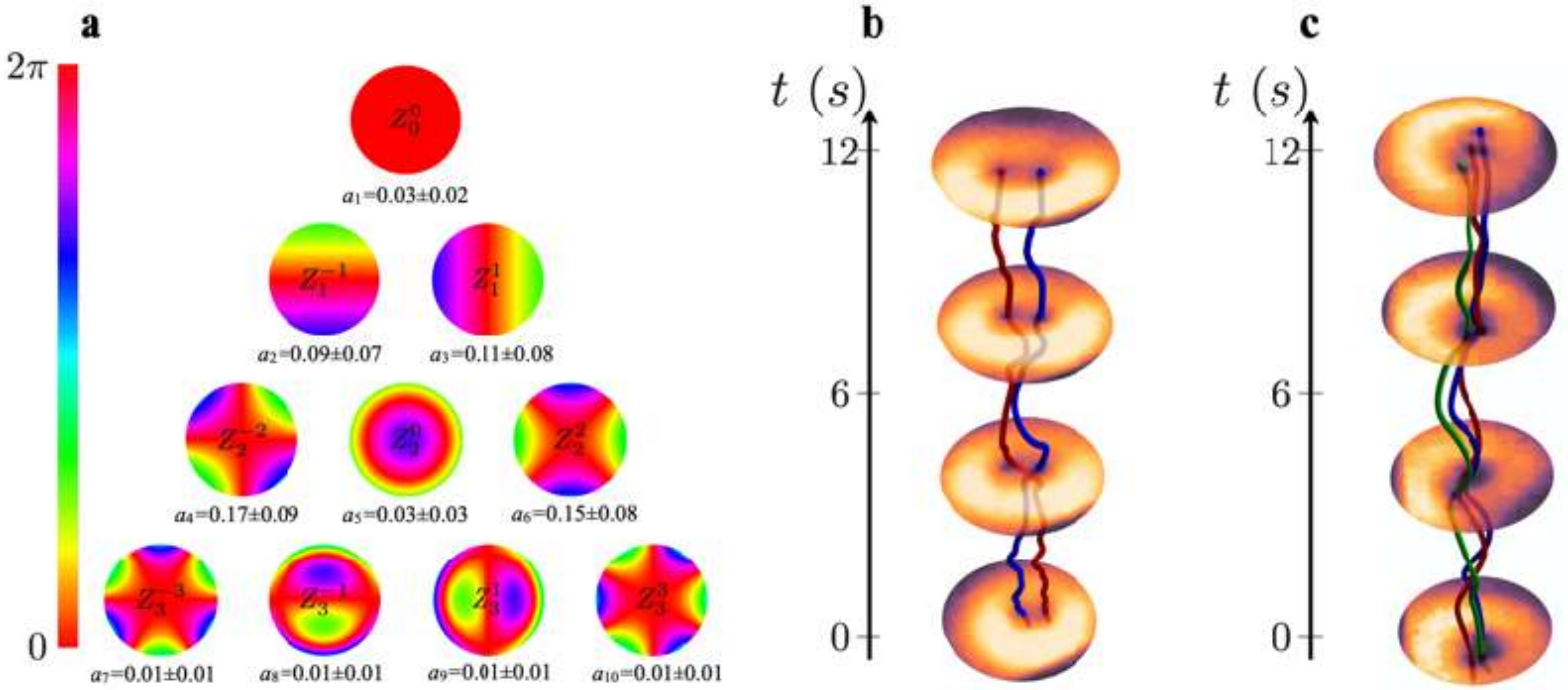
S. A. Sullivan, Opt. Soc. Am. J., 53, 962--968, (1963).
https://en.wikipedia.org/wiki/Electromagnetic_absorption_by_water

Other channels: water

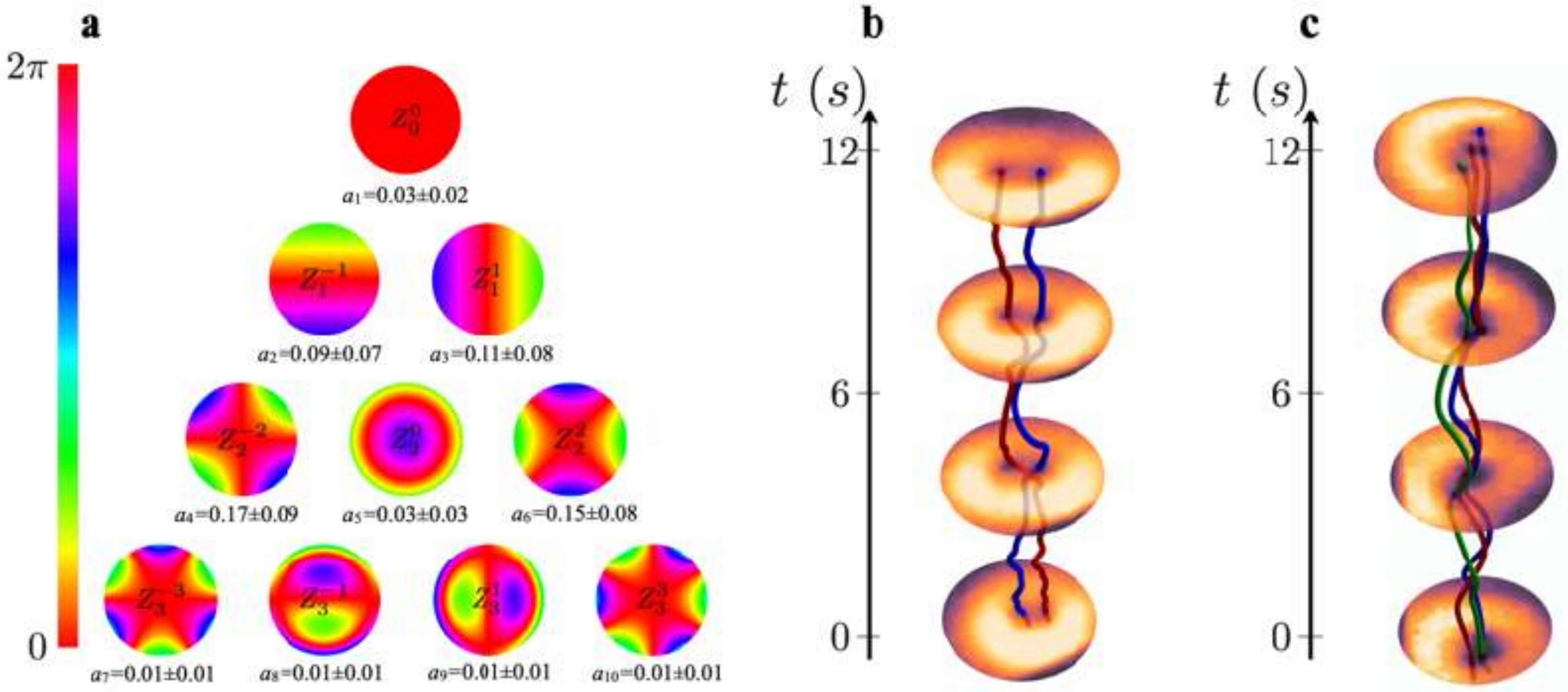


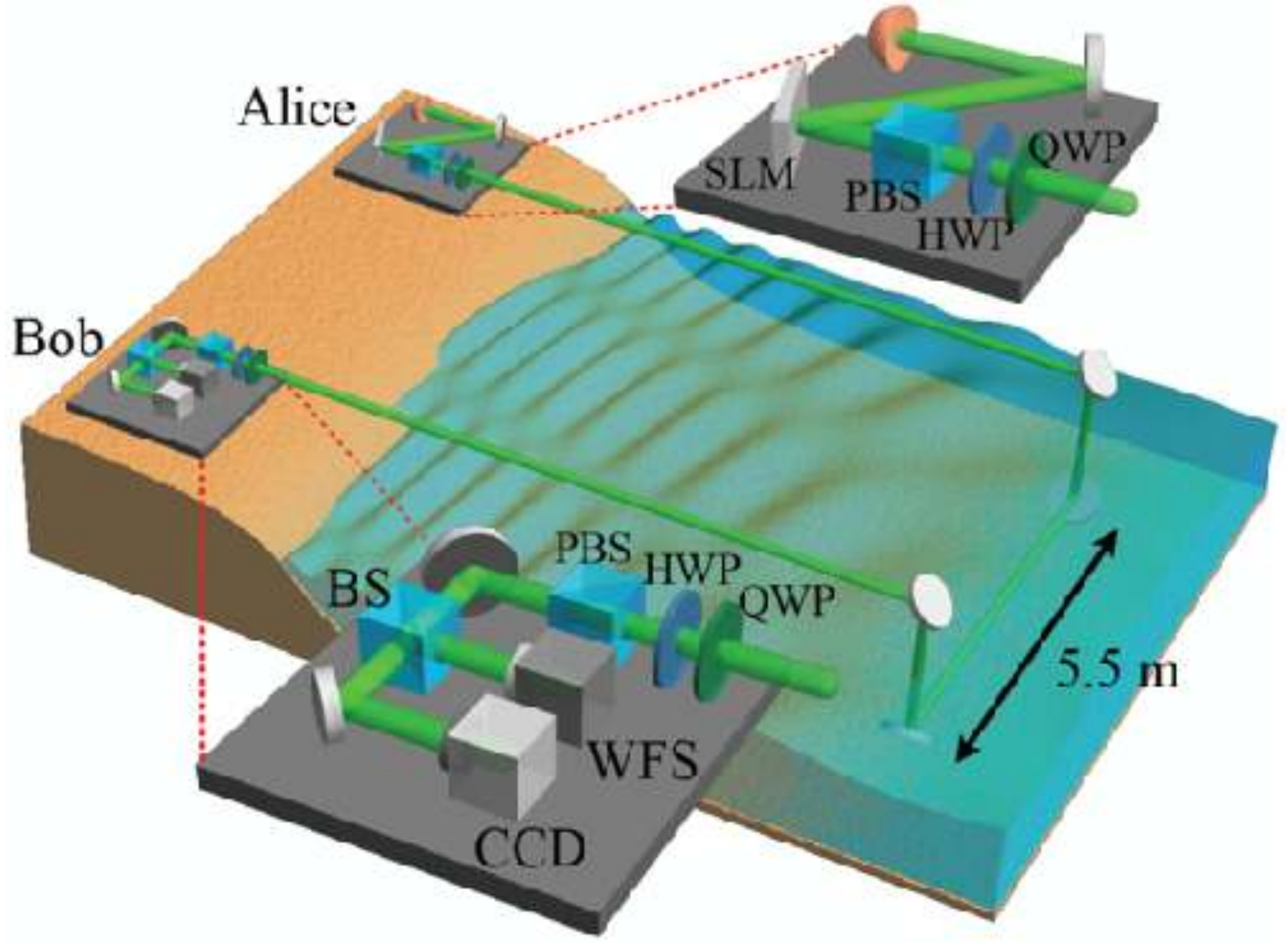
Quantum Cryptography through Underwater Channels

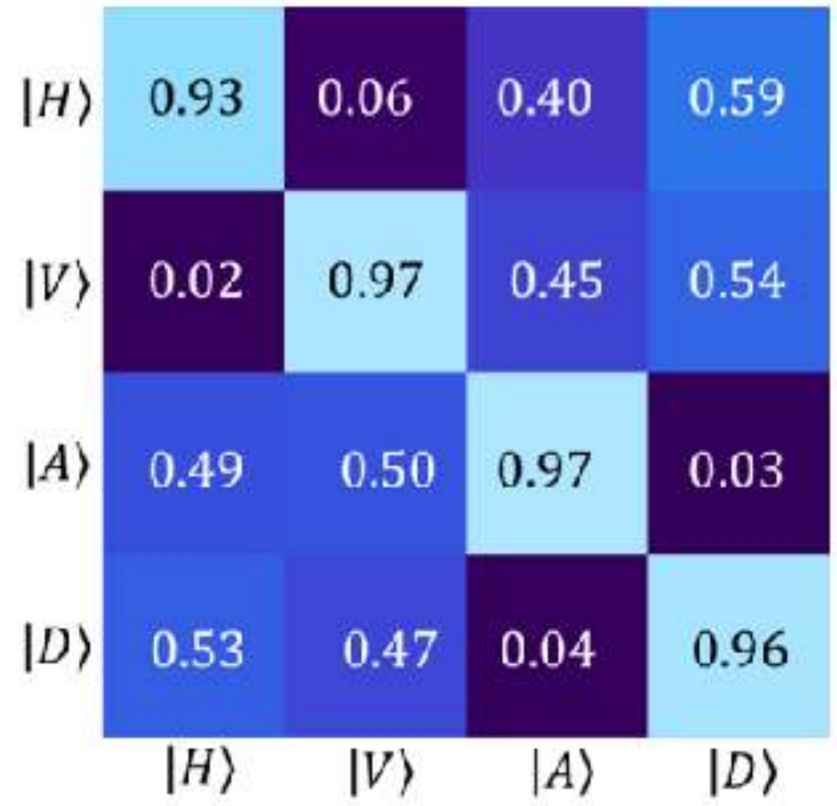
Quantum Cryptography through Underwater Channels



Quantum Cryptography through Underwater Channels

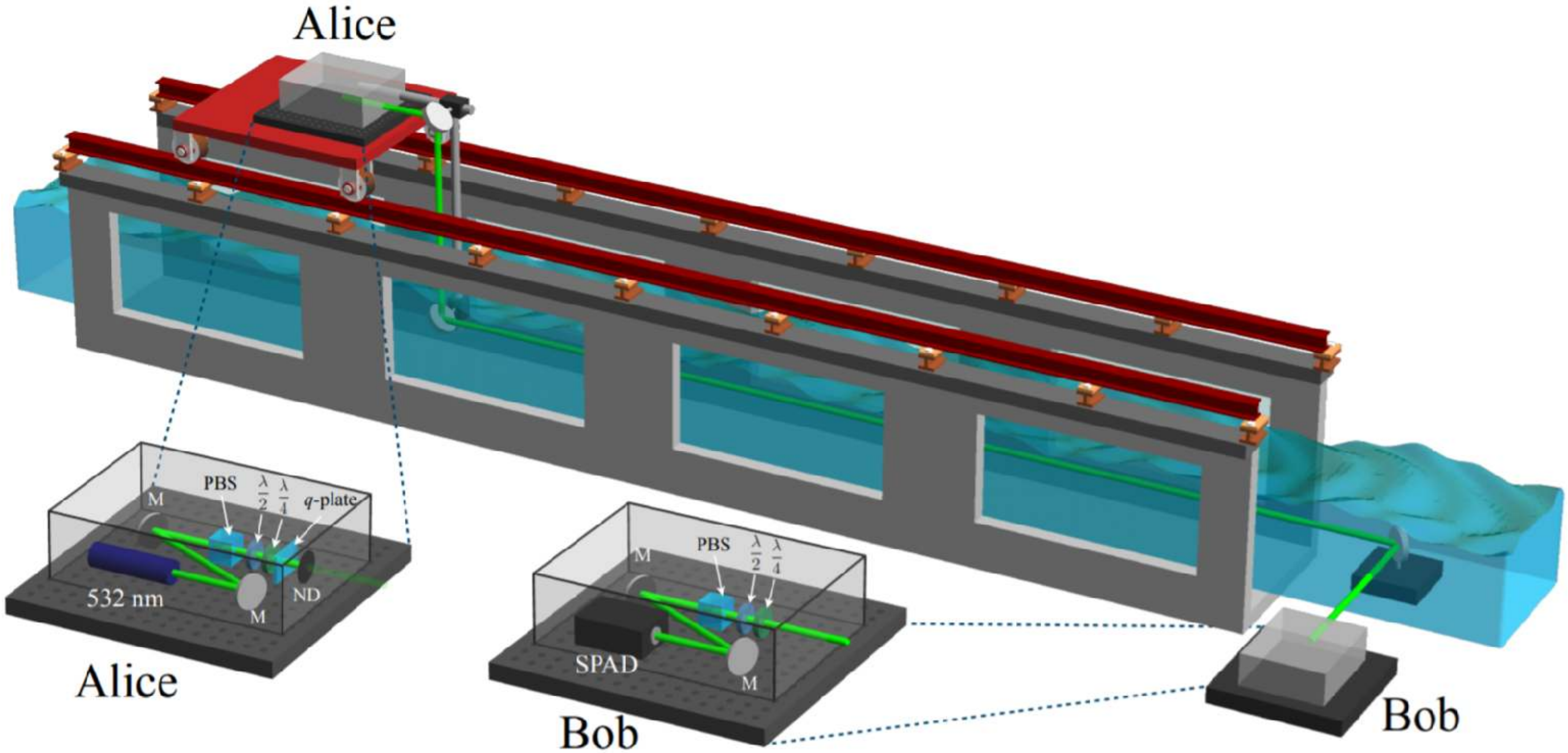






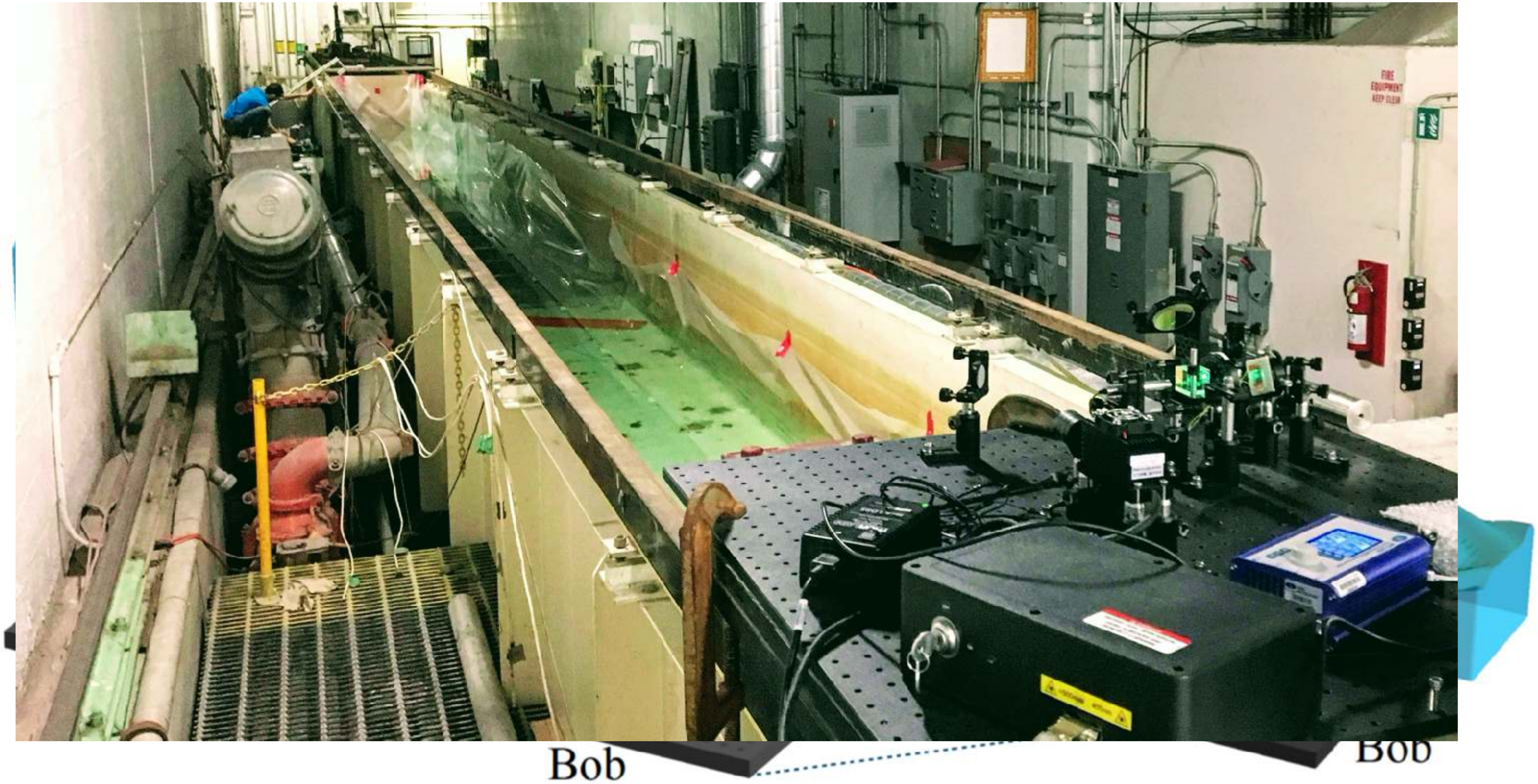
$\|H\rangle$	0.93	0.06	0.40	0.59
$\|V\rangle$	0.02	0.97	0.45	0.54
$\|A\rangle$	0.49	0.50	0.97	0.03
$\|D\rangle$	0.53	0.47	0.04	0.96
	$\|H\rangle$	$\|V\rangle$	$\|A\rangle$	$\|D\rangle$

Underwater Quantum Cryptography through 30 m Channel



F Hufnagel, A Sit, F Bouchard, Y Zhang, D England, K Heshami, B J Sussman & E.K., *New Journal of Physics* **22**, 093074 (2020).

Underwater Quantum Cryptography through 30 m Channel



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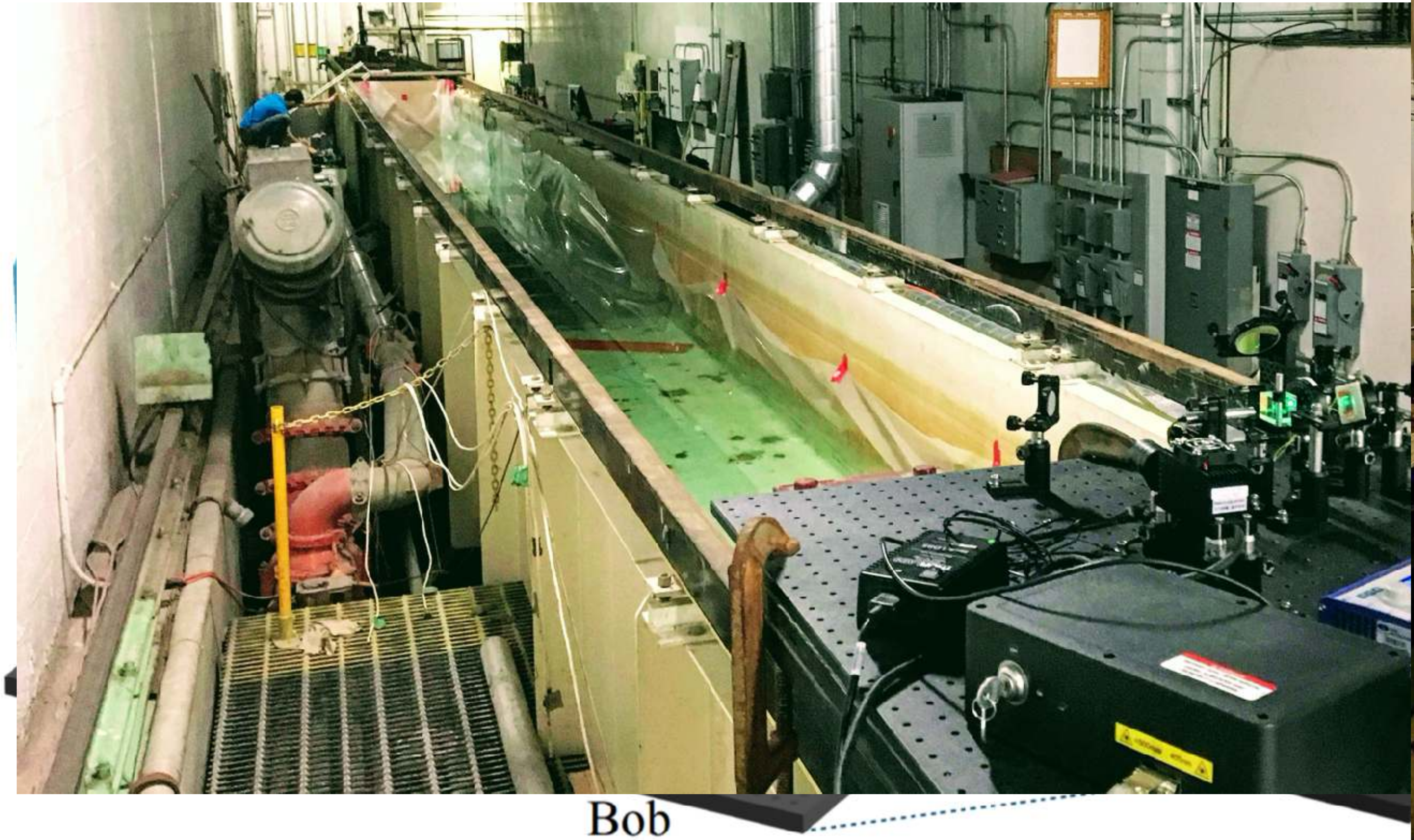
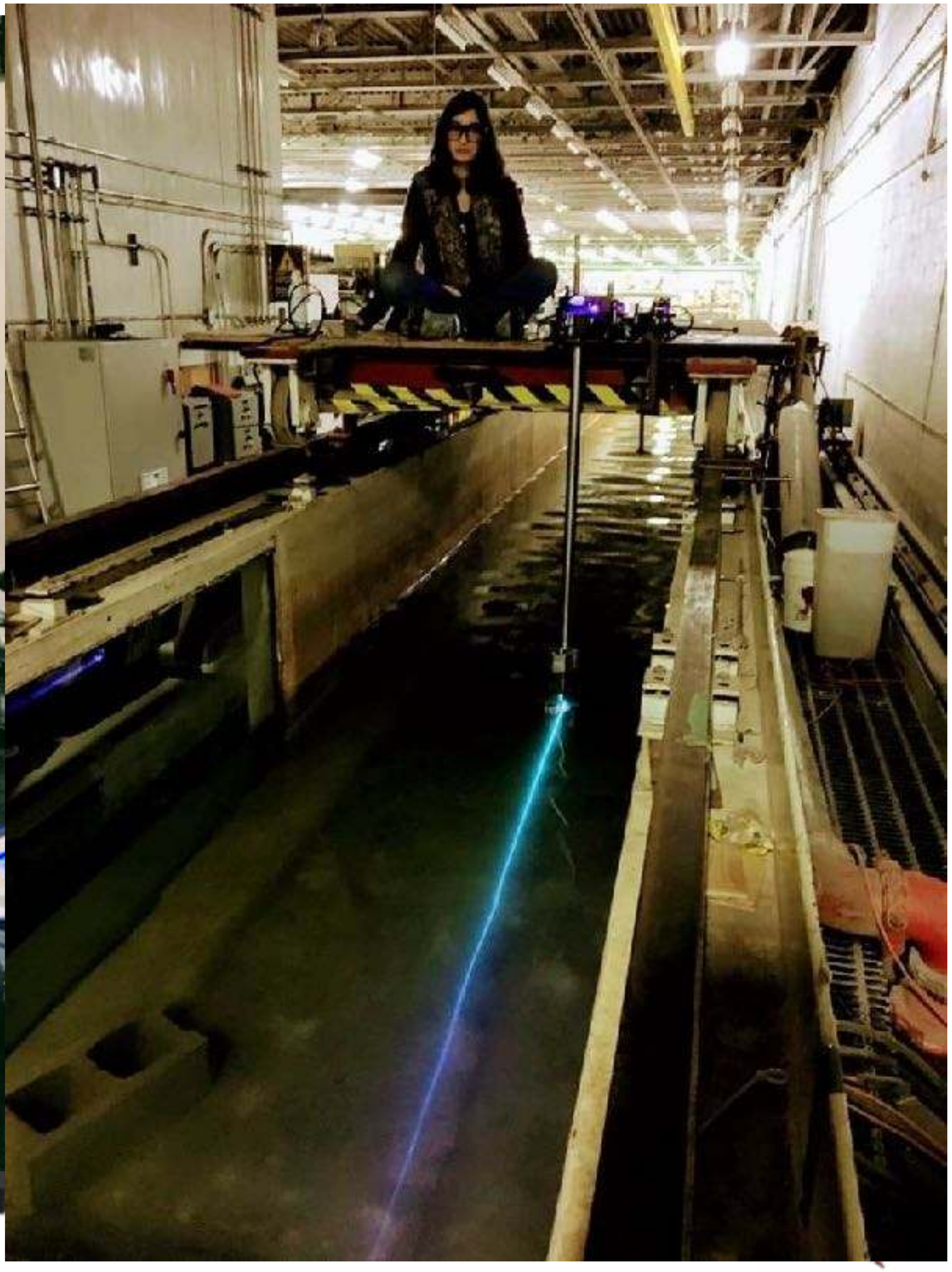
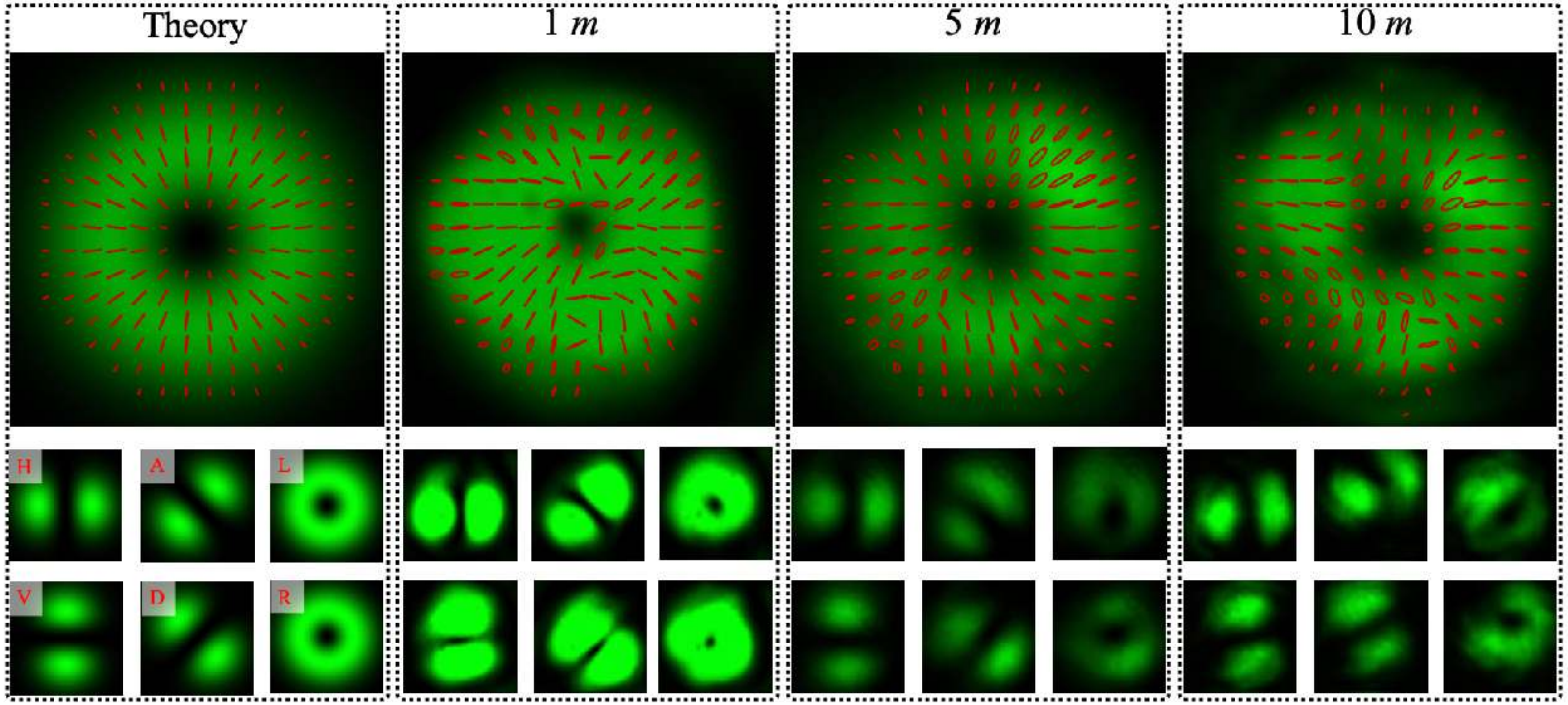
Underwater Quantum Cryptography through 30 m Channel





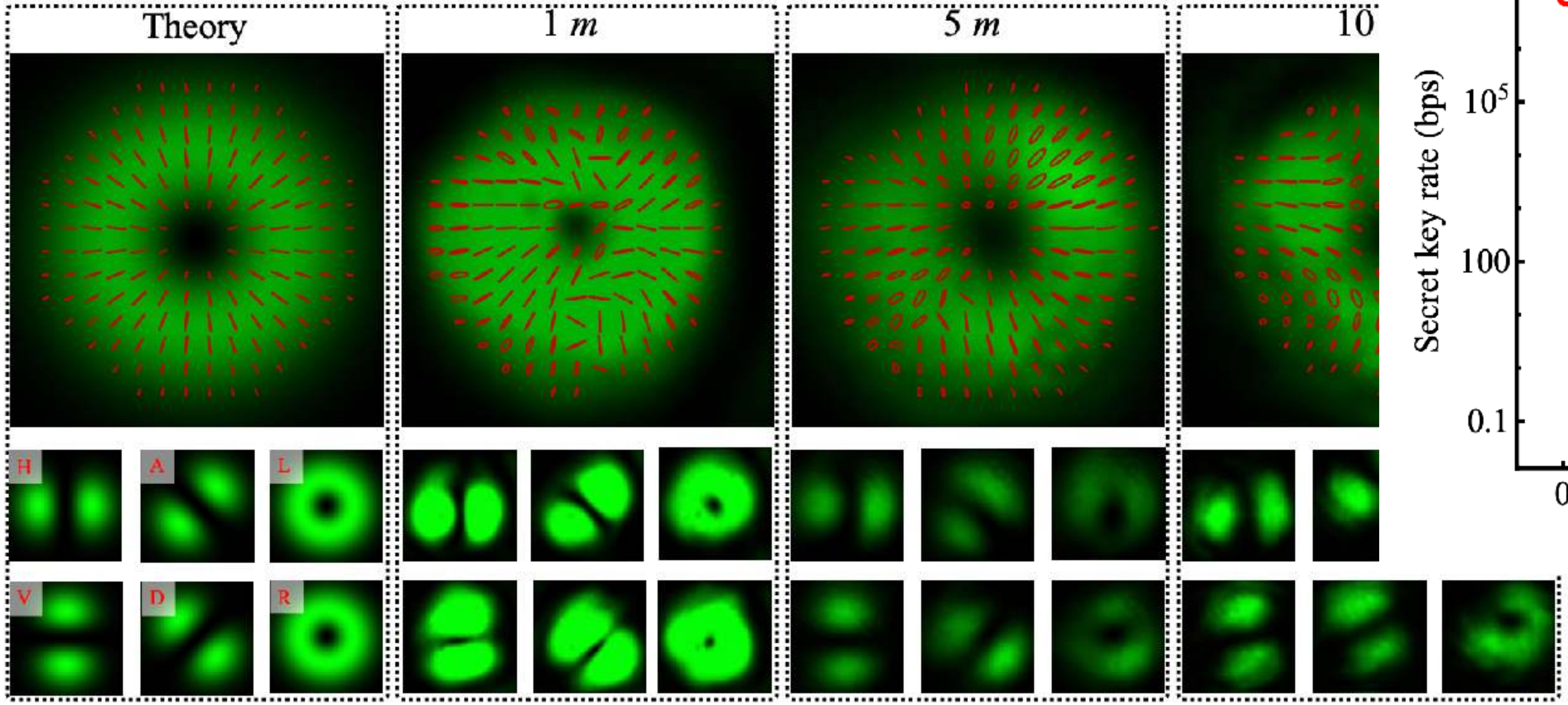
F Hufnagel, A Sit, F Bouchard, Y Zhang, D England, K Heshami, B J Sussman & E.K., *New Journal of Physics* **22**, 093074 (2020).

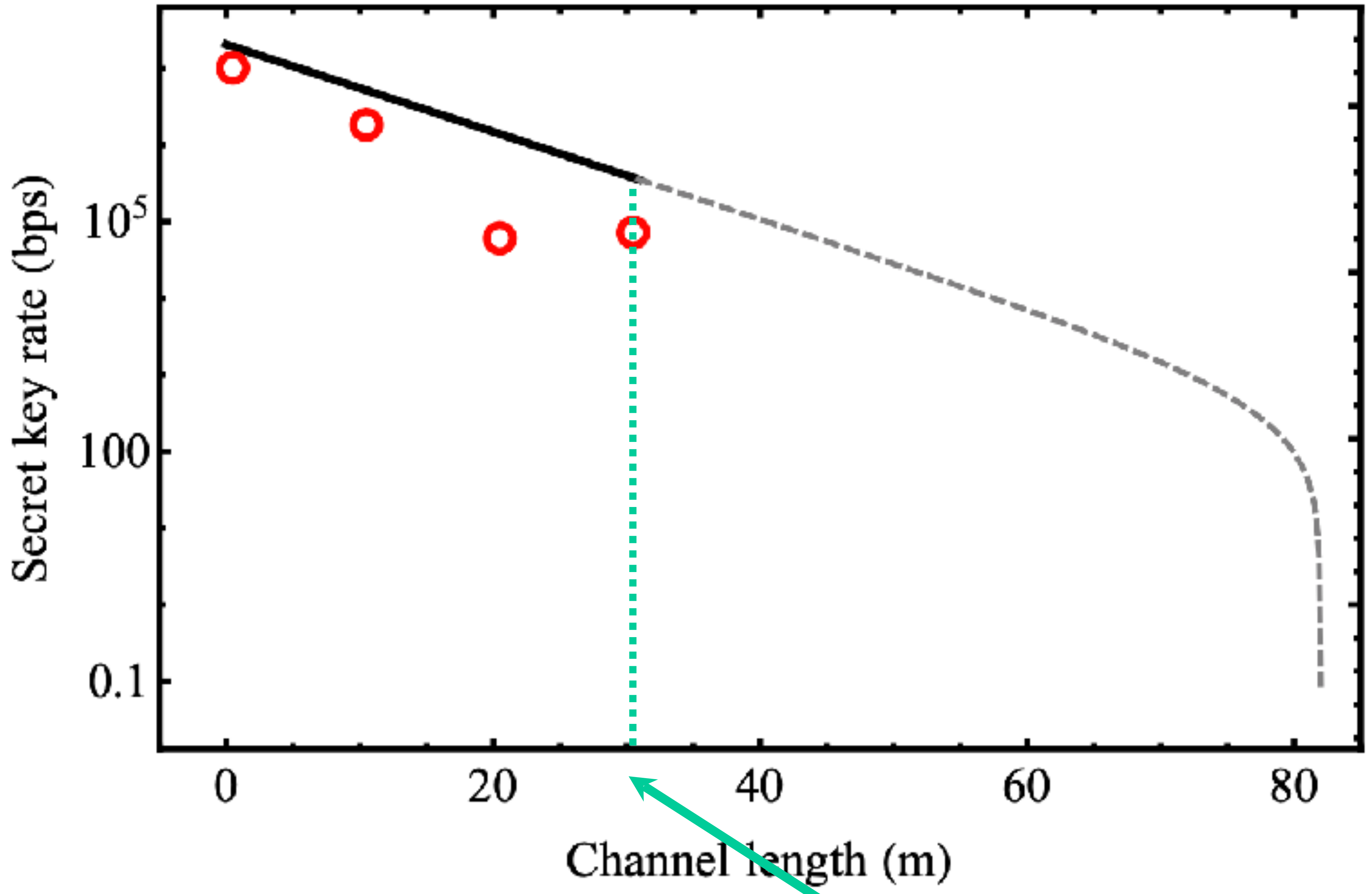
Underwater Quantum Cryptography in the NRC Flumes



F Hufnagel, A Sit, F Bouchard, Y Zhang, D England, K Heshami, B J Sussman & E.K., *New Journal of Physics* **22**, 093074 (2020).

Underwater Quantum Cryptography in the NRC Flumes

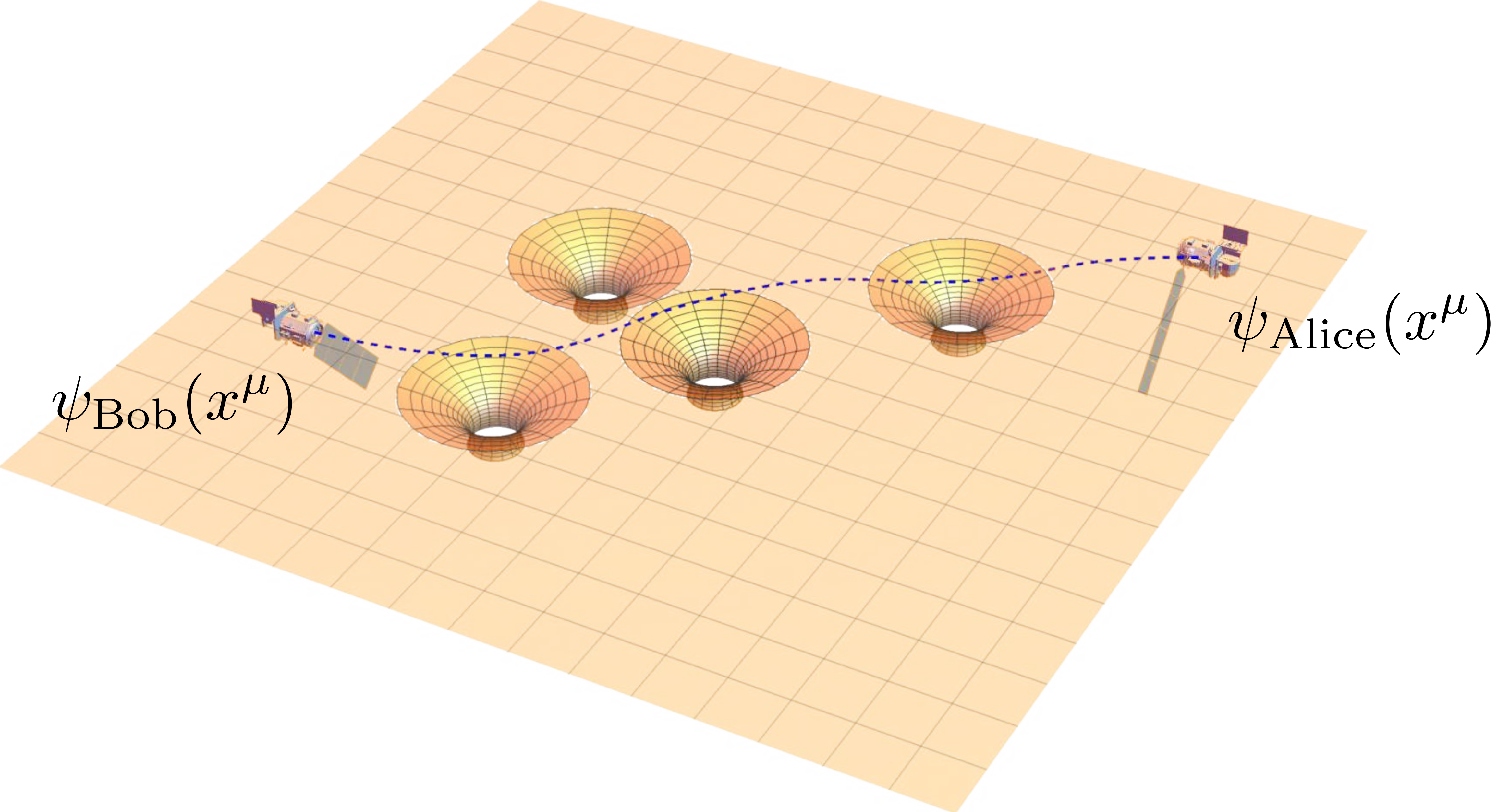


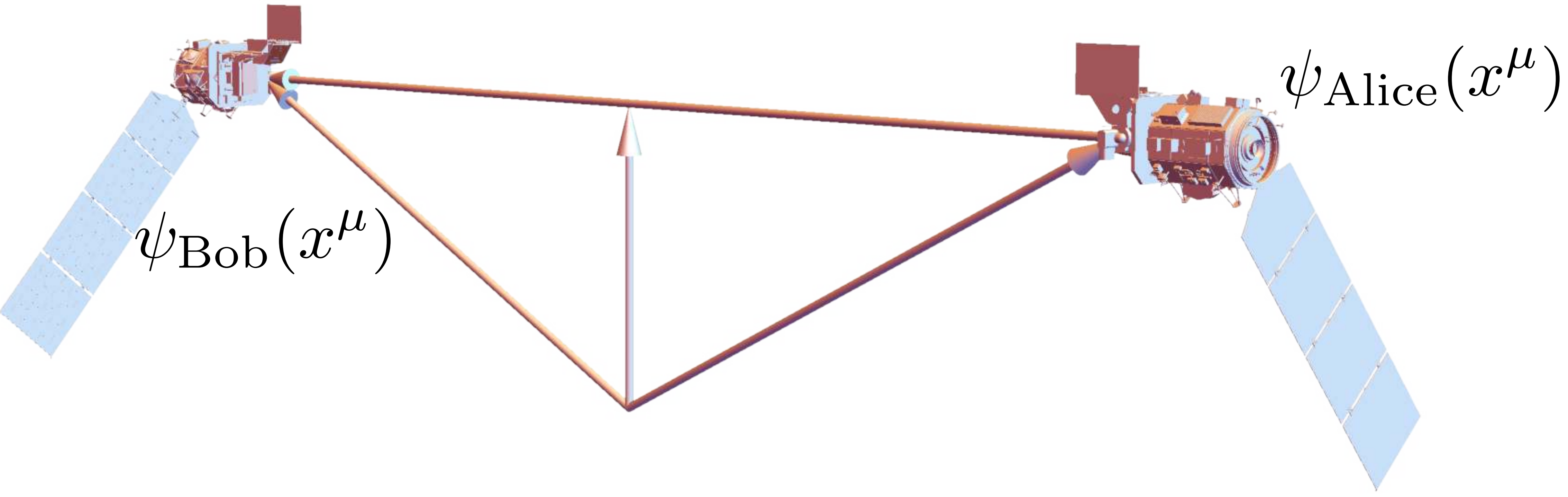


Key rate at 30.5 m is about 80 kb/s

F Hufnagel, A Sit, F Bouchard, Y Zhang, D England, K Heshami, B J Sussman & E.K., *New Journal of Physics* **22**, 093074 (2020).

Quantum Communication in a Curved Spacetime Geometry



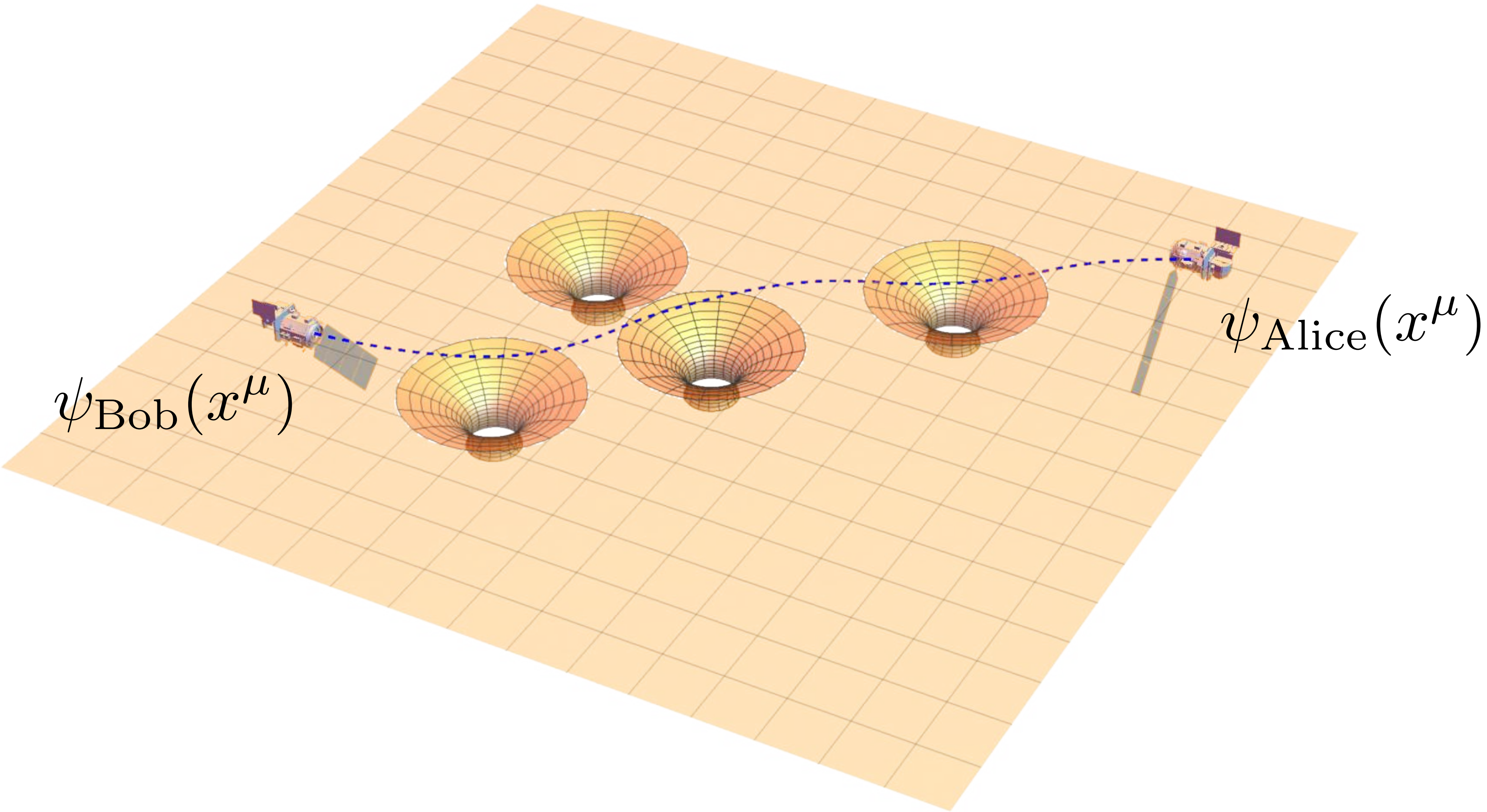


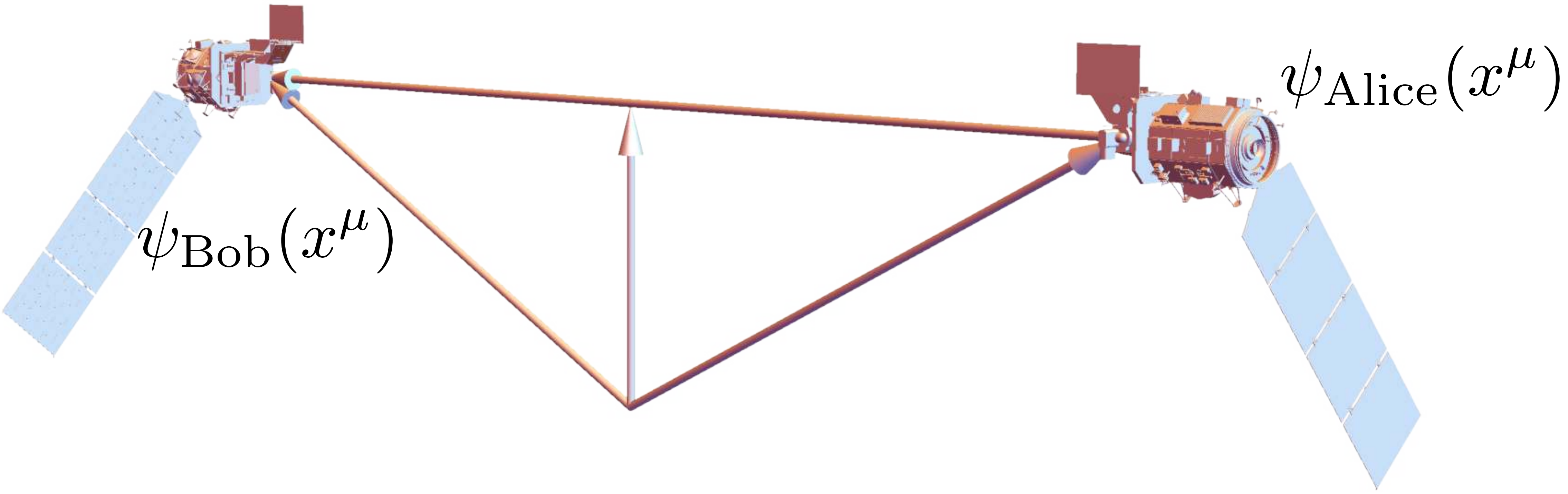
$$\psi_{\text{Bob}}(x^\mu) \simeq \psi^{(0)}(x^\mu) + \epsilon\psi^{(1)}(x^\mu) + \dots$$

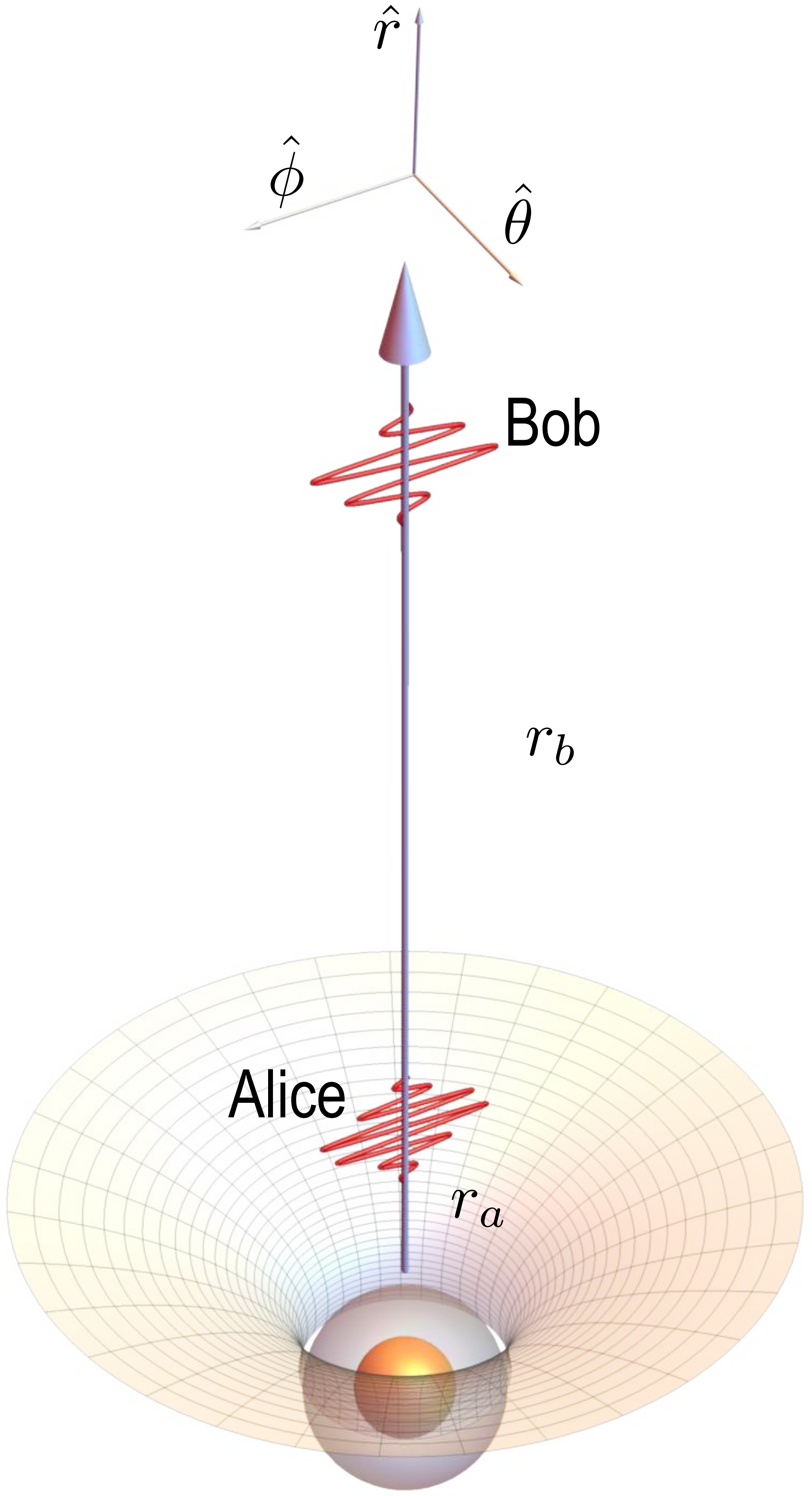
$$\Box^{(0)}\psi^{(1)} = -R_{+\bar{a}+\bar{b}}\; x^{\bar{a}}x^{\bar{b}}\partial_-^2\psi^{(0)}$$

Q Exirifard, E Culf & E.K., under review *arXiv:2009.04217*

Quantum Communication in a Curved Spacetime Geometry







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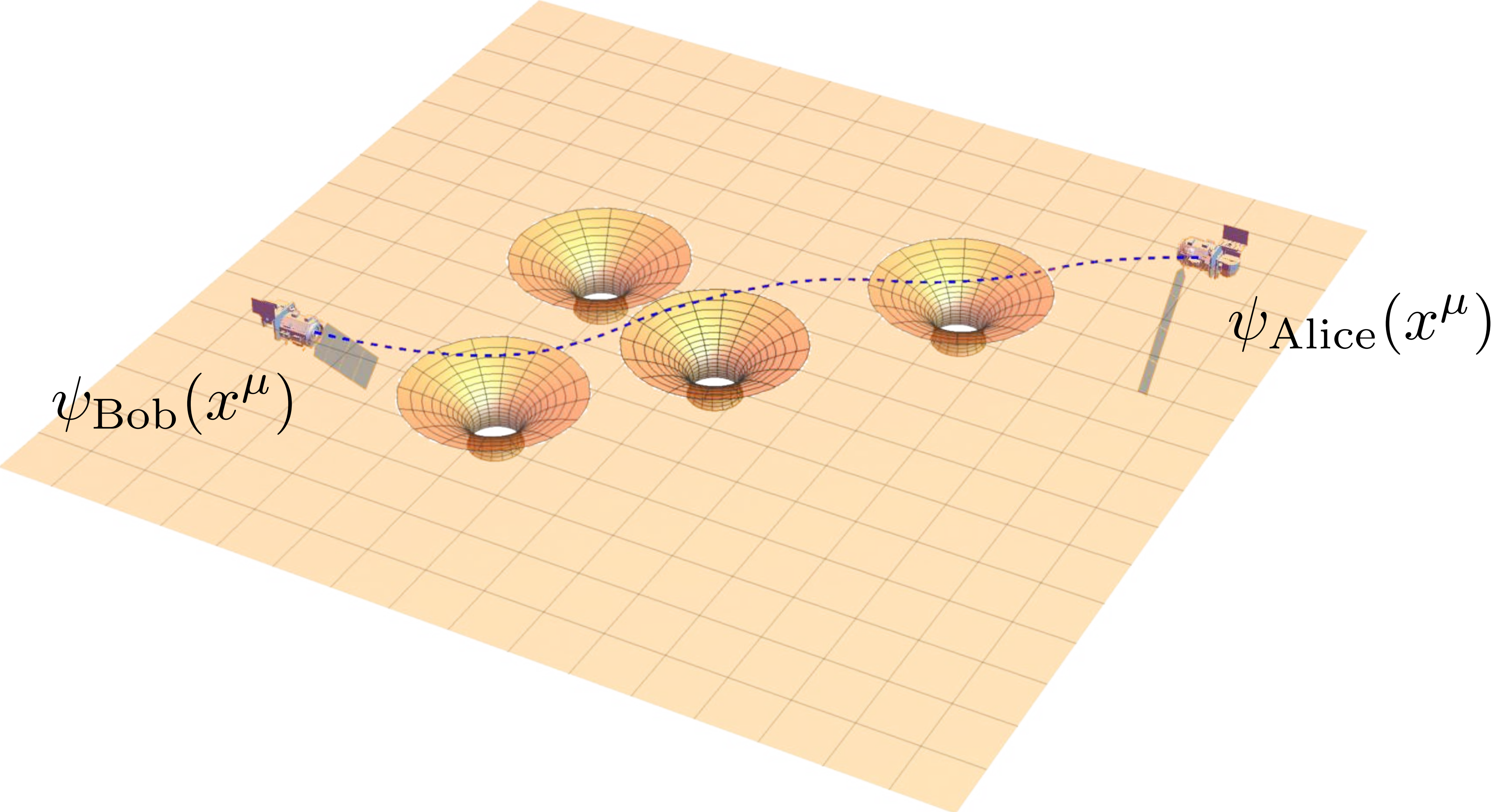

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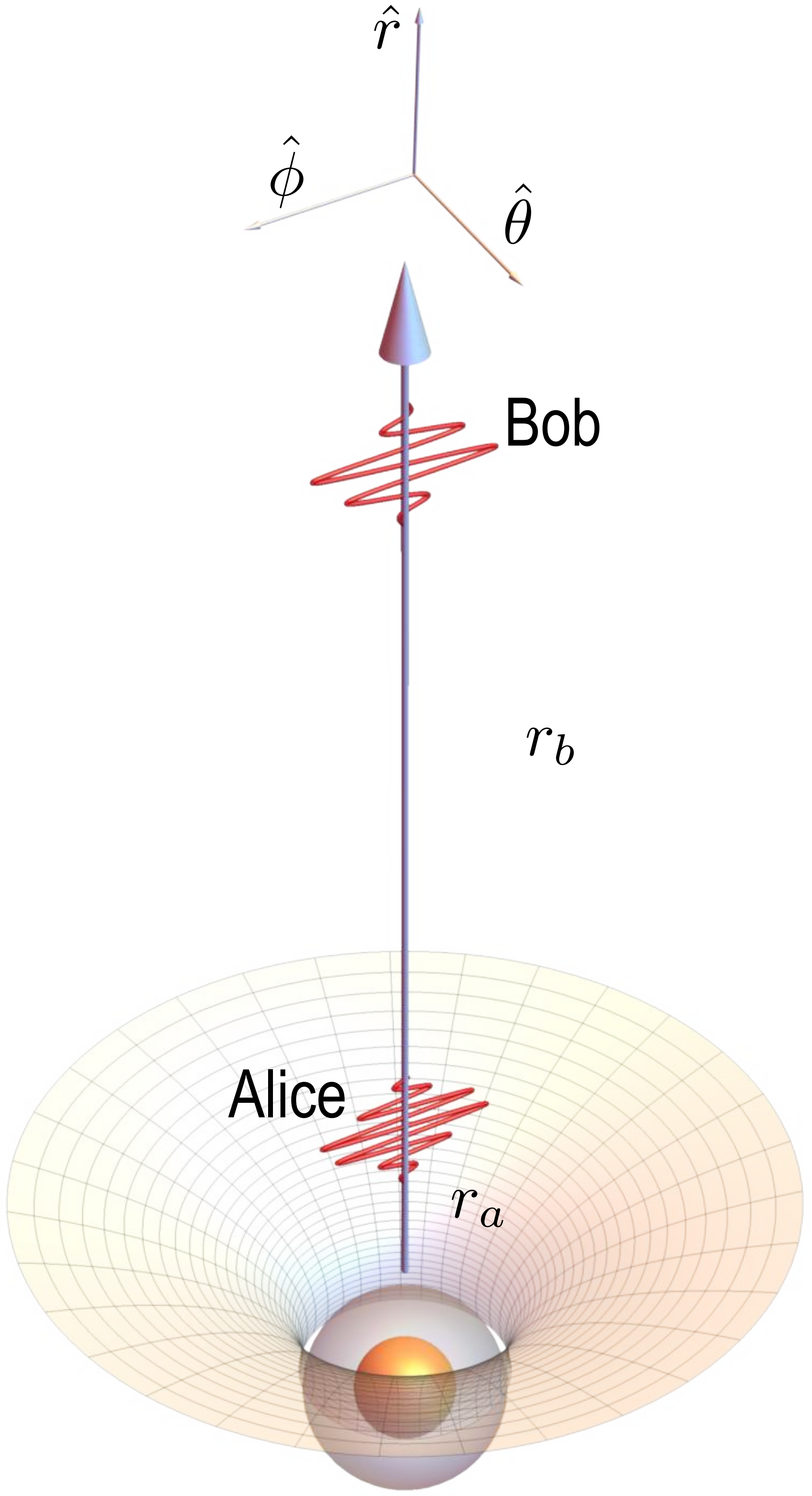

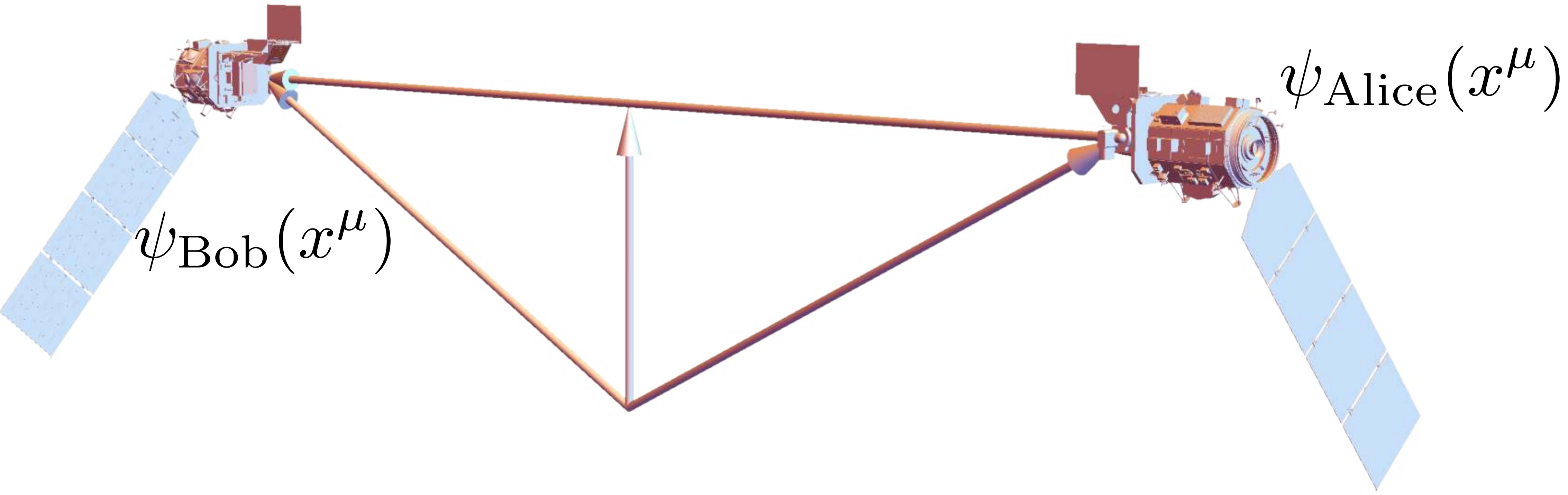

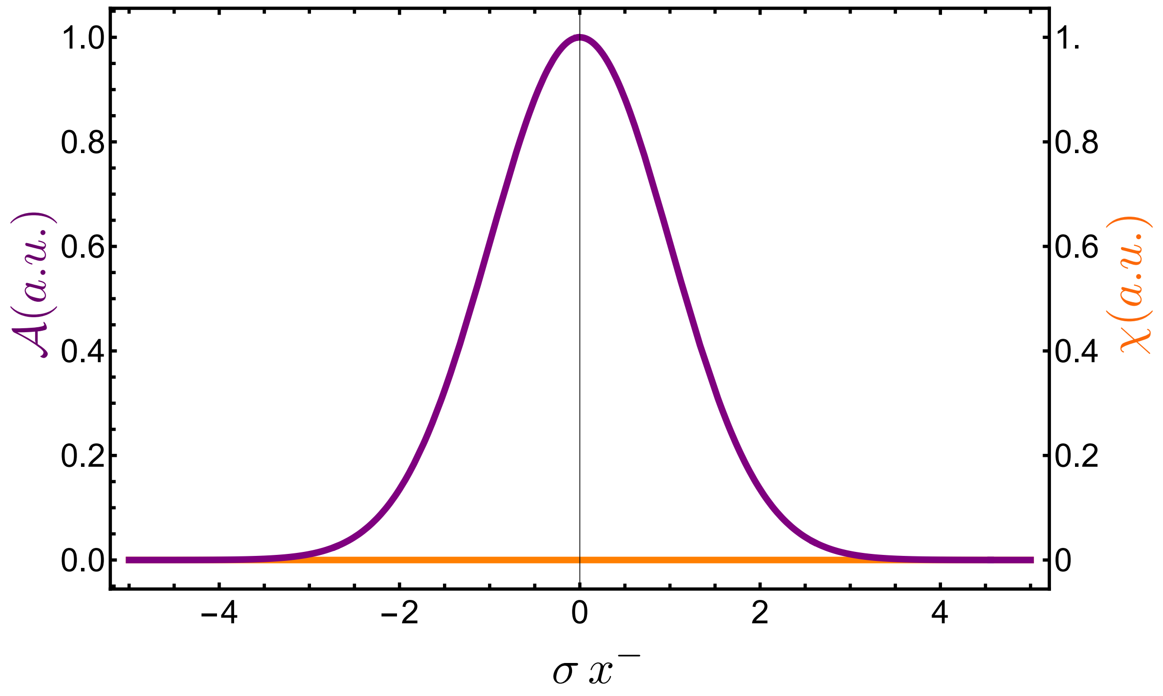

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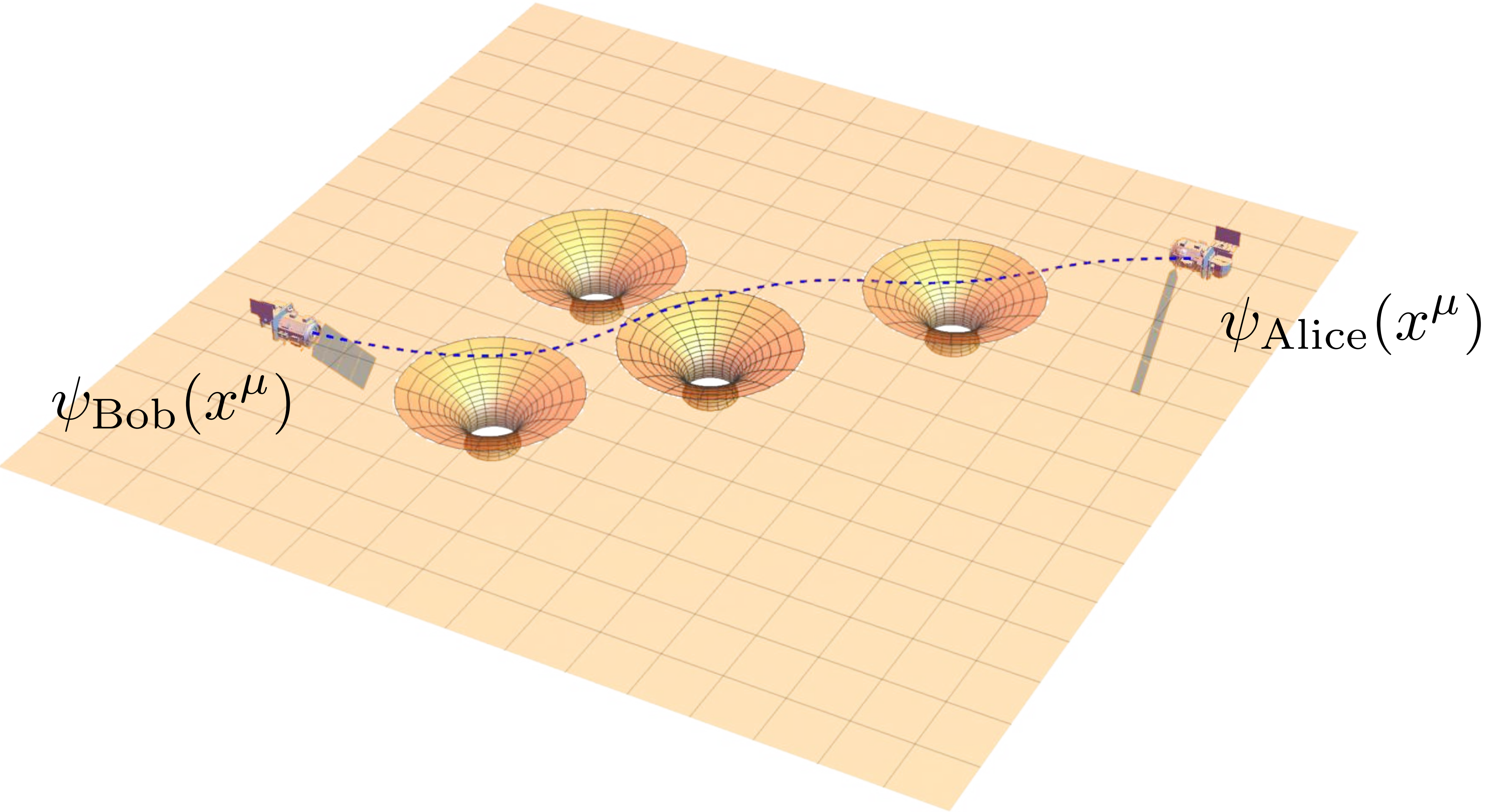

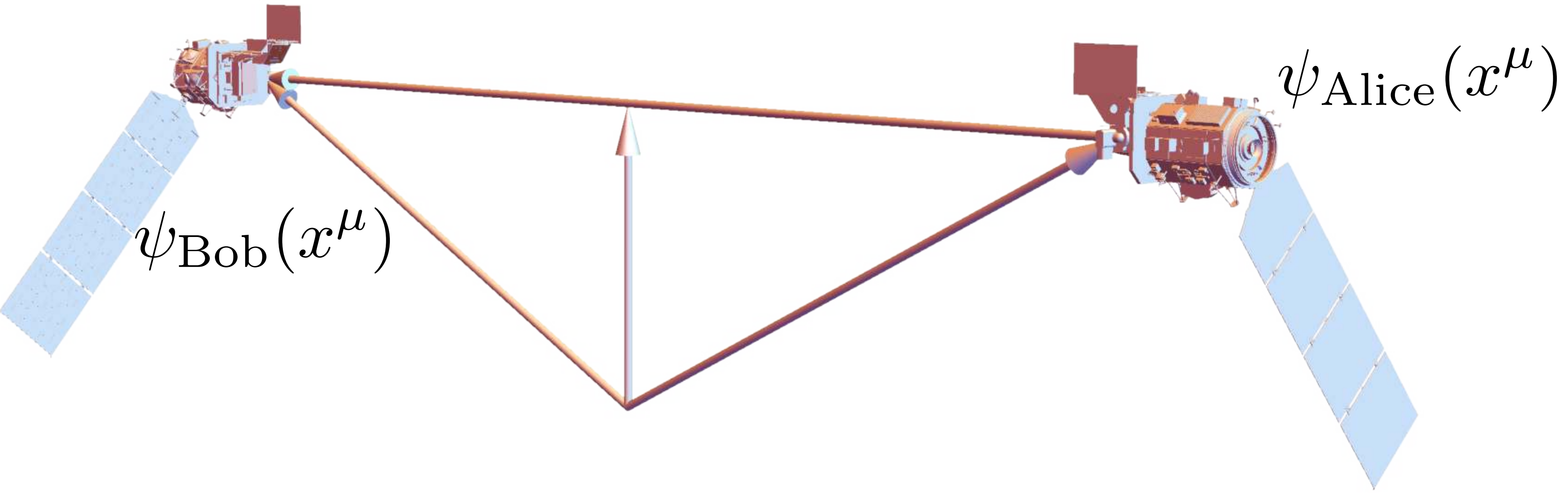

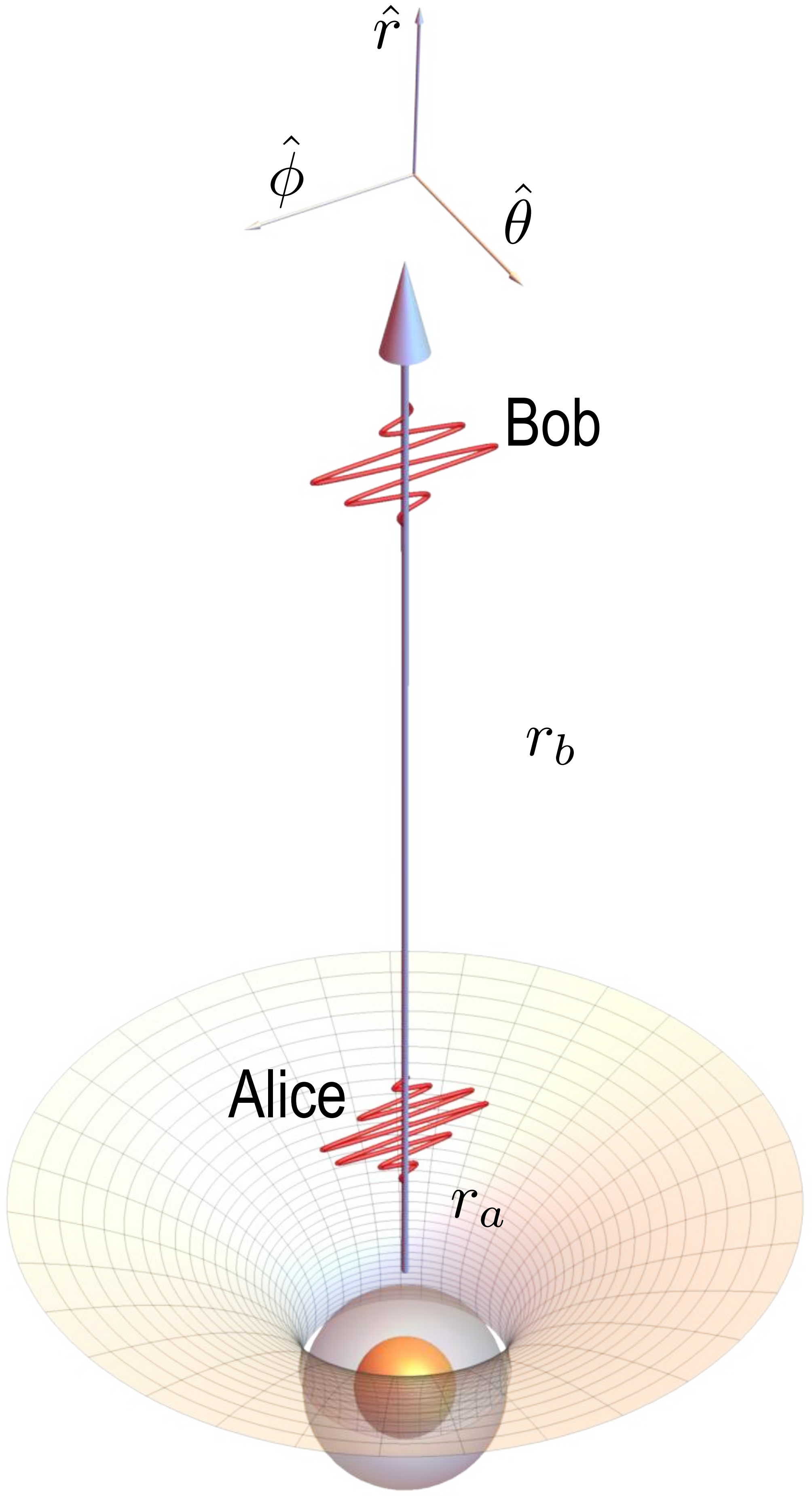

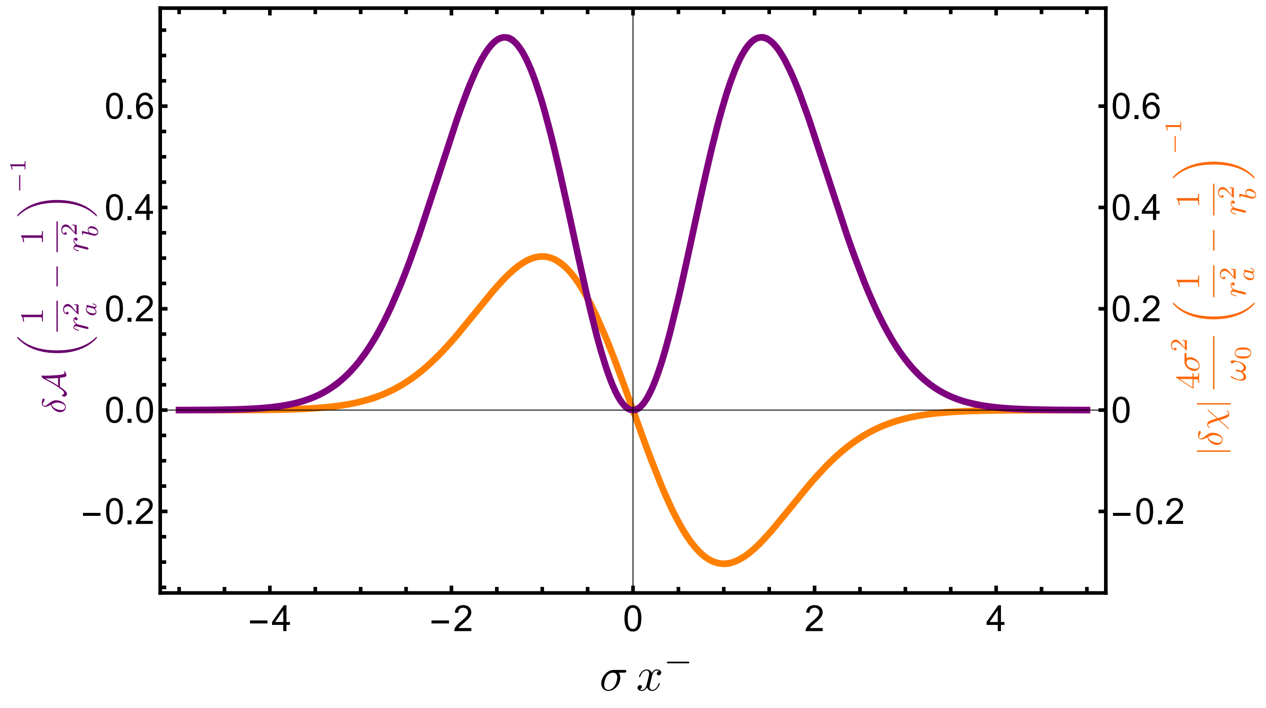

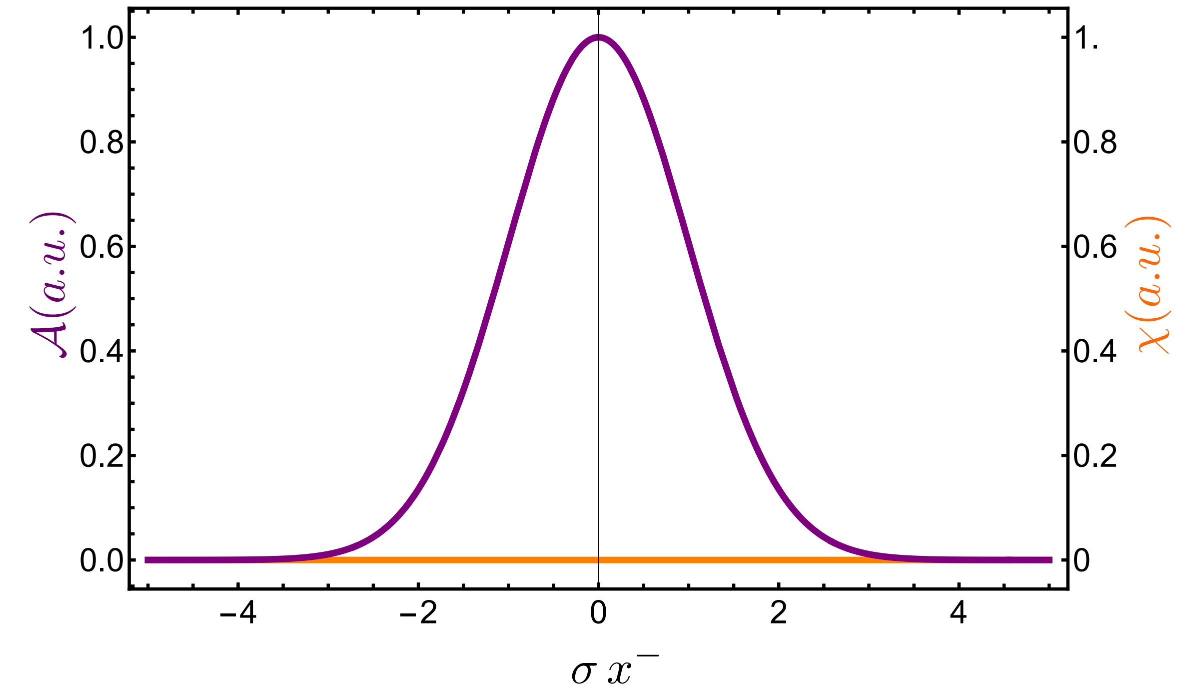

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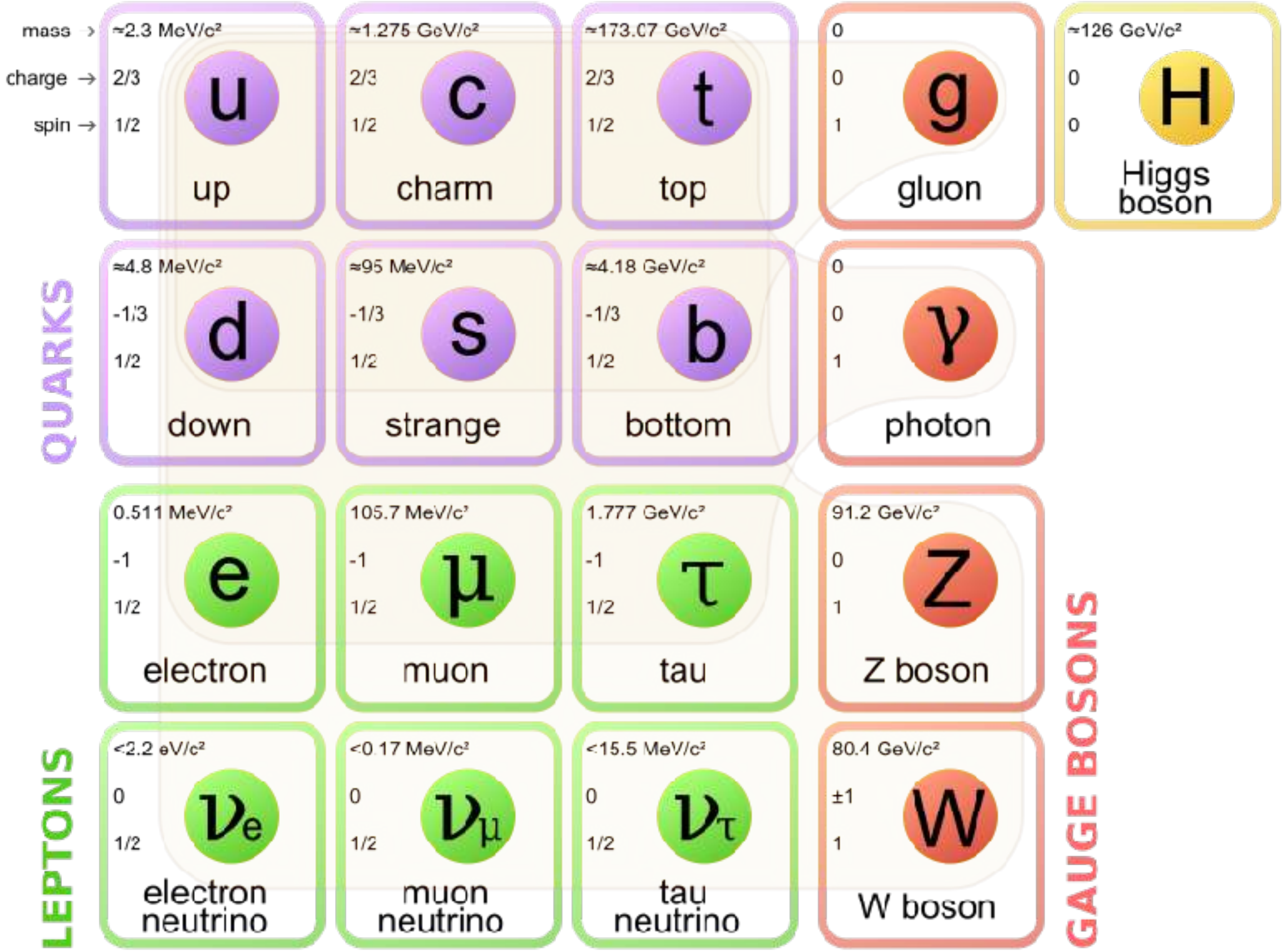
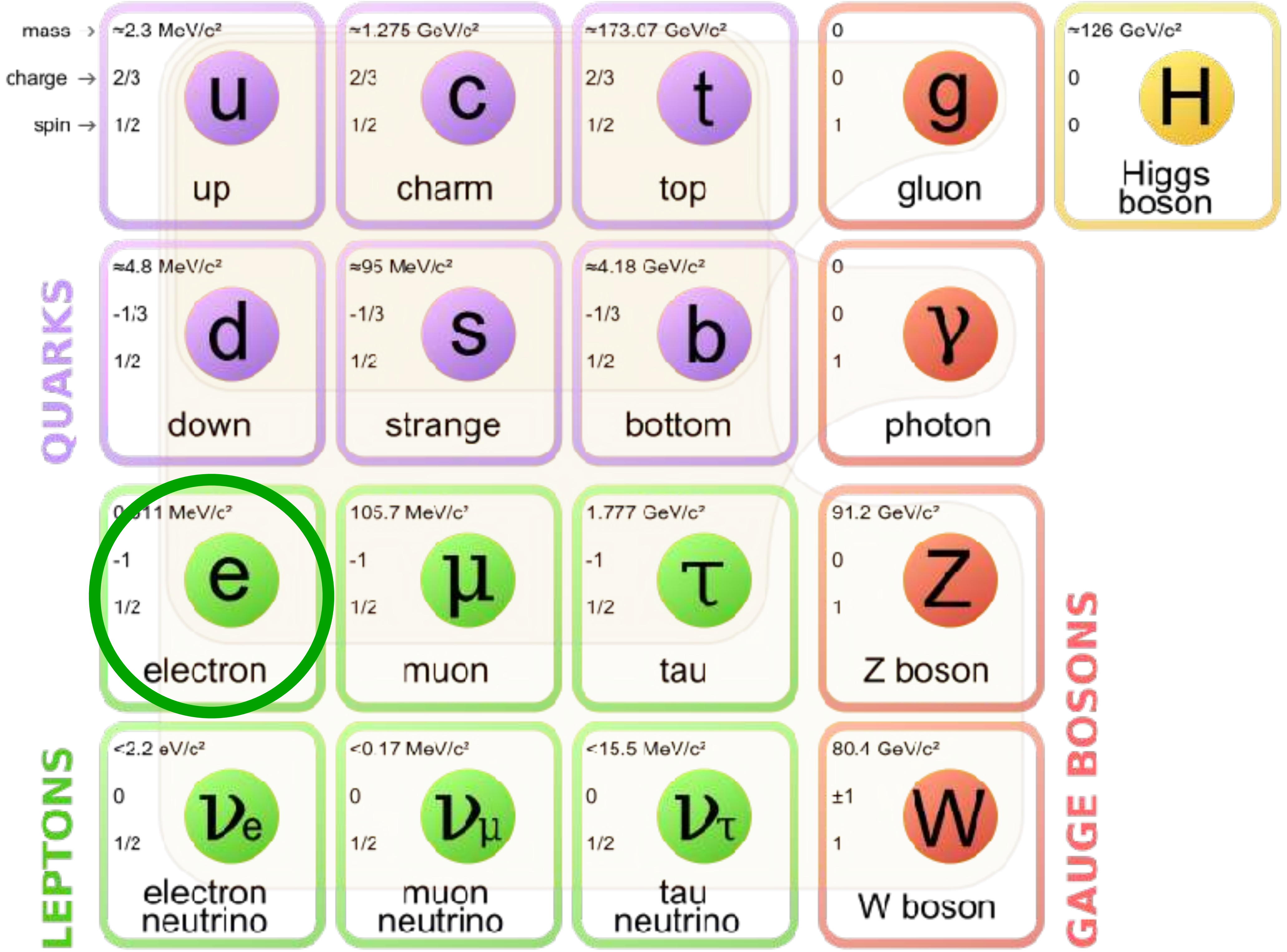
Structured Matter Waves

Elementary particles



Elementary particles



» An elementary particle

$$m_e = 9.10 \times 10^{-31}\, kg$$

$$e = -1.6 \times 10^{-19}\, C$$

$$|\mathbf{S}| = \frac{1}{2}$$

Structured Massive Particles

$\psi(\mathbf{r}; t)$ Wavefunction

K.Y. Bliokh, Y. P. Bliokh, S. Savel'Ev, F. Nori, *Phys. Rev. Lett.* **99**, 190404 (2007).
H Larocque, I Kaminer, V Grillo, G Leuchs, M J Padgett, R W Boyd, M Segev & E.K., *Contemporary Physics* **59**, 1 (2018).
J. Harris, V Grillo, E Mafakheri, G C Gazzadi, S Frabboni, R W Boyd, & E.K., *Nature Physics* **11**, 629 (2015).

Structured Massive Particles

$\psi(\mathbf{r};t)$ Wavefunction

relativistic $$(i\hbar\gamma^{\mu}\partial_{\mu} - mc)\psi(\mathbf{r};t) = 0$$

K.Y. Bliokh, Y. P. Bliokh, S. Savel'Ev, F. Nori, *Phys. Rev. Lett.* **99**, 190404 (2007).
H Larocque, I Kaminer, V Grillo, G Leuchs, M J Padgett, R W Boyd, M Segev & E.K., *Contemporary Physics* **59**, 1 (2018).
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Structured Massive Particles

$\psi(\mathbf{r};t)$ Wavefunction

non-relativistic $$-\frac{\hbar^2}{2m}\nabla^2\psi(\mathbf{r};t)=i\hbar\,\partial_t\psi(\mathbf{r};t)$$

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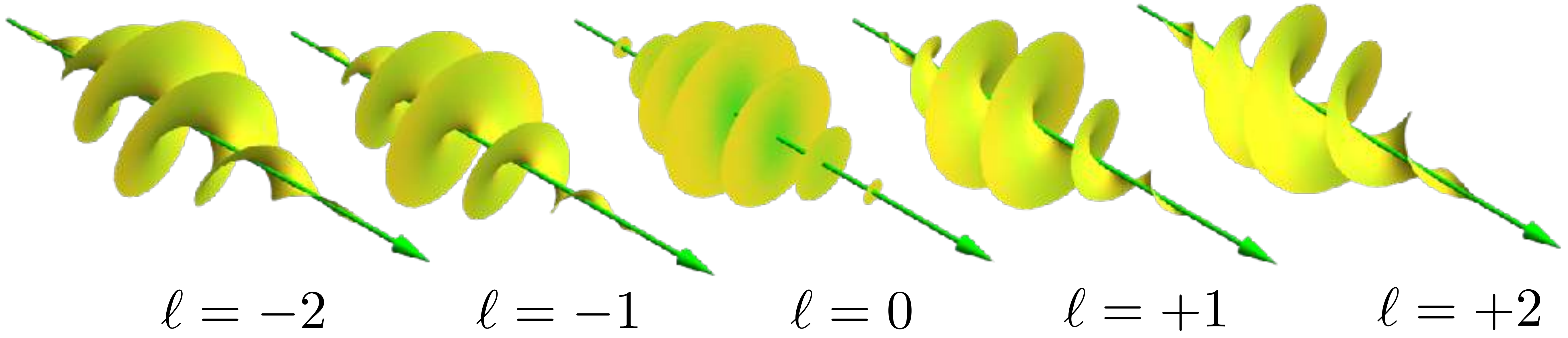
Structured Massive Particles

$\psi(\mathbf{r};t)$ Wavefunction



non-relativistic $$-\frac{\hbar^2}{2m}\nabla^2\psi(\mathbf{r};t)=i\hbar\,\partial_t\psi(\mathbf{r};t)$$

$$\phi_{\ell,p,n}(r,\varphi,z;\,t)=\psi^{\mathrm{LG}}_{\ell,p}(r,\varphi;\,t)\,u^{\mathrm{HG}}_{n}(z-(p_0/m_e)t)$$

azimuthal

radial

longitudinal index

transverse indices

K.Y. Bliokh, Y. P. Bliokh, S. Savel'Ev, F. Nori, *Phys. Rev. Lett.* **99**, 190404 (2007).
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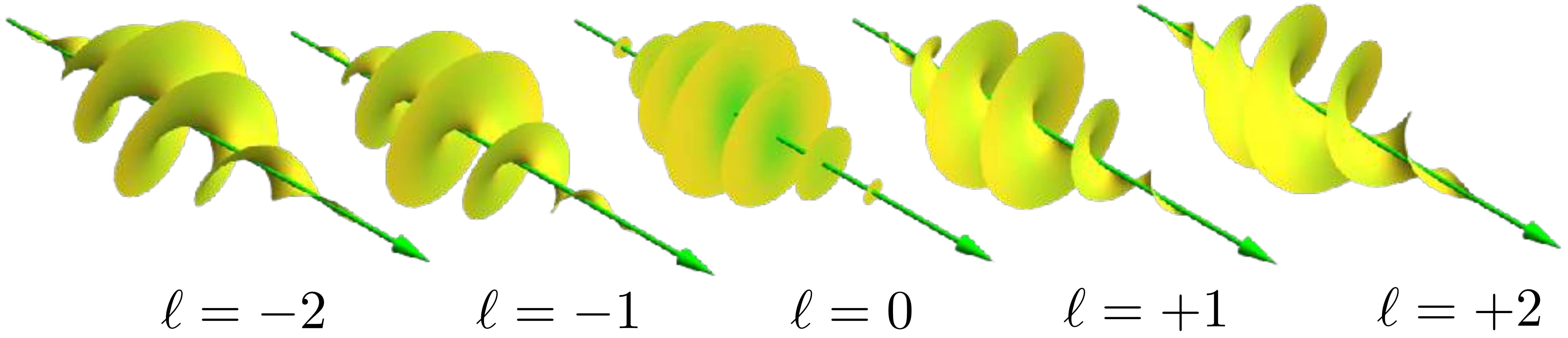
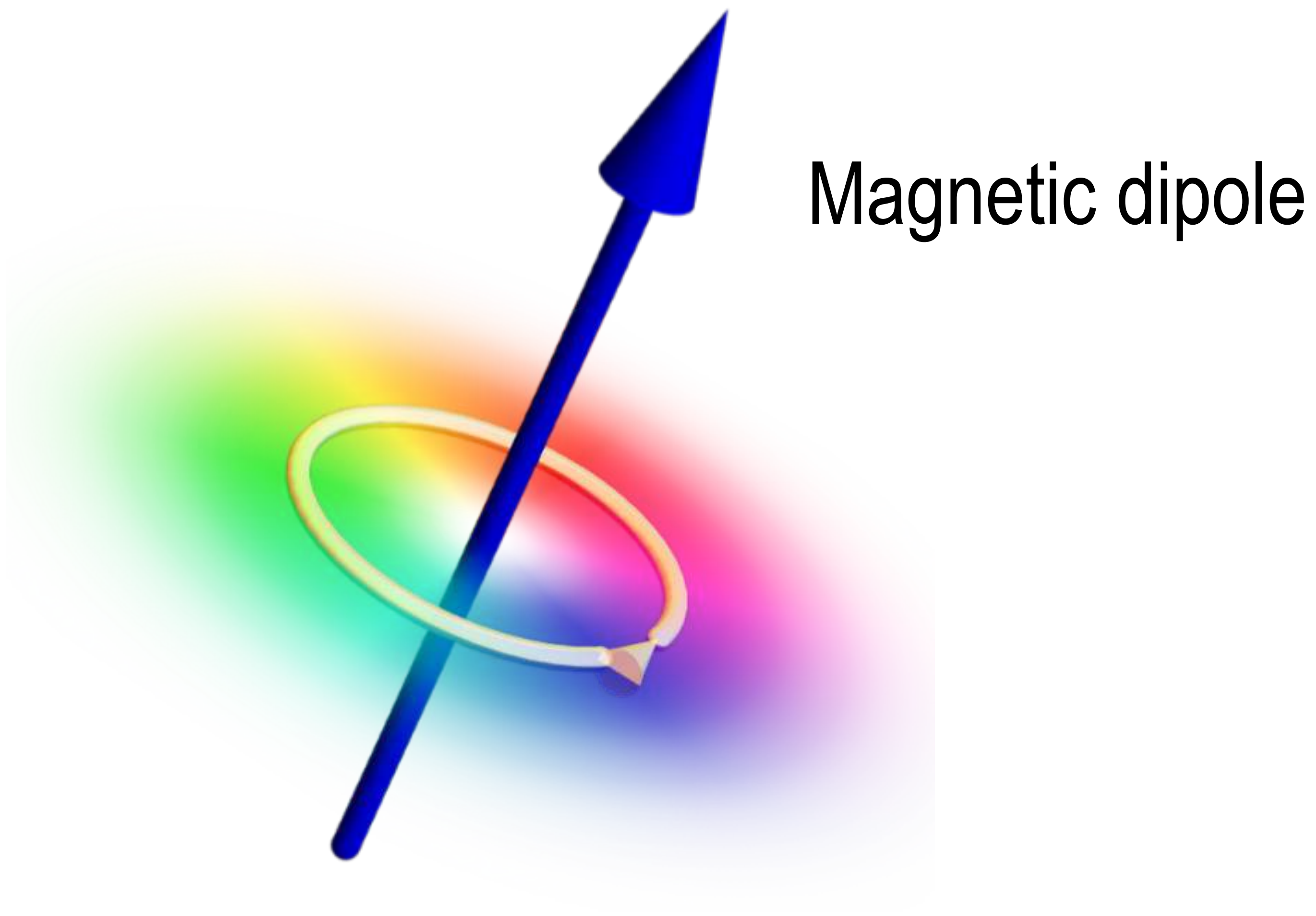
Structured Massive Particles

$\psi(\mathbf{r};t)$ Wavefunction



non-relativistic $$-\frac{\hbar^2}{2m}\nabla^2\psi(\mathbf{r};t) = i\hbar\,\partial_t\psi(\mathbf{r};t)$$



$$\phi_{\ell,p,n}(r,\varphi,z;t) = \psi^{\mathrm{LG}}_{\ell,p}(r,\varphi;t)\,u^{\mathrm{HG}}_{n}(z-(p_0/m_e)t)$$

azimuthal

radial

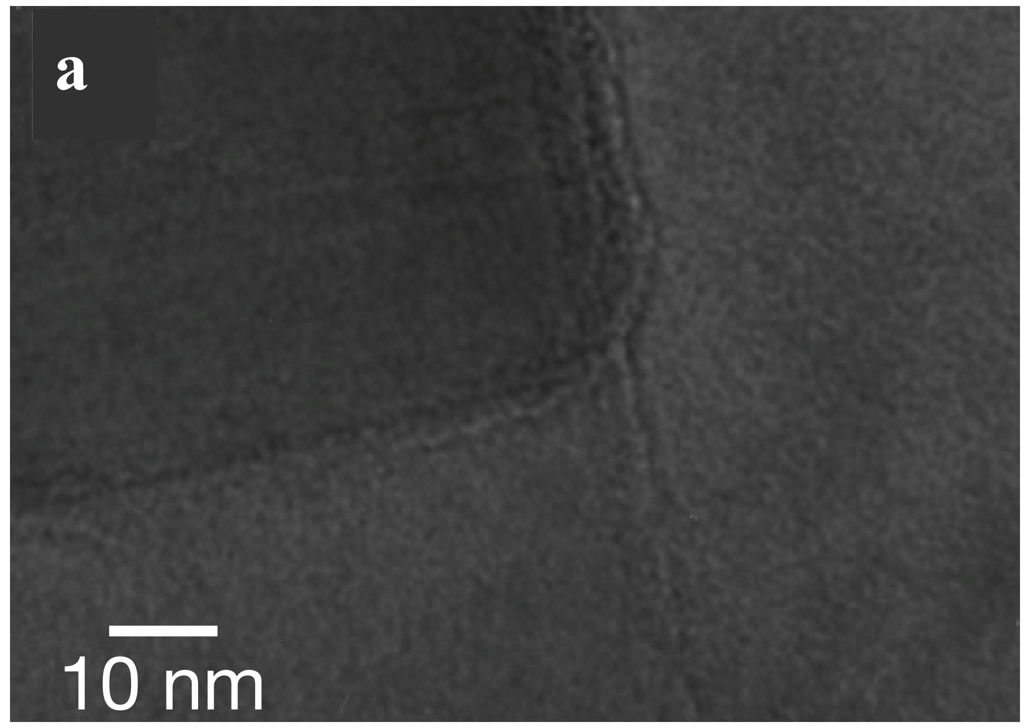
longitudinal index

transverse indices

$$\boldsymbol{\mu} = \frac{e\hbar}{2m}\ell\,\hat{\mathbf{z}}$$

K.Y. Bliokh, Y. P. Bliokh, S. Savel'Ev, F. Nori, *Phys. Rev. Lett.* **99**, 190404 (2007).
H Larocque, I Kaminer, V Grillo, G Leuchs, M J Padgett, R W Boyd, M Segev & E.K., *Contemporary Physics* **59**, 1 (2018).
J. Harris, V Grillo, E Mafakheri, G C Gazzadi, S Frabboni, R W Boyd, & E.K., *Nature Physics* **11**, 629 (2015).

Structured Electrons



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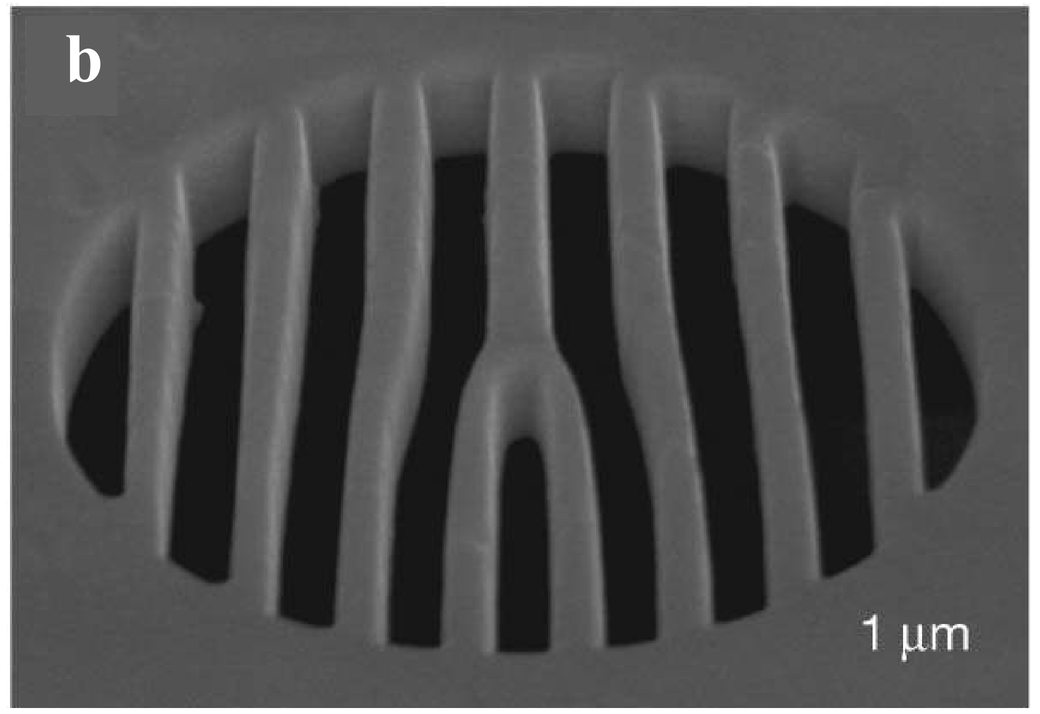

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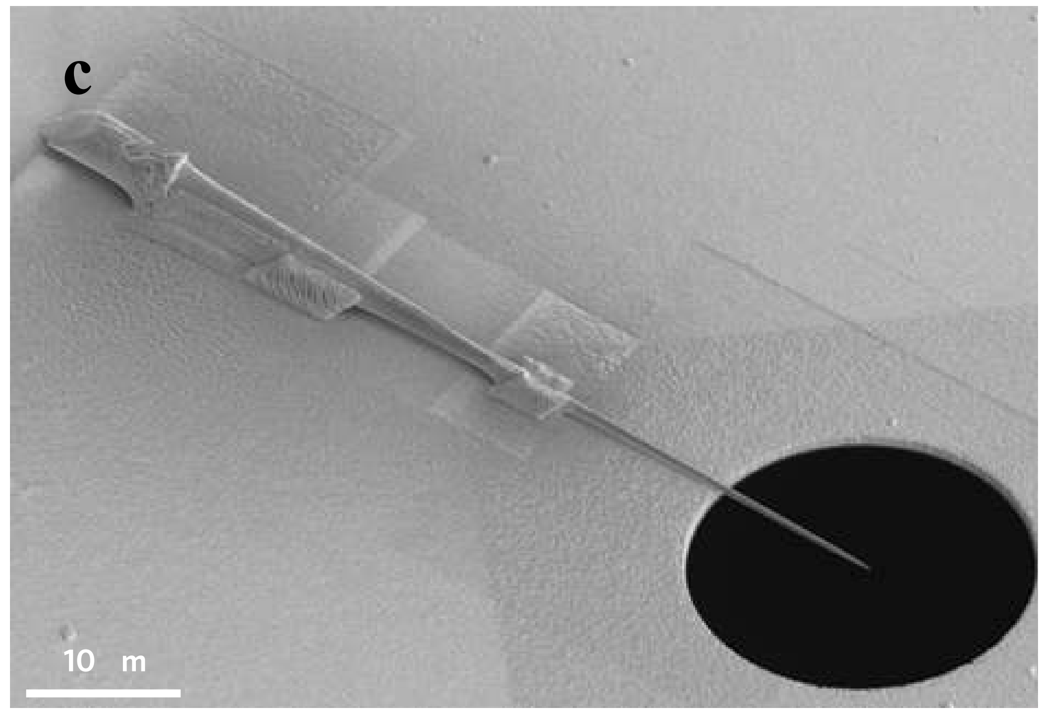

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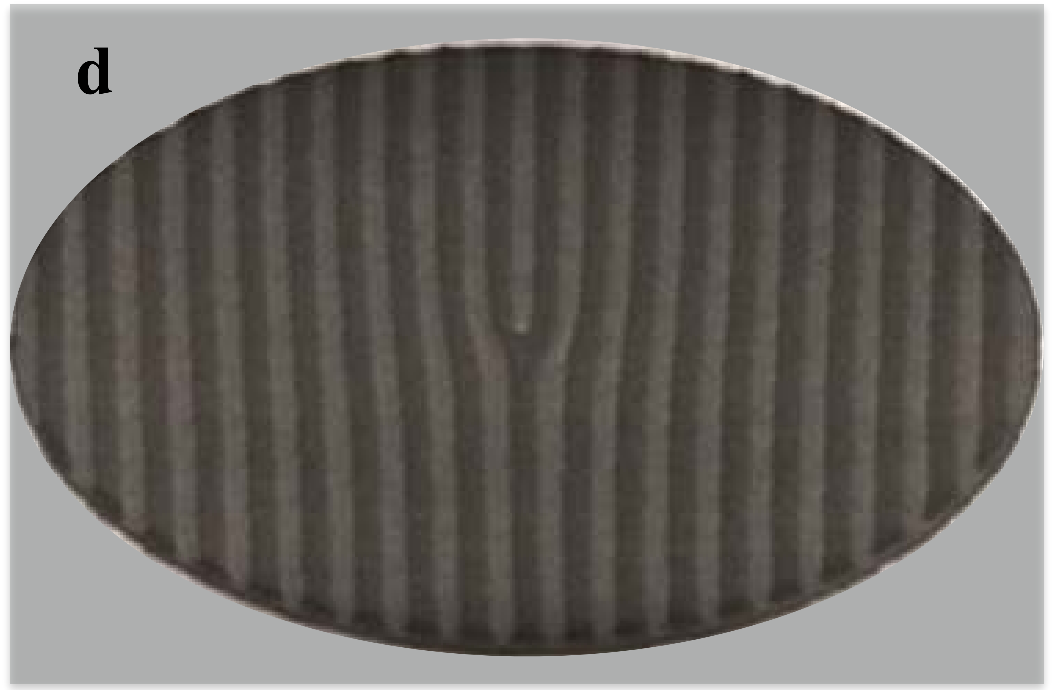
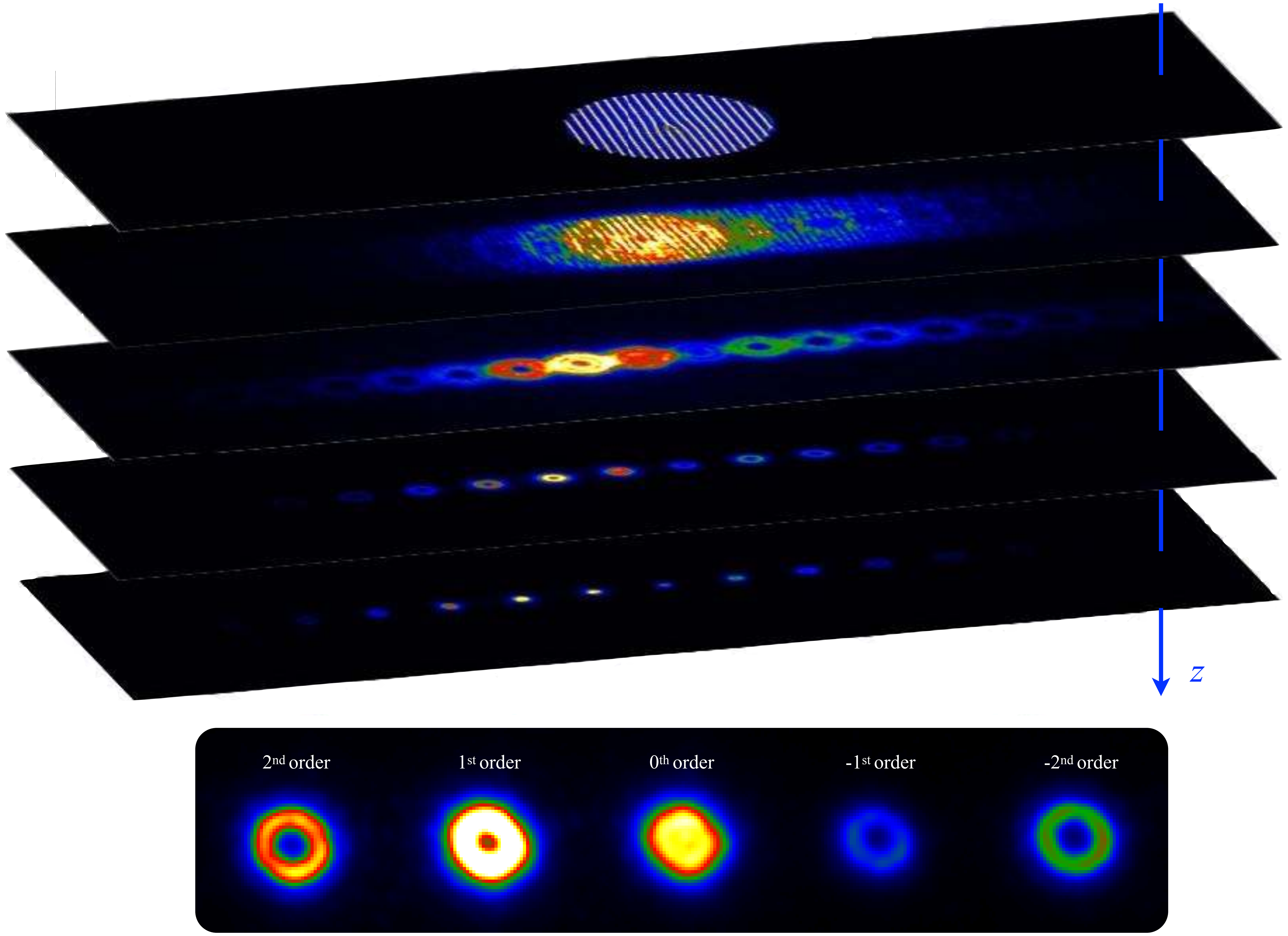


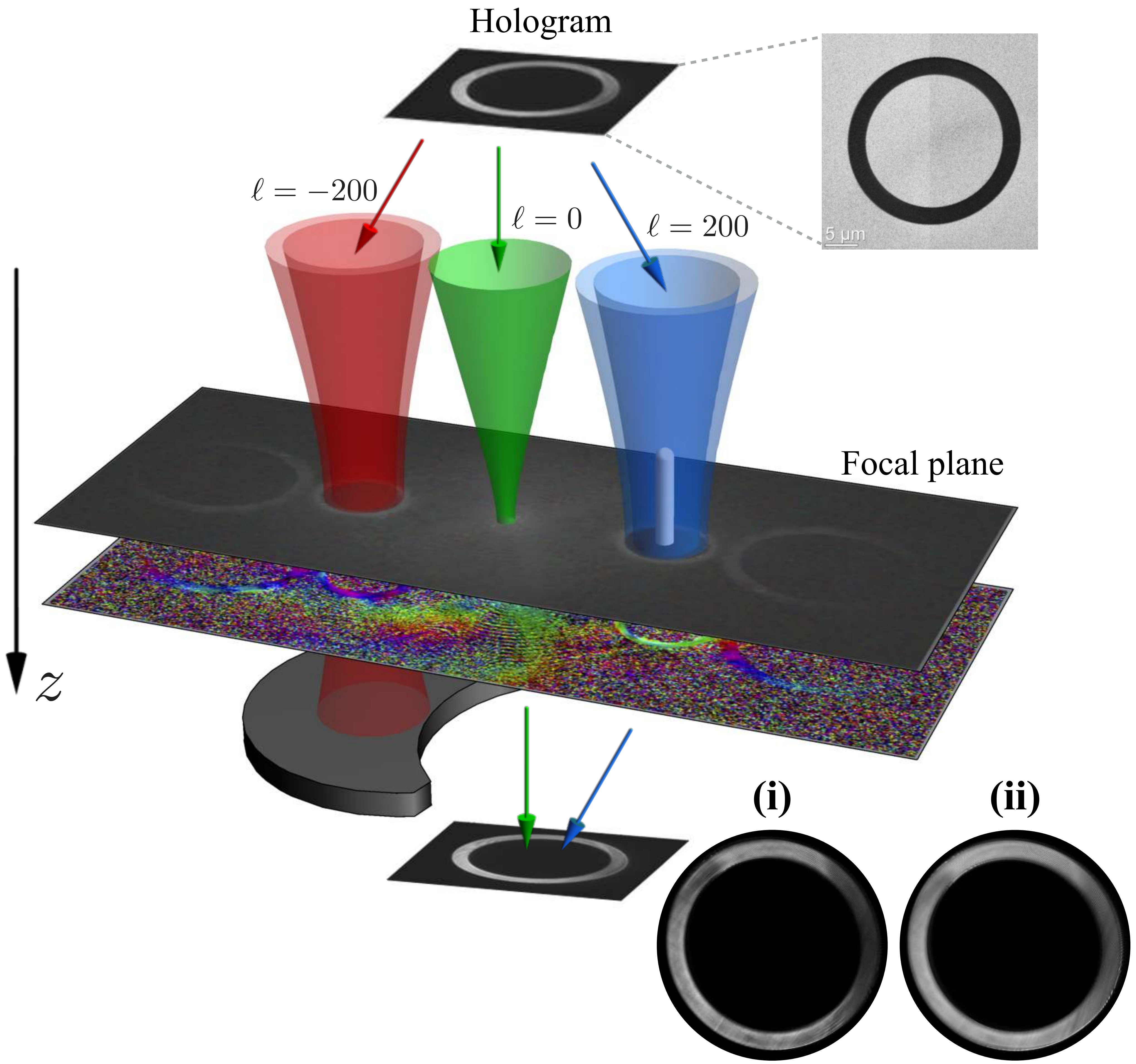
Grillo *et al.*, Appl. Phys. Lett. **104**, 043109 (2014).



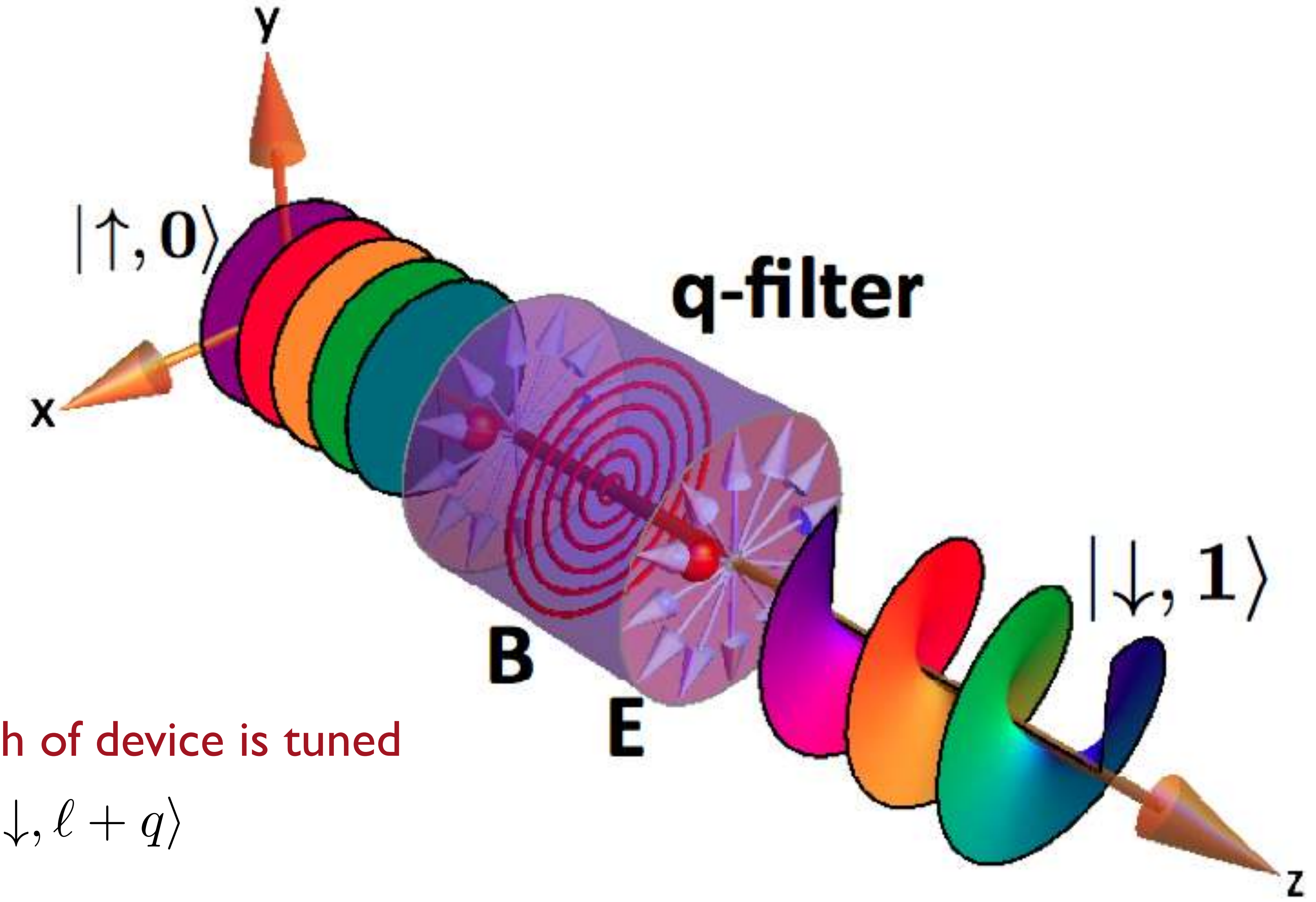
V Grillo, G C Gazzadi, E. K., E Mafakheri, R W Boyd, and S Frabboni, *Applied Physics Letters* **104**, 043109 (2014).

J. Harris, V Grillo, E Mafakheri, G C Gazzadi, S Frabboni, R W Boyd & E.K., *Nature Physics* **11**, 629 (2015).
H Larocque, I Kaminer, V Grillo, G Leuchs, M J Padgett, R W Boyd, M Segev & E.K., *Contemporary Physics* **59**, 1 (2018).

Structured Electrons: Applications



V Grillo, T R Harvey, F Venturi, J S Pierce, R Balboni, F Bouchard, G C Gazzadi, S Frabboni, A H Tavabi, Z-A Li, R E Dunin-Borkowski, R W Boyd, B J McMorran & E.K. *Nature Communications* **8**, 689 (2017).



If the length of device is tuned

$$|\uparrow, \ell\rangle \to |\downarrow, \ell + q\rangle$$

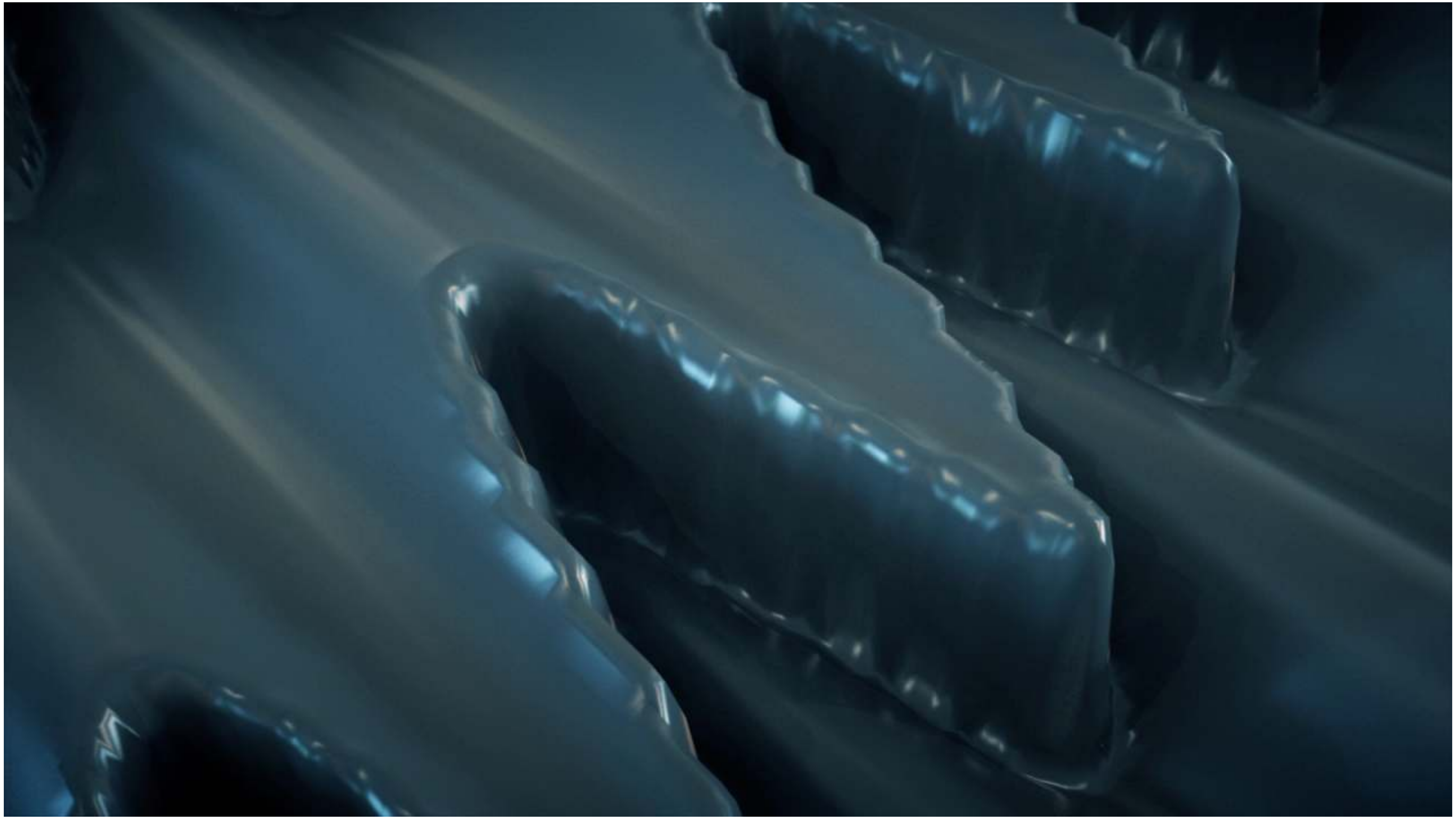
a general expression

$$|\uparrow, \ell\rangle \to \cos(\delta/2)|\uparrow, \ell\rangle + i\sin(\delta/2)|\downarrow, \ell + q\rangle$$
$$|\downarrow, \ell\rangle \to \cos(\delta/2)|\downarrow, \ell\rangle + i\sin(\delta/2)|\uparrow, \ell - q\rangle$$

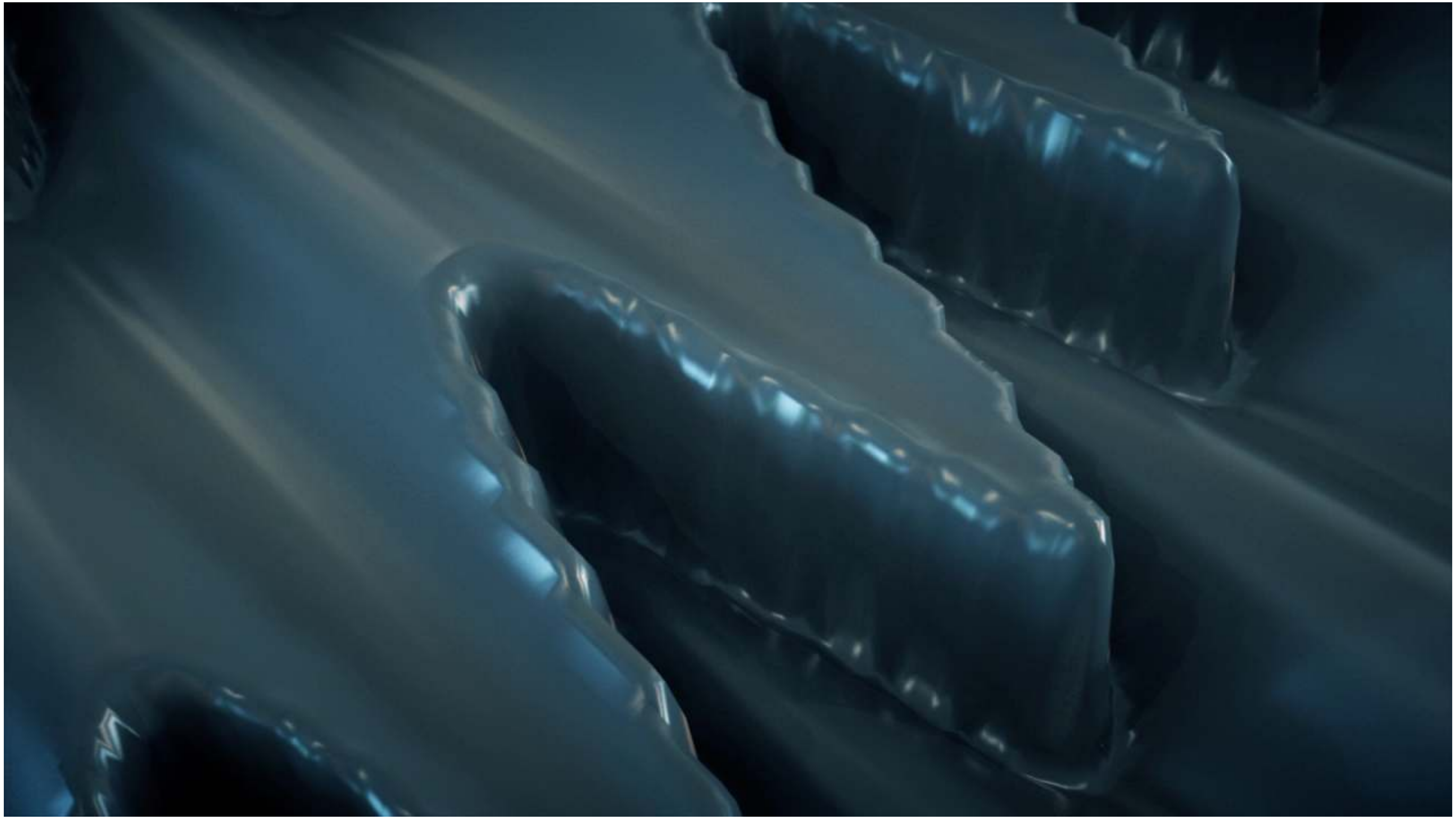
E K., L Marrucci, V Grillo, E Santamato, *Physical Review Letters* **108**, 044801 (2012).

J. Harris, V Grillo, E Mafakheri, G C Gazzadi, S Frabboni, R W Boyd & E.K., *Nature Physics* **11**, 629 (2015).
H Larocque, I Kaminer, V Grillo, G Leuchs, M J Padgett, R W Boyd, M Segev & E.K., *Contemporary Physics* **59**, 1 (2018).

Generation: Holographic Technique



Generation: Holographic Technique



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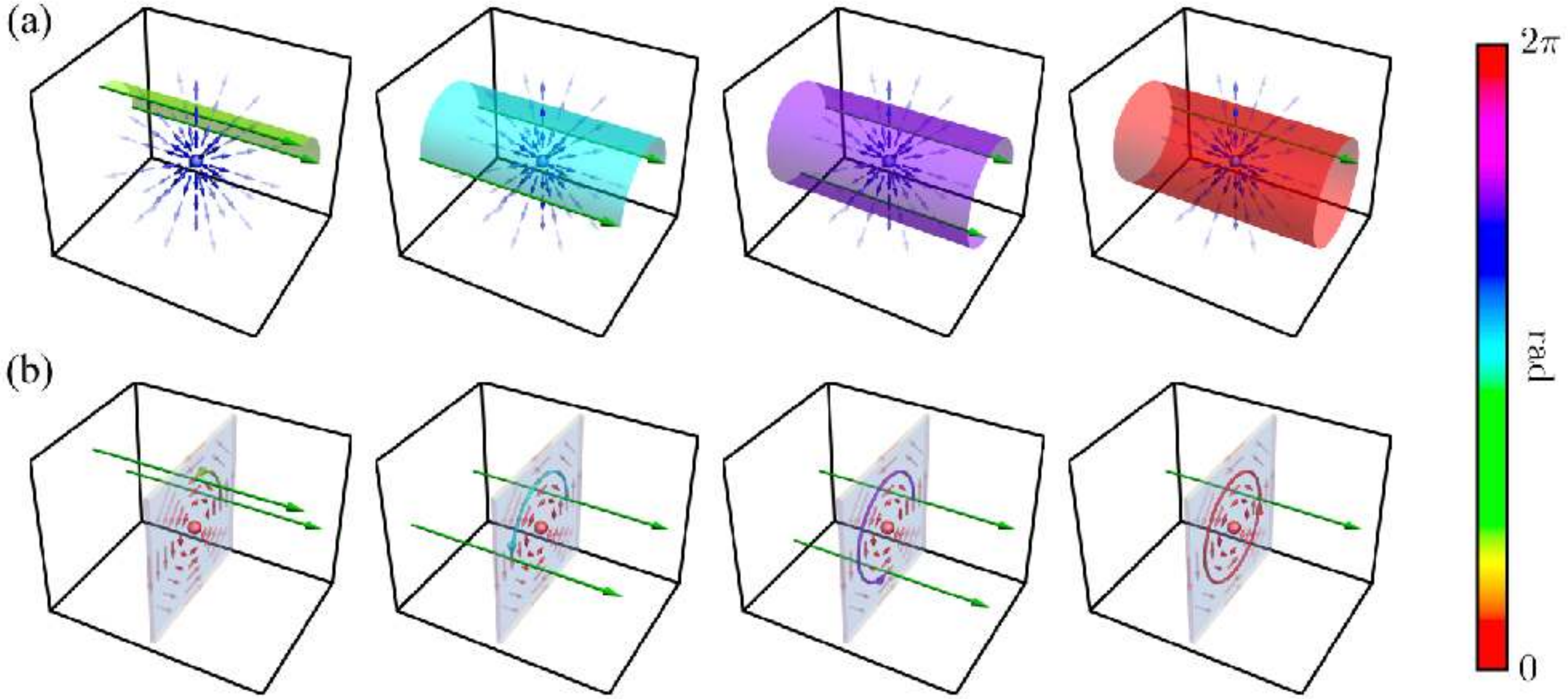
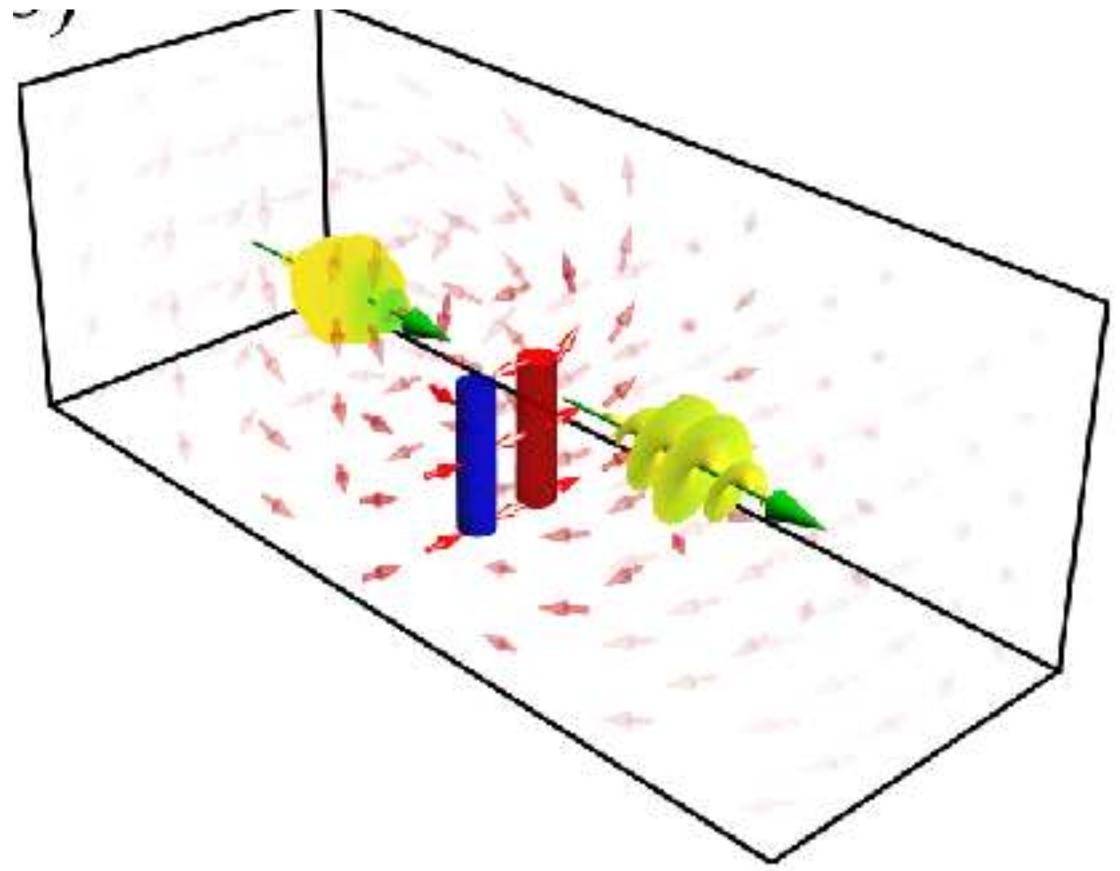
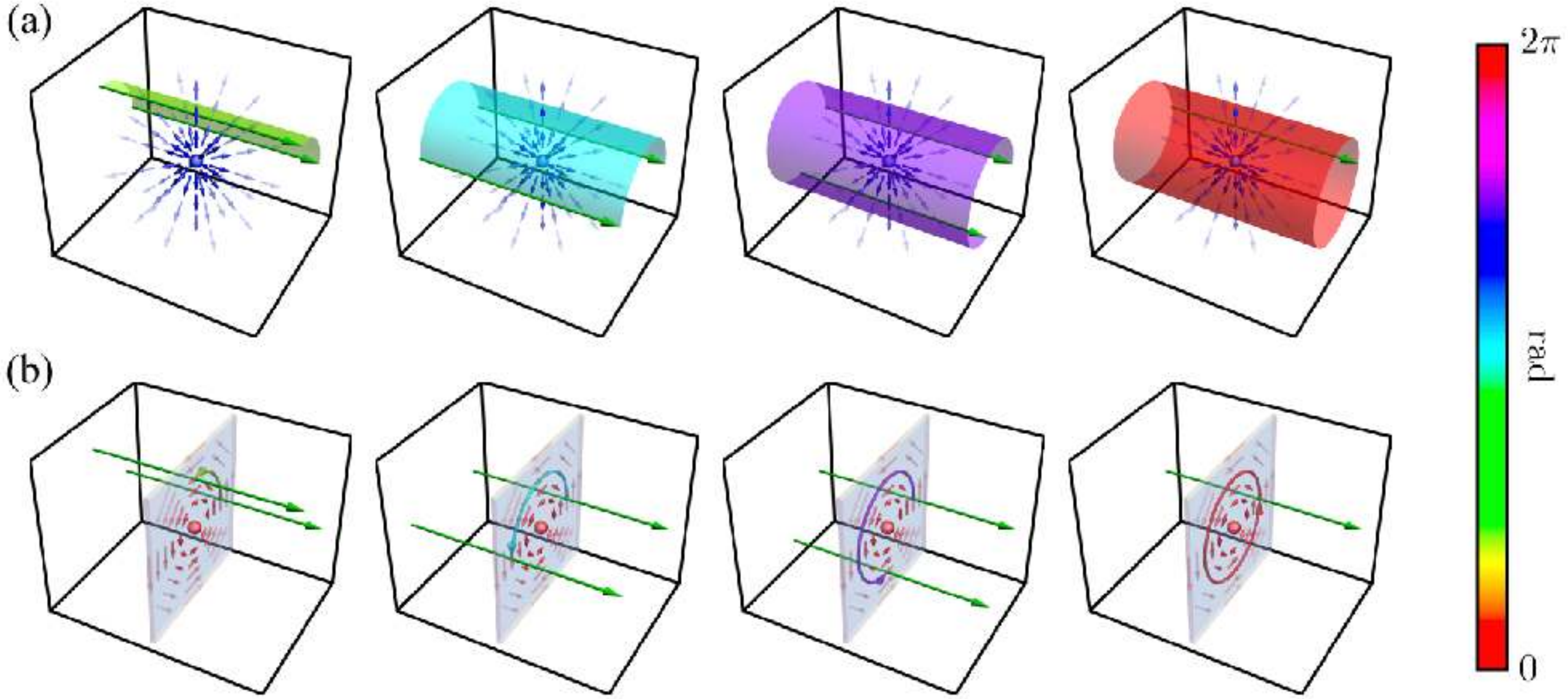
Dynamic Generation

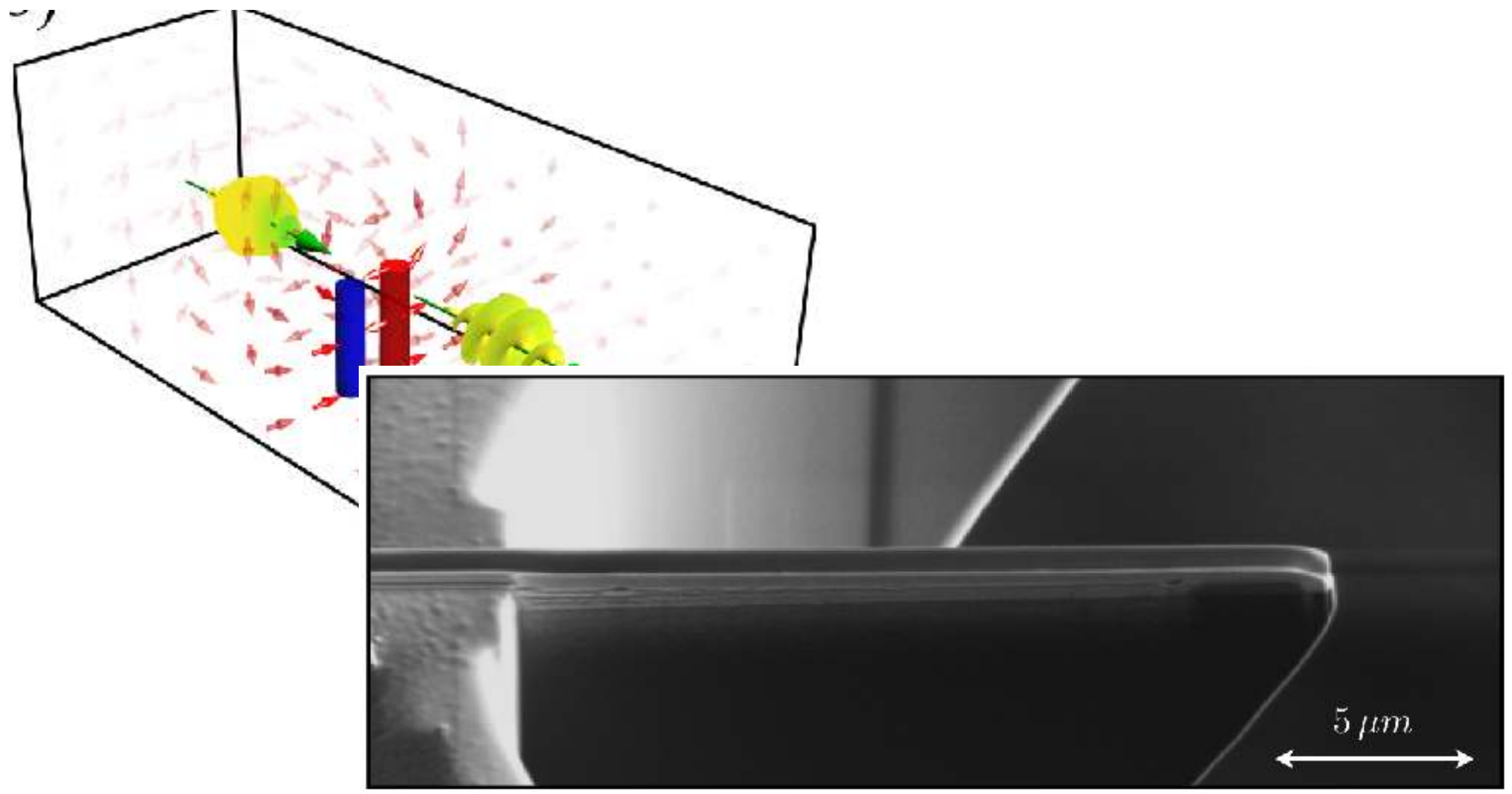


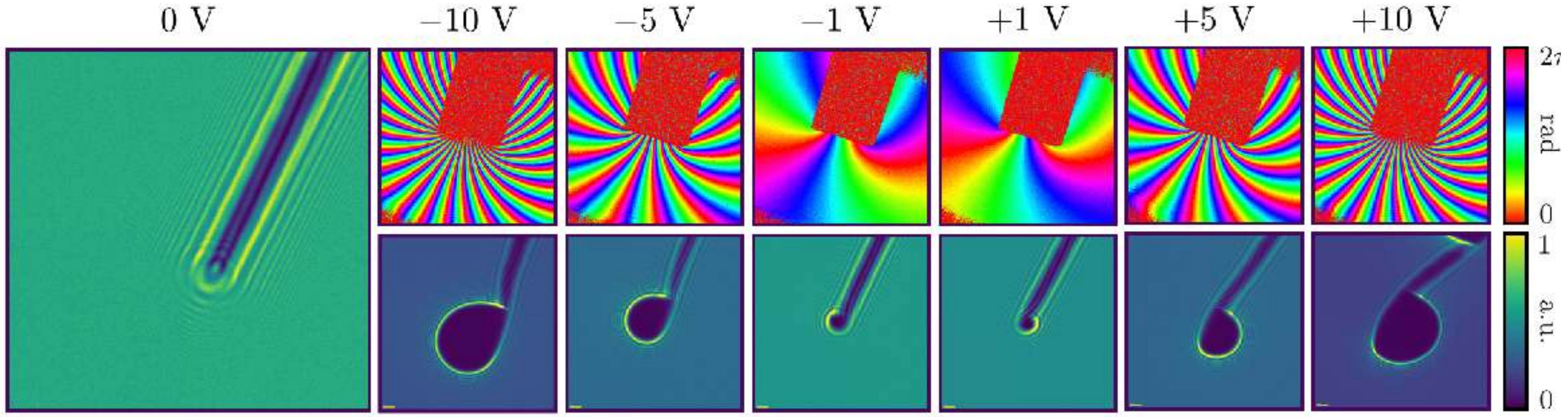


E Cohen, H Larocque, F Bouchard, F Nejadsattari, Y Gefen & E.K., *Nature Reviews Physics* **1,** 437 (2019).
A H Tavabi, H Larocque, P-H Lu, M Duchamp, V Grillo, E. K., R E Dunin-Borkowski & G Pozzi, *Physical Review Research* **2**, 013185 (2020).

Dynamic Generation







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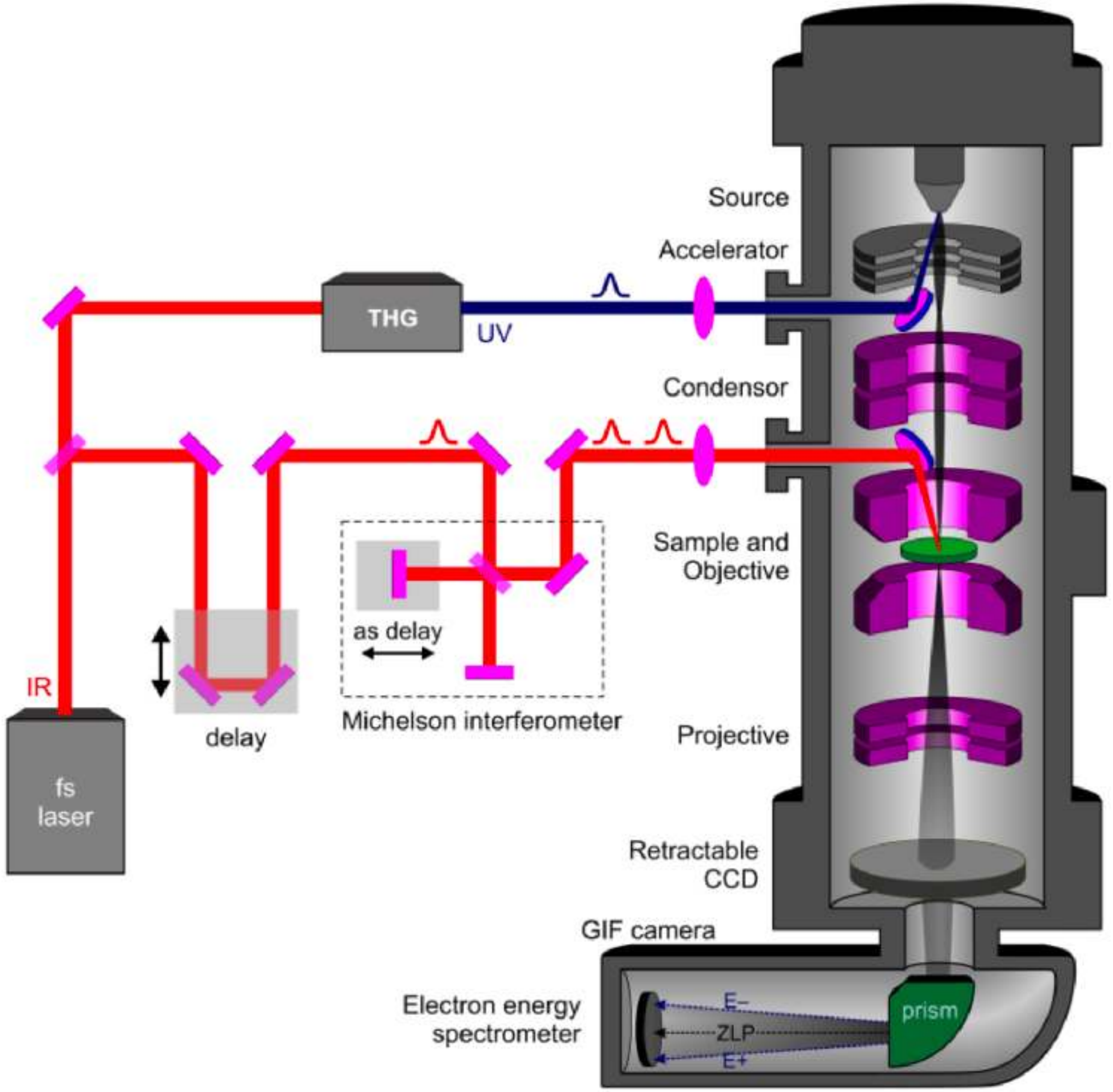
Attosecond generation of Twisted electrons



G. M. Vanacore, G. Berruto, I. Madan, E. Pomarico, P. Biagioni, R. J. Lamb, D. McGrouther, O. Reinhardt, I. Kaminer, B. Barwick, H. Larocque, V. Grillo, E. K., F. J. García de Abajo & F. Carbone, *Nature Materials* **18**, *573* (2019).

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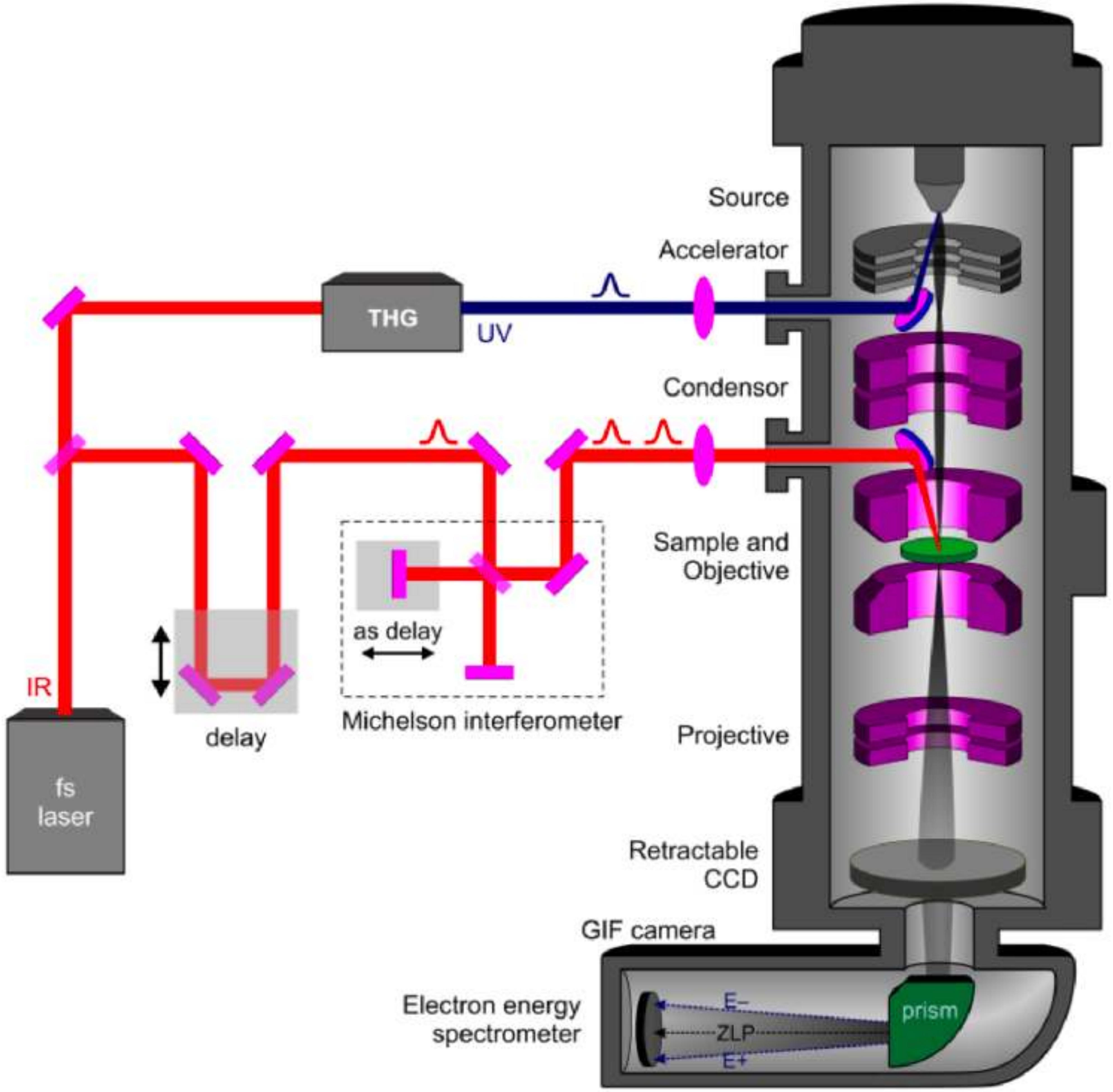

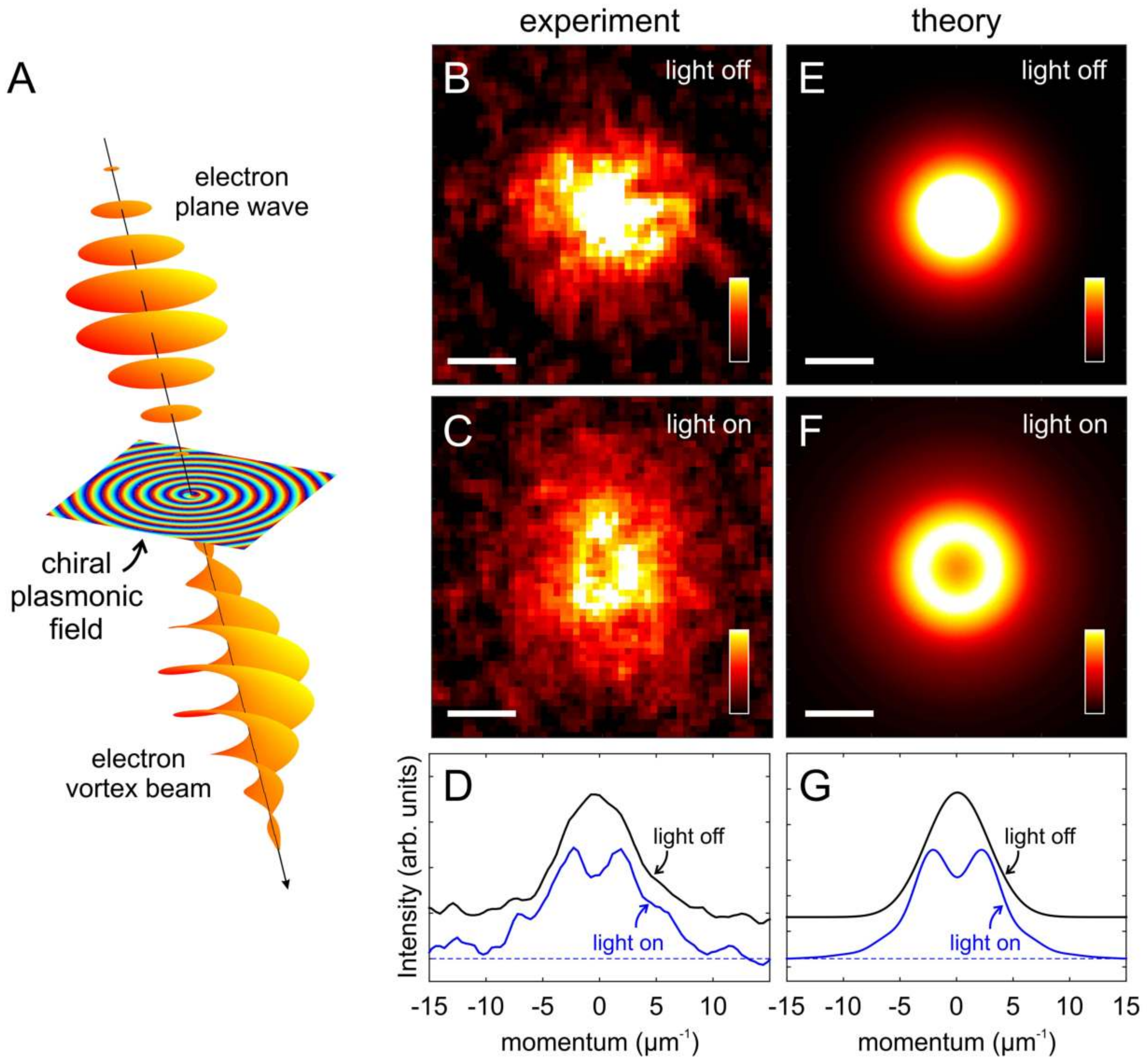

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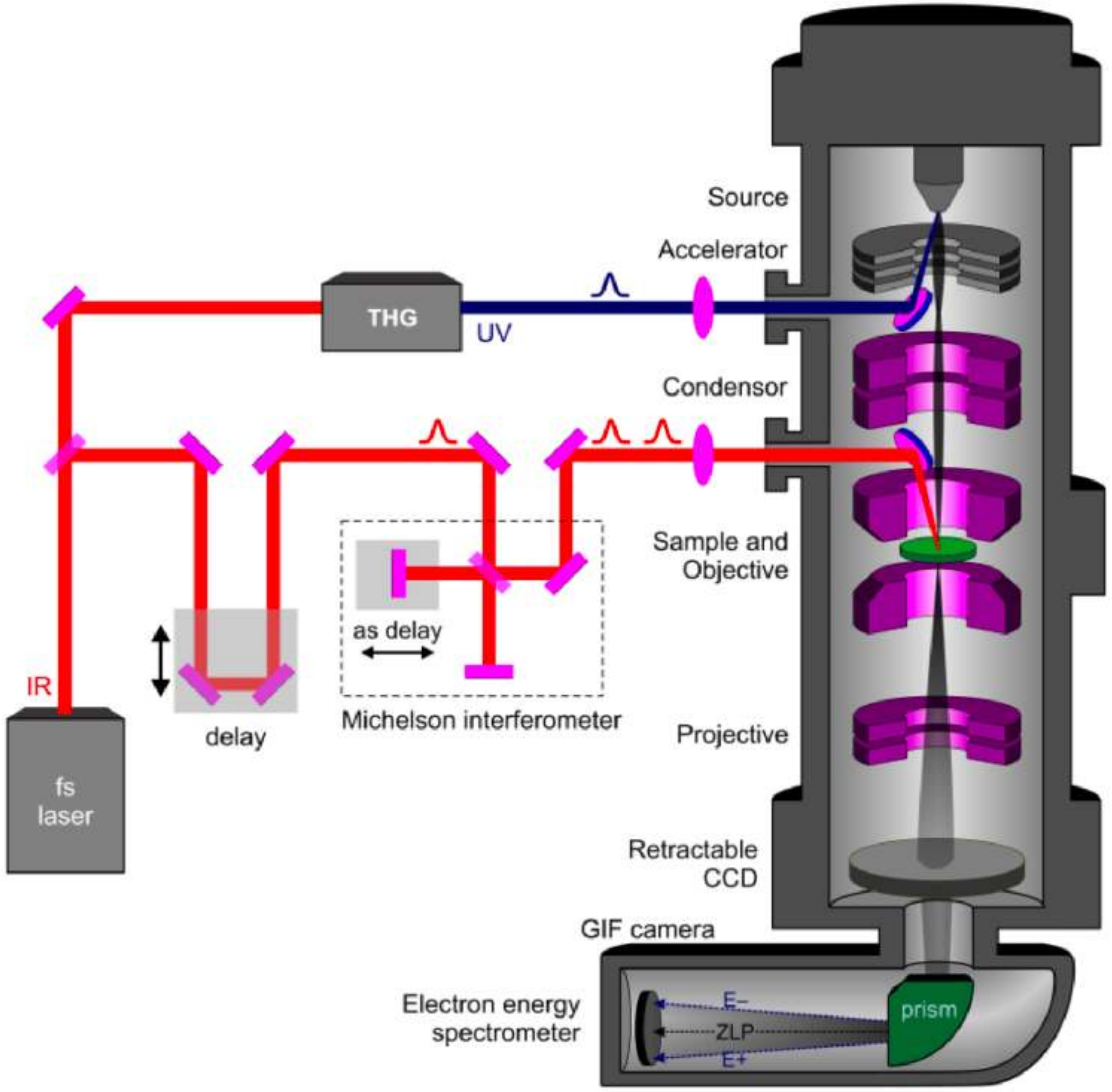

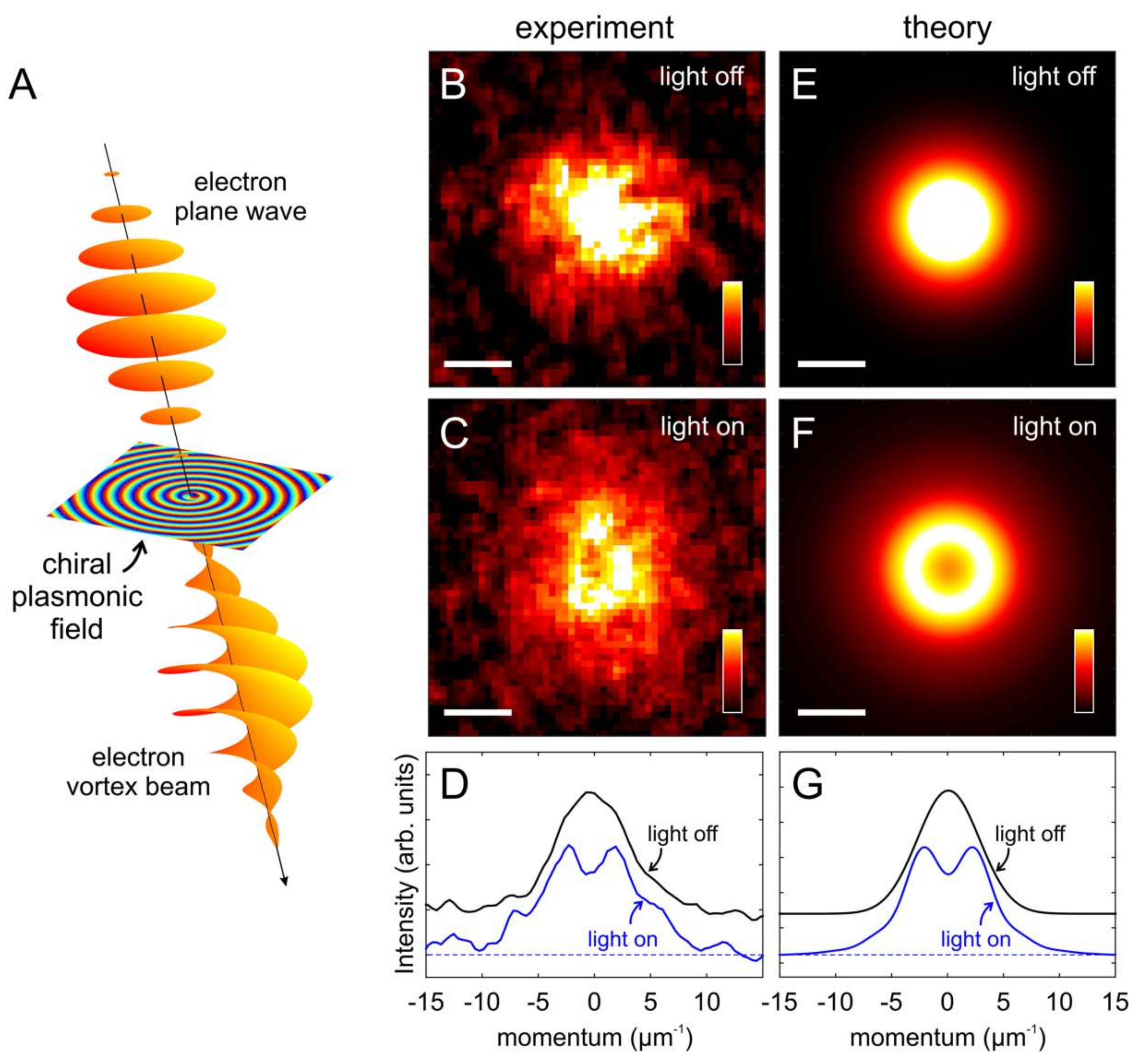

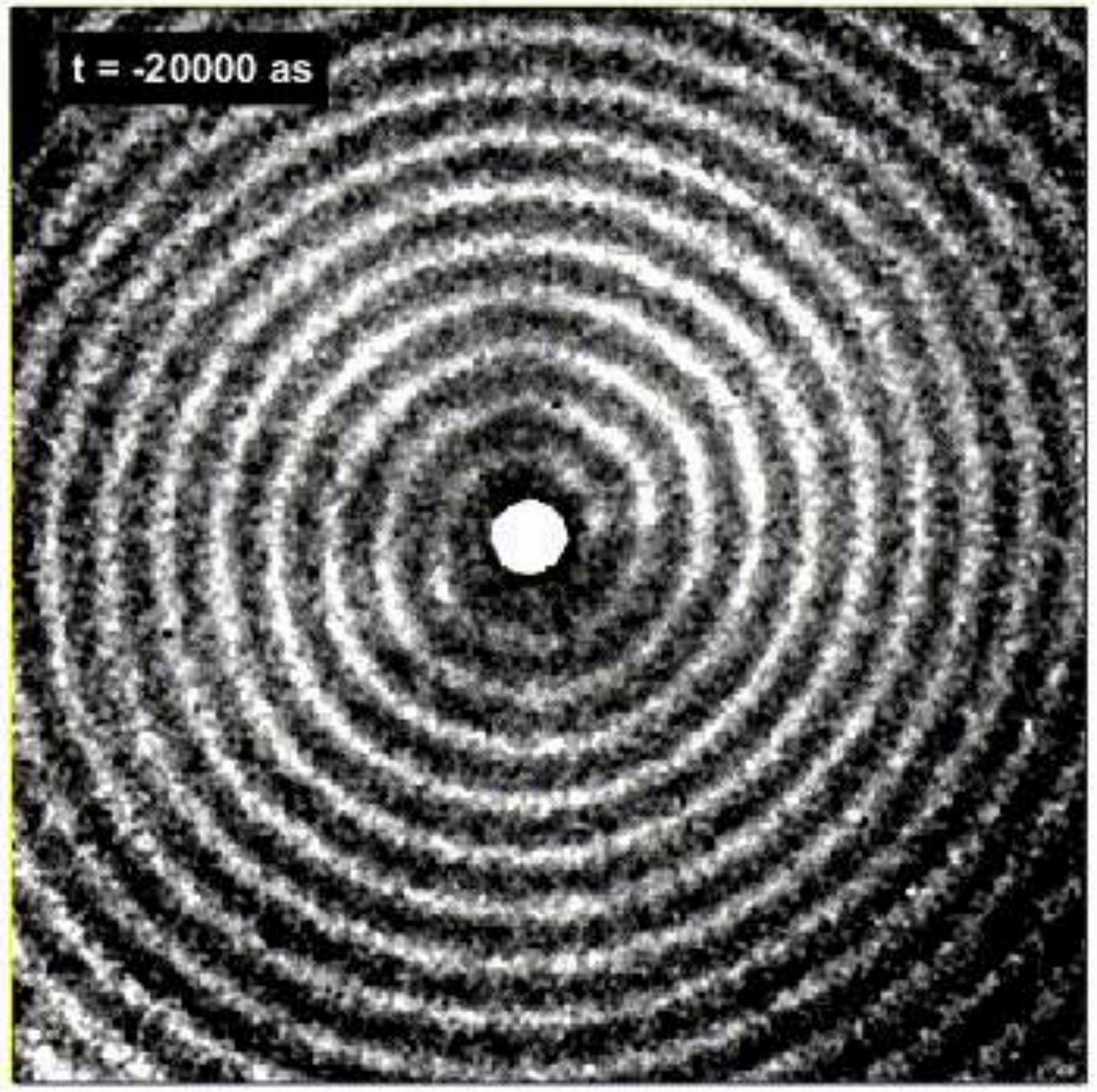

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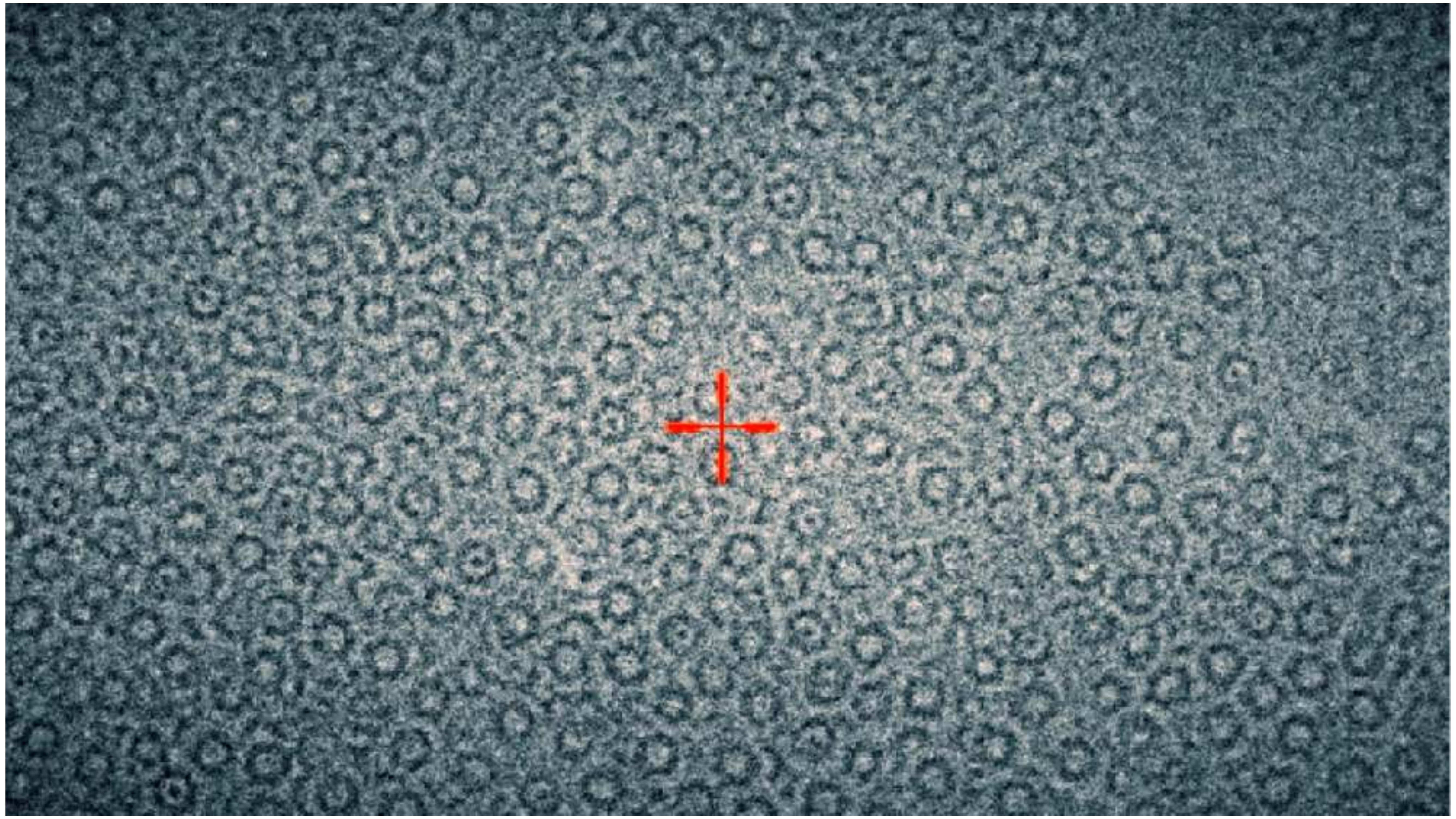
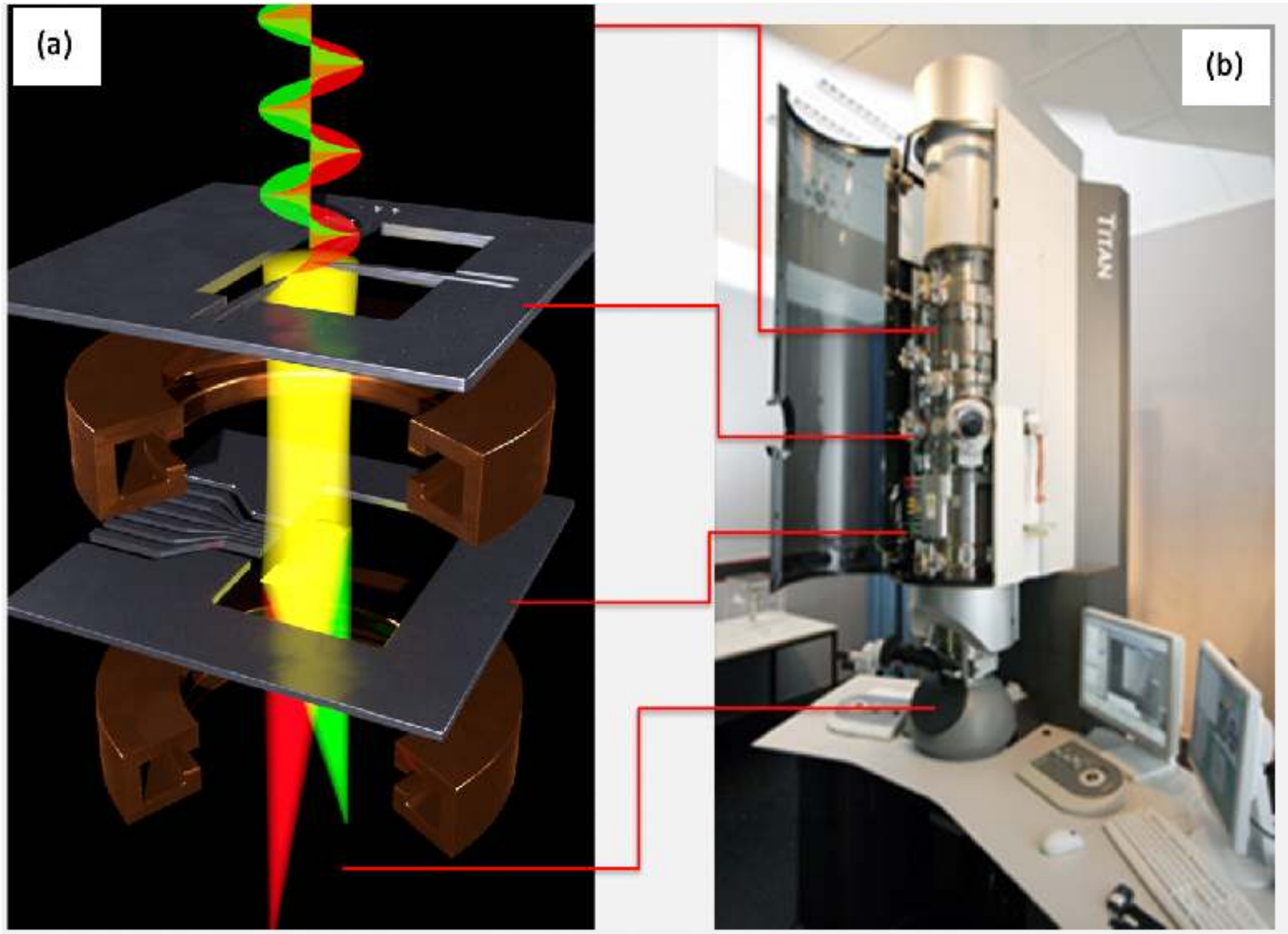
Protein recognition



EspB protein of *Mycobacterium tuberculosis*



AH Tavabi, P Rosi, E Rotunno, A Roncaglia, L Belsito, S Frabboni, G Pozzi, G C Gazzadi, P-H Lu, R Nijland, M Ghosh, P Tiemeijer, E. K., R E Dunin-Borkowski, V. Grillo Physical Review Letters **126**, 094802 (2021).

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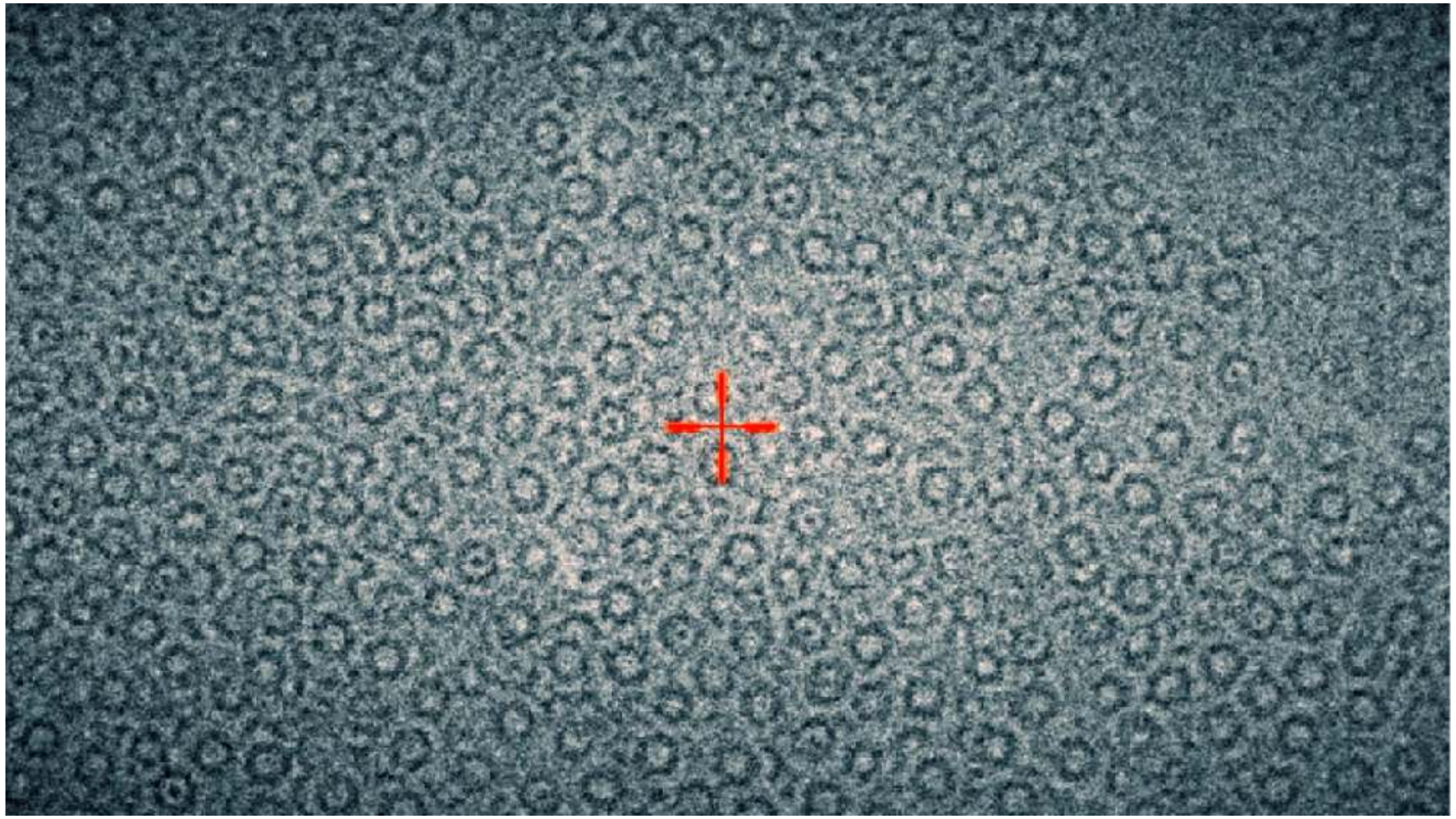

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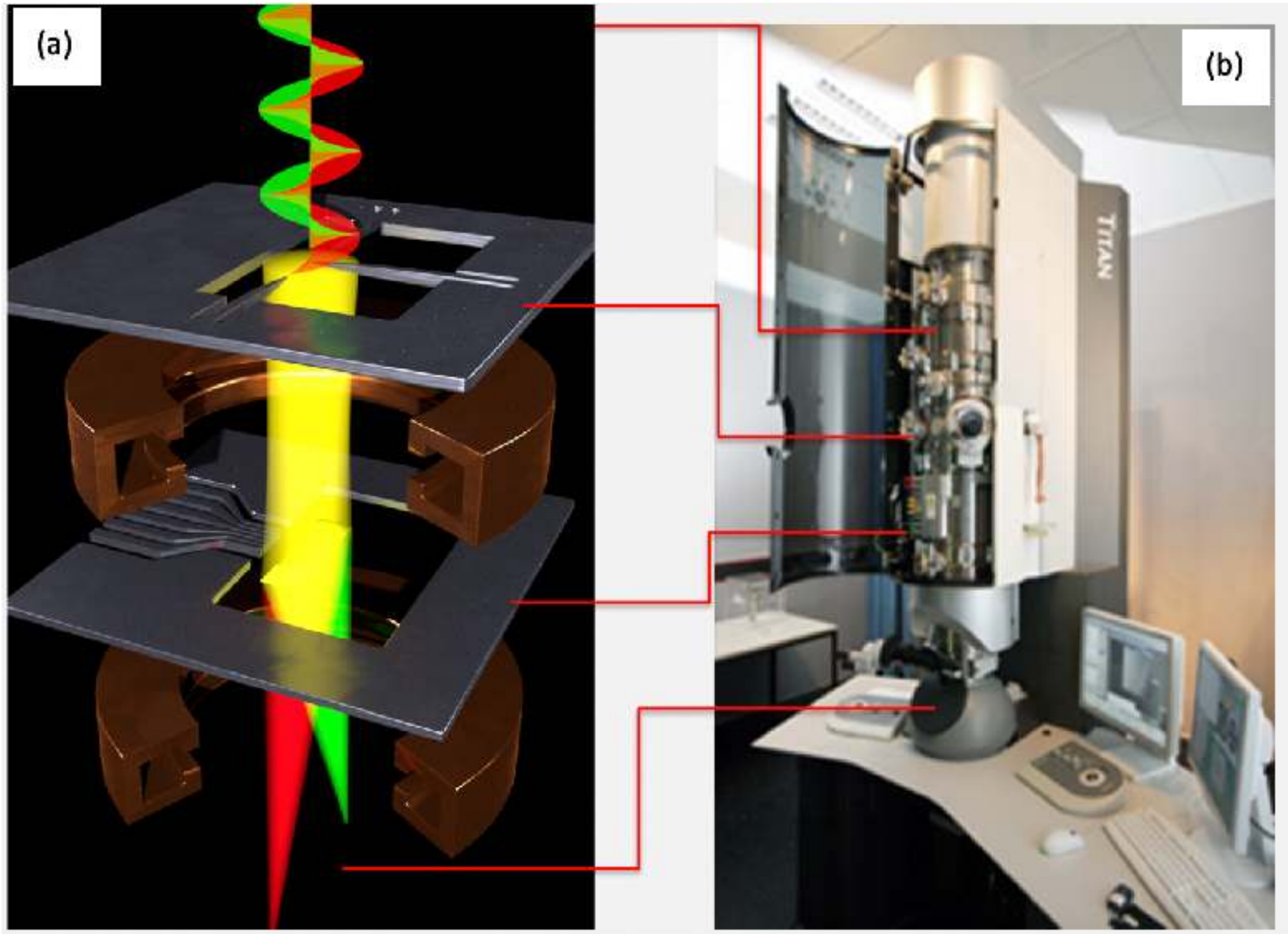

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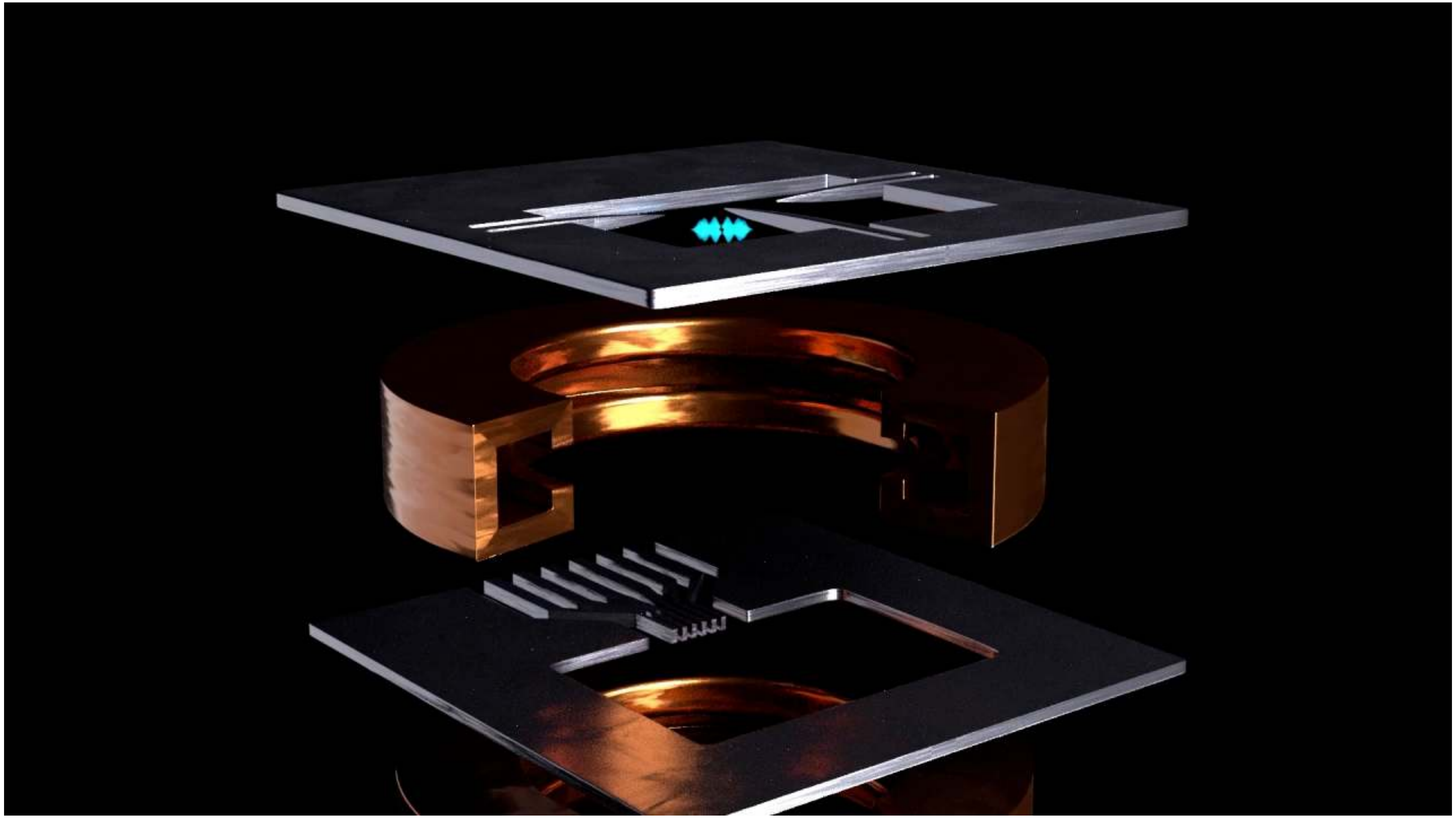
Electron sorter



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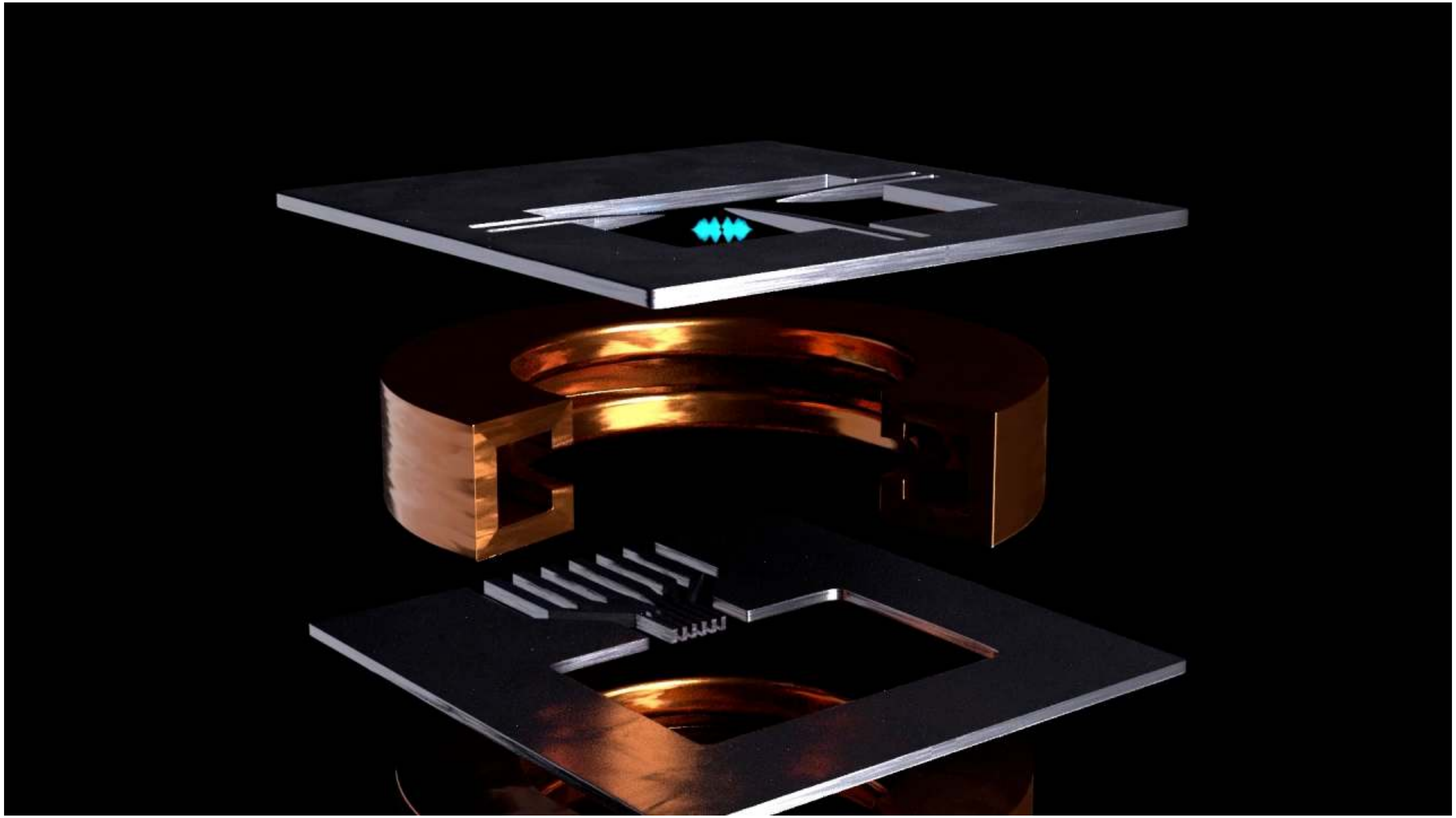
Electron sorter



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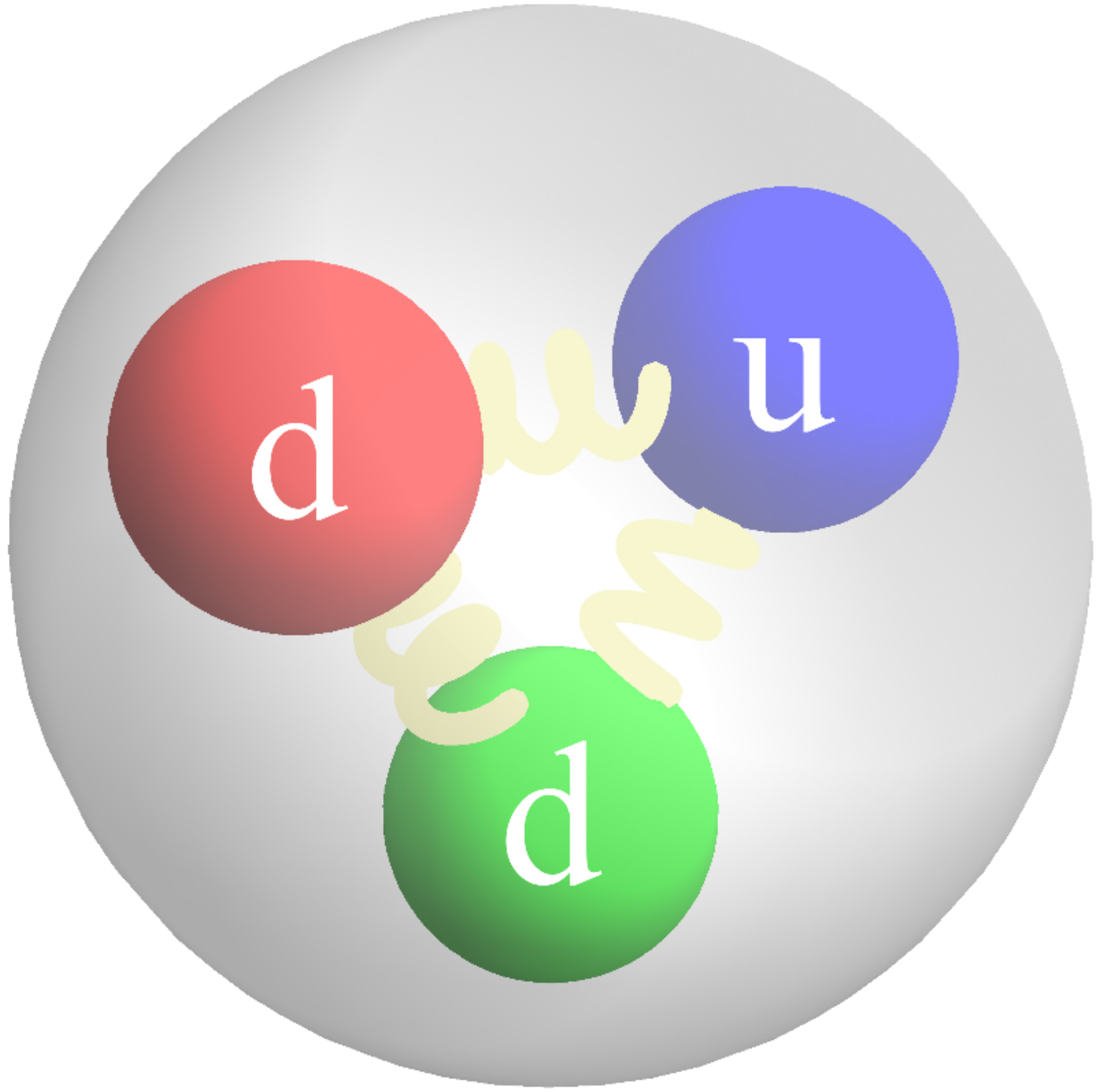
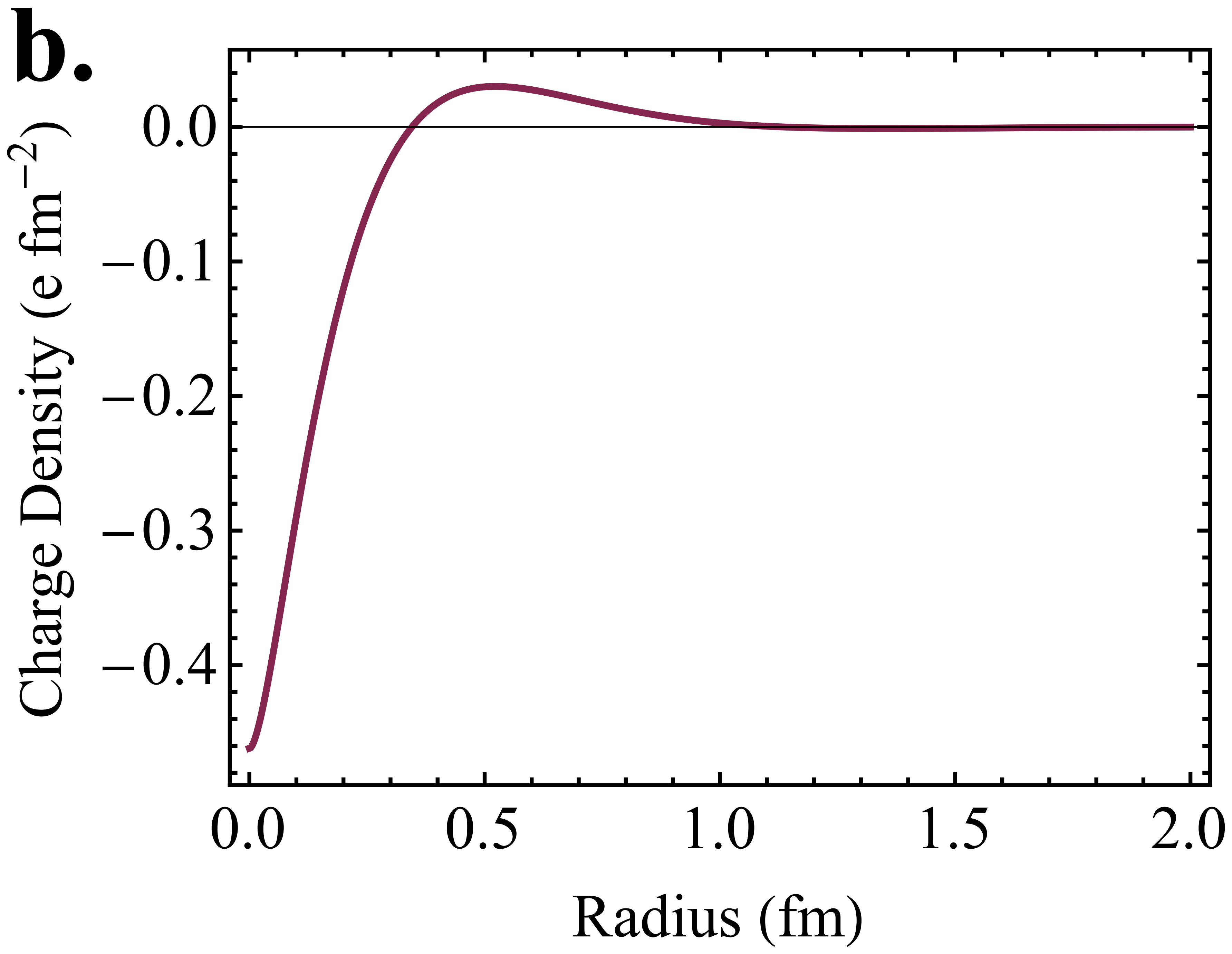
Neutrons

Form Factors

$$\rho(r) = \frac{1}{2\pi}\int_0^\infty q dq \left(\frac{4m_n G_{\mathrm{E}}(q^2) + q^2 G_{\mathrm{M}}(q^2)}{4m_n + q^2}\right) J_0(q\,r)$$





G. A. Miller, *Physical Review Letters* **99**, 112001 (2007).
G. A. Miller, *Physical Review C* **80**, 045210 (2009).

Neutrons

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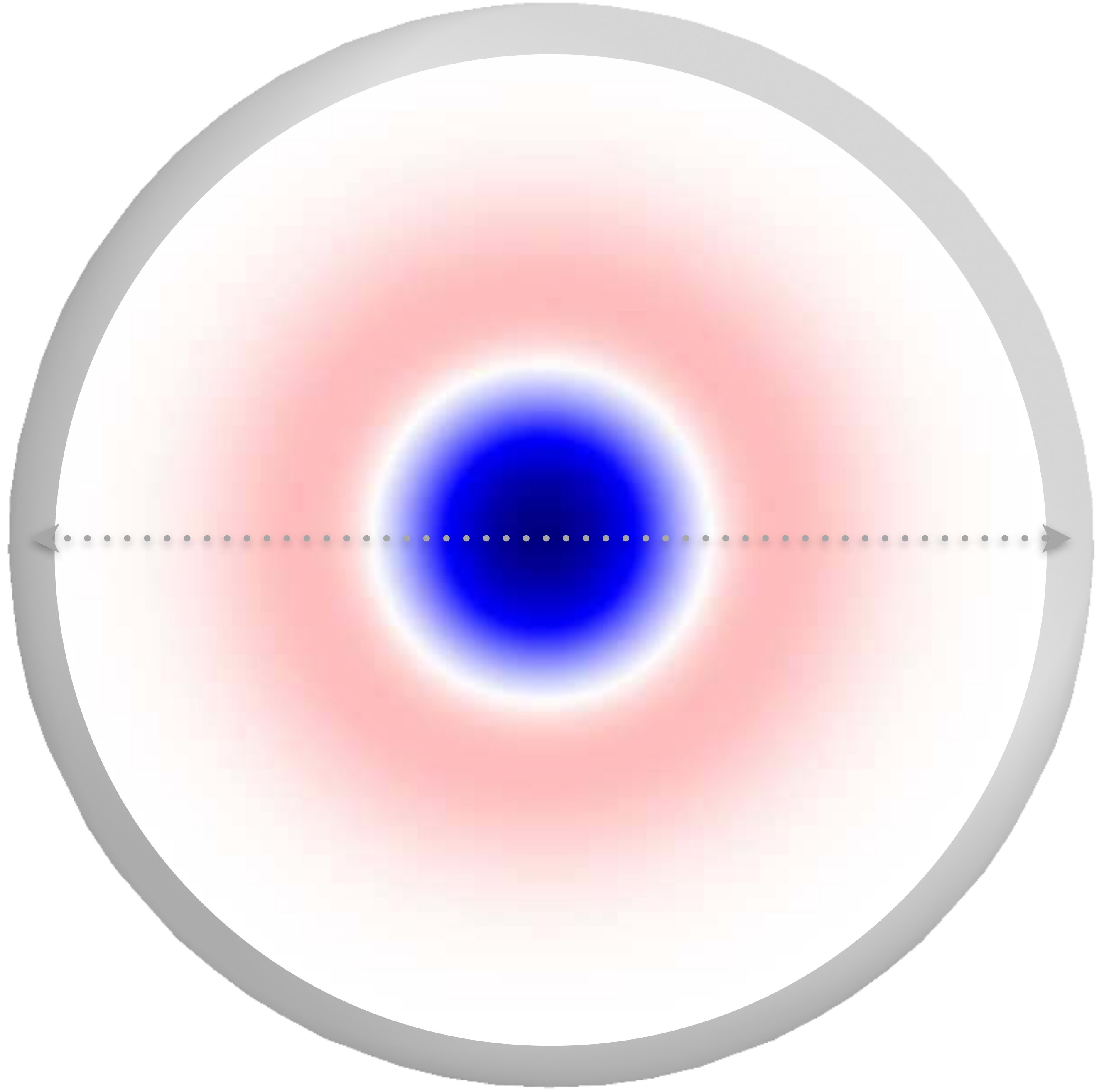
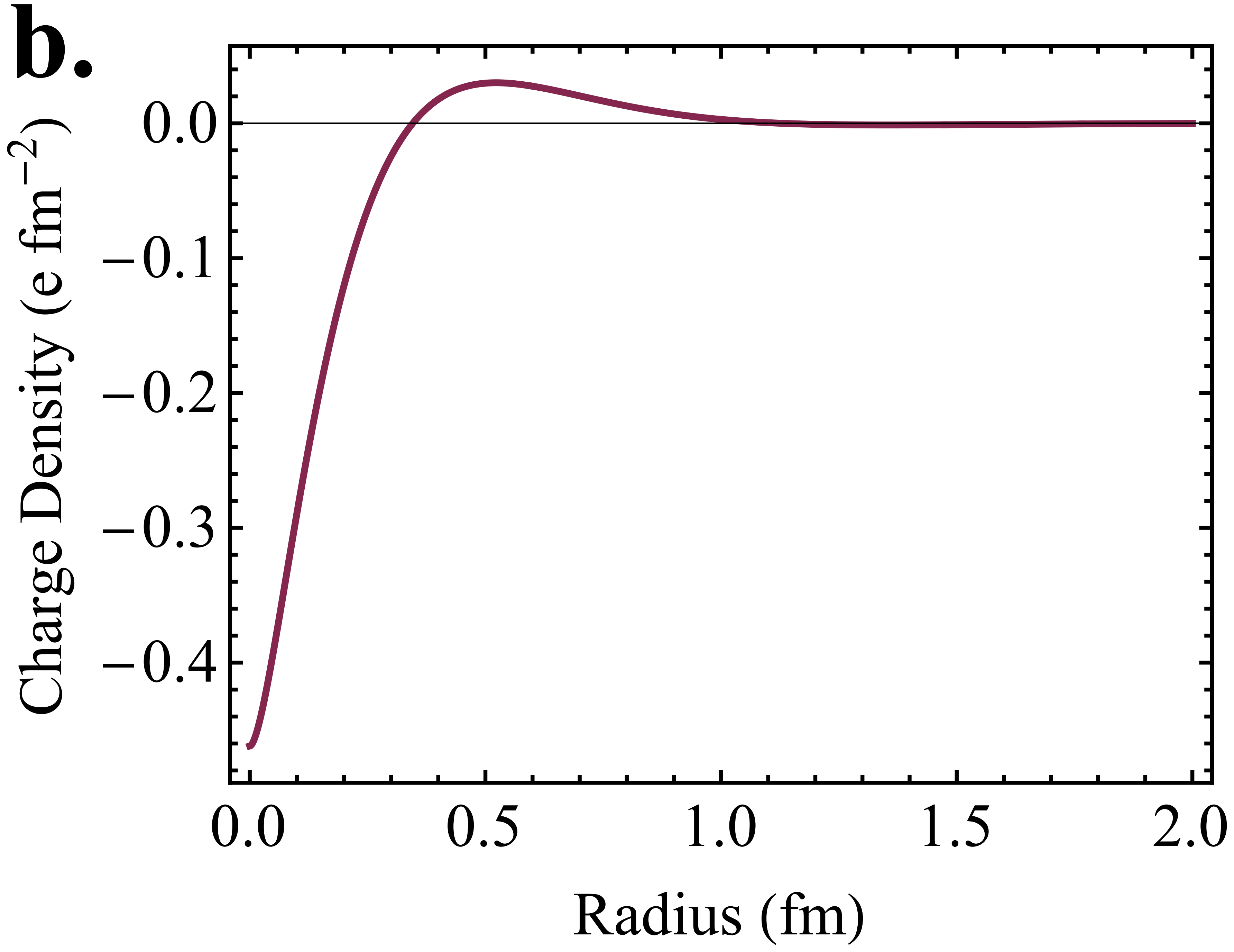


$2\,f\mathrm{m}$



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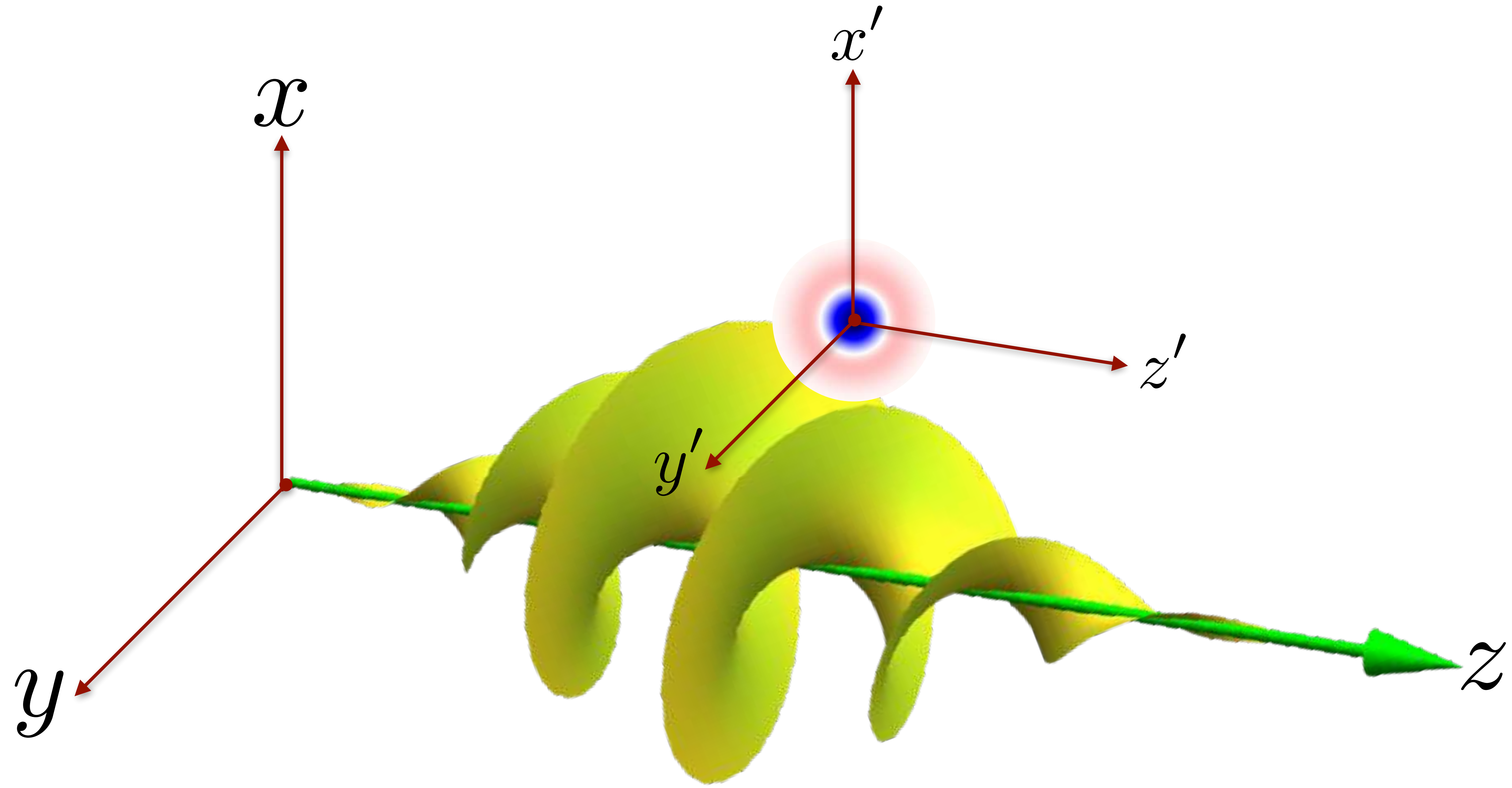
Twisted Neutrons



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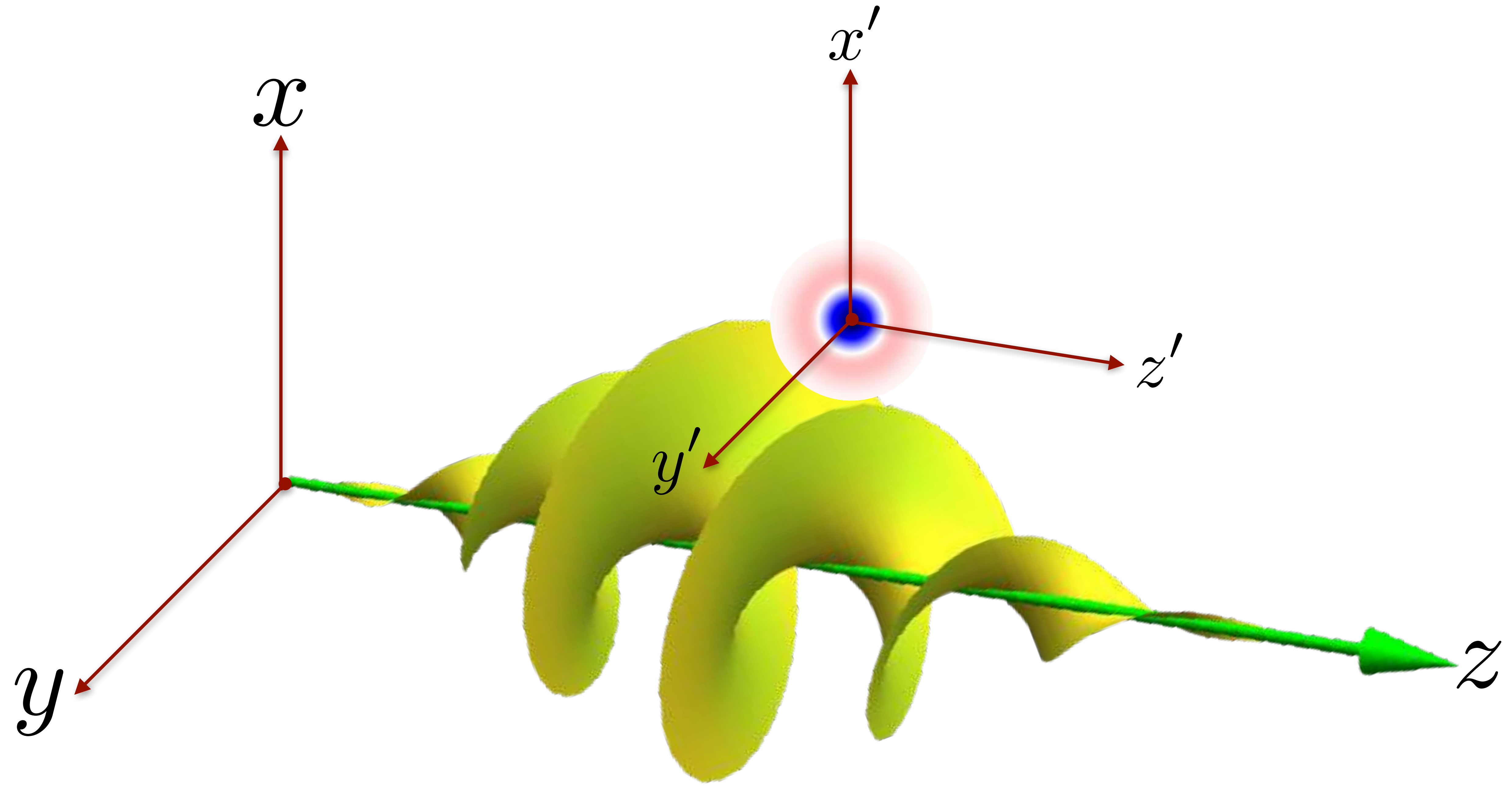
Twisted Neutrons

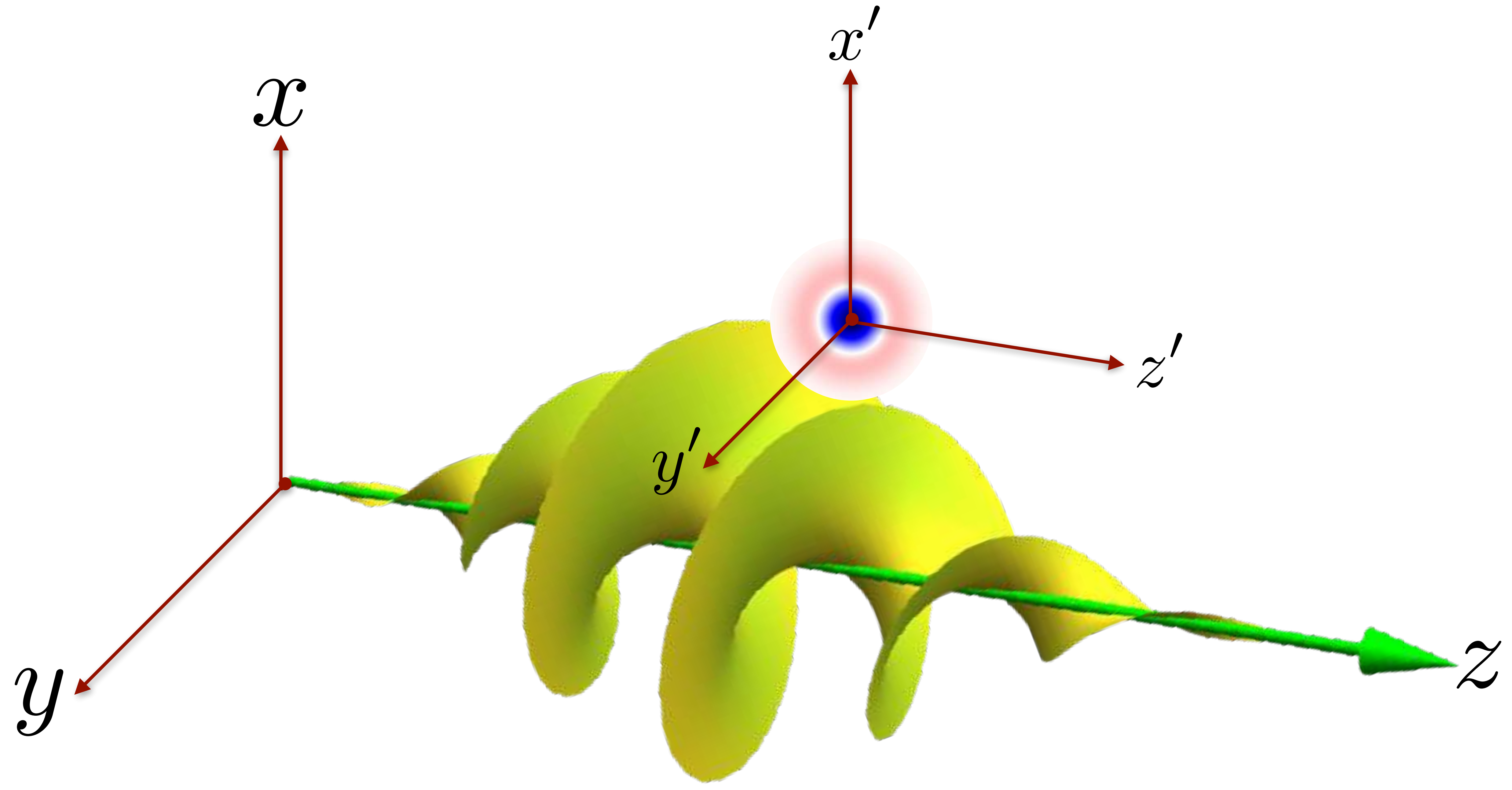


$$\rho_\ell(\mathbf{r}) = \int \rho(\mathbf{r}' - \mathbf{r})\,|\psi_\ell(\mathbf{r}')|^2\,d^3\mathbf{r}'$$

$$\mathbf{J}_\ell(\mathbf{r}) = \int \rho(\mathbf{r}' - \mathbf{r})\,\mathbf{j}_\ell(\mathbf{r}')\,d^3\mathbf{r}'$$

H Larocque, I Kaminer, V Grillo, R W Boyd & EK, *Nature Physics* **14**, 1–2 (2018).

Twisted Neutrons



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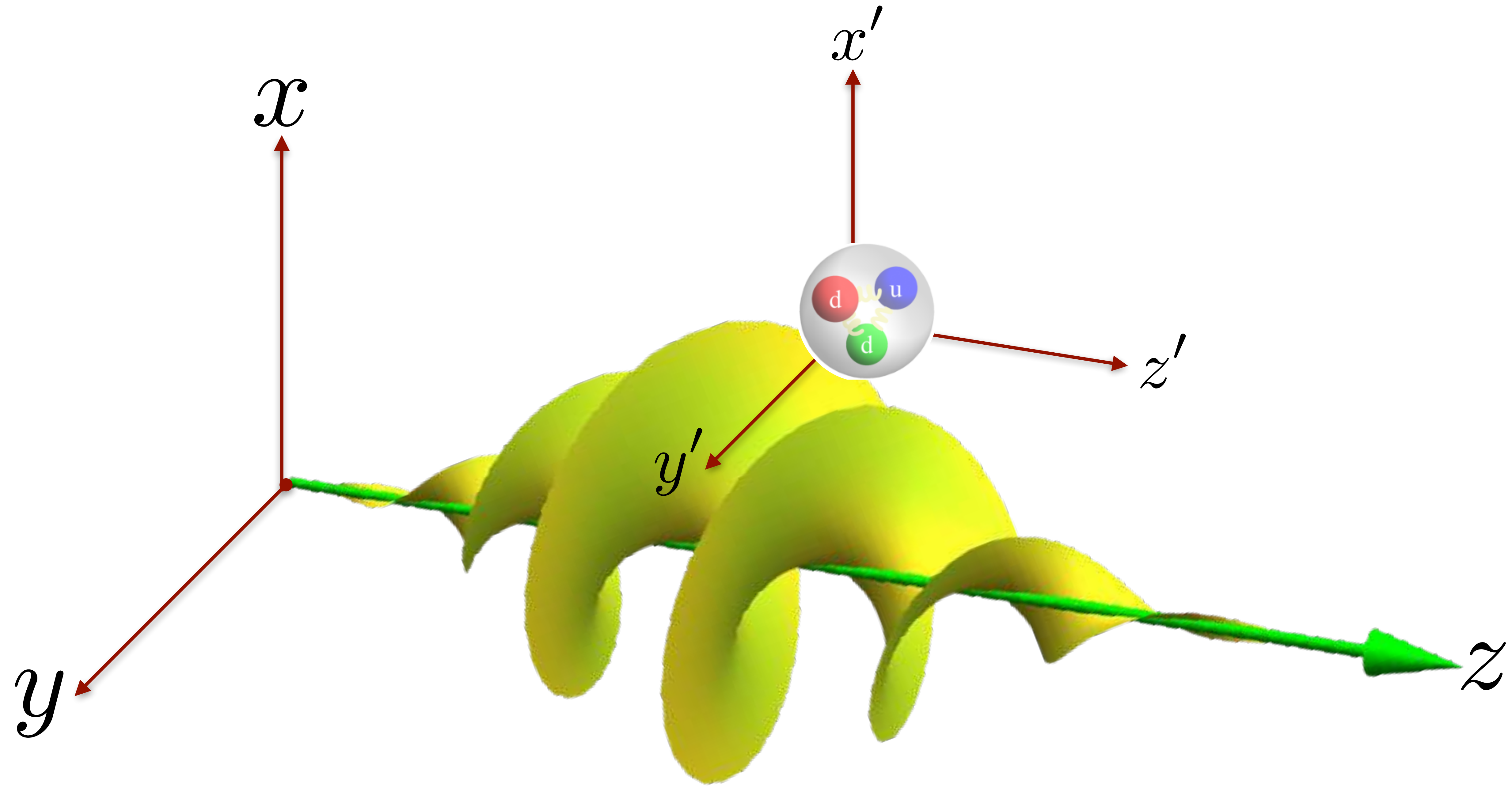
$$\mathbf{J}_\ell(\mathbf{r}) = \int \rho(\mathbf{r}' - \mathbf{r})\, \mathbf{j}_\ell(\mathbf{r}') \, d^3\mathbf{r}'$$

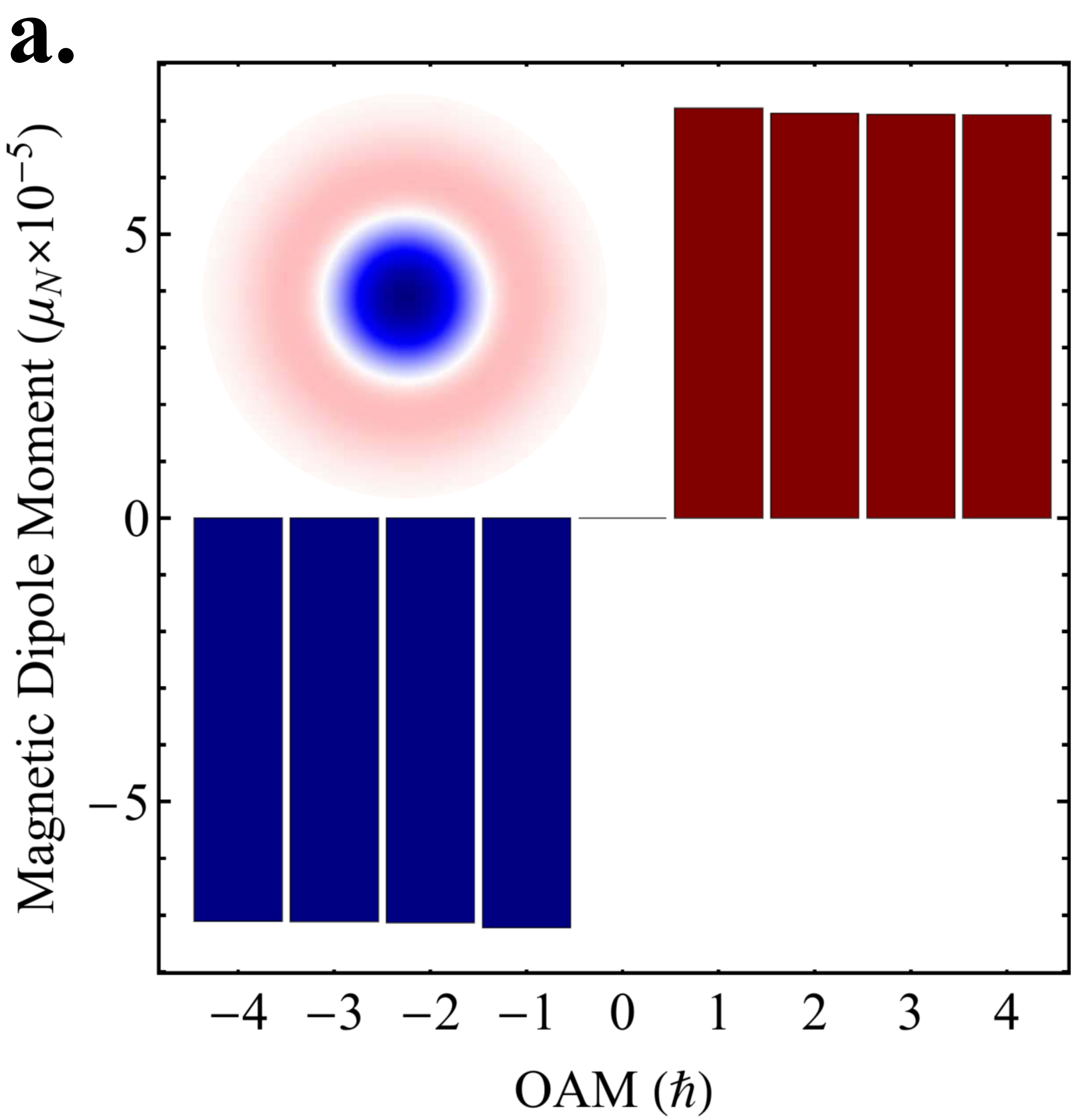
$$\rho_\ell(\mathbf{r}) = \frac{2}{\pi} \frac{\sigma^{2|\ell|}}{(w^2+\sigma^2)^{|\ell|+1}} \exp\left(-\frac{2r^2}{\sigma^2}\right) {}_1F_1\left(|\ell|+1;\ 1;\ \frac{2r^2w^2}{\sigma^2(w^2+\sigma^2)}\right)$$

$$\mathbf{J}_\ell(\mathbf{r}) = \frac{\hbar\ell}{m_N} \frac{2\sqrt{2}}{\pi w} \frac{\Gamma\left(|\ell|+\frac{1}{2}\right)}{\Gamma\left(|\ell|+1\right)} \frac{(\sigma^2)^{|\ell|-1/2}}{(w^2+\sigma^2)^{|\ell|+1/2}} \exp\left(-\frac{2r^2}{\sigma^2}\right) {}_1F_1\left(|\ell|+\frac{1}{2};\ 1;\ \frac{2r^2w^2}{\sigma^2(w^2+\sigma^2)}\right) \mathbf{e}_\varphi$$

H Larocque, I Kaminer, V Grillo, R W Boyd & EK, *Nature Physics* **14**, 1–2 (2018).

Twisted Neutrons





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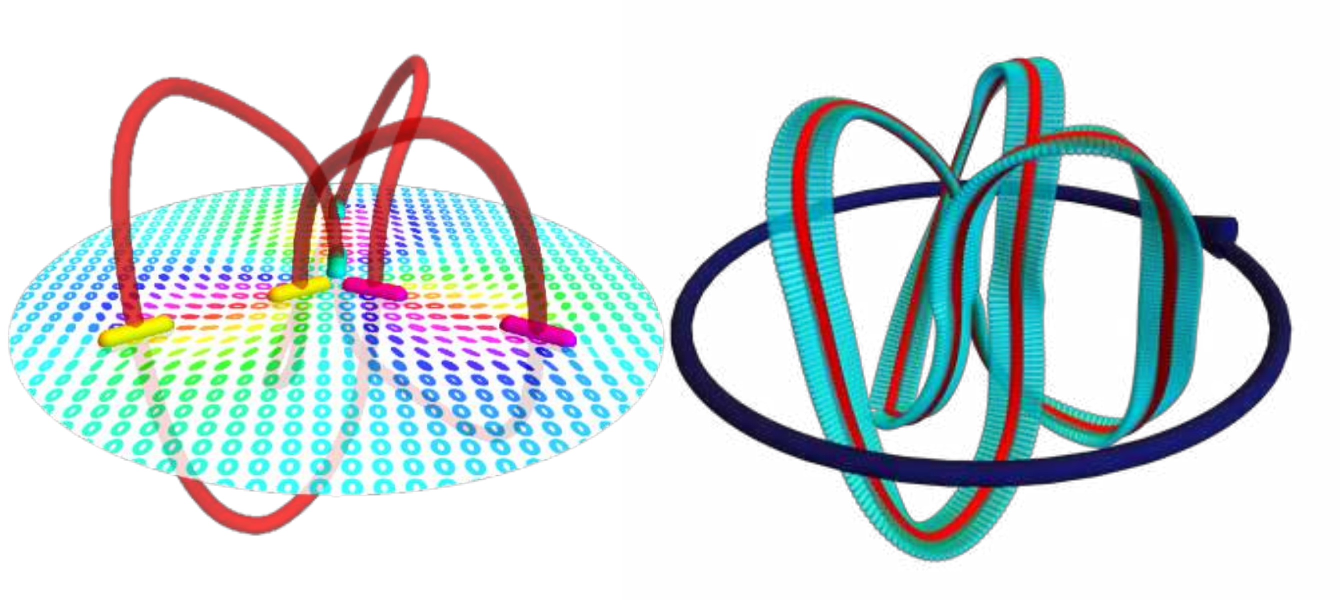
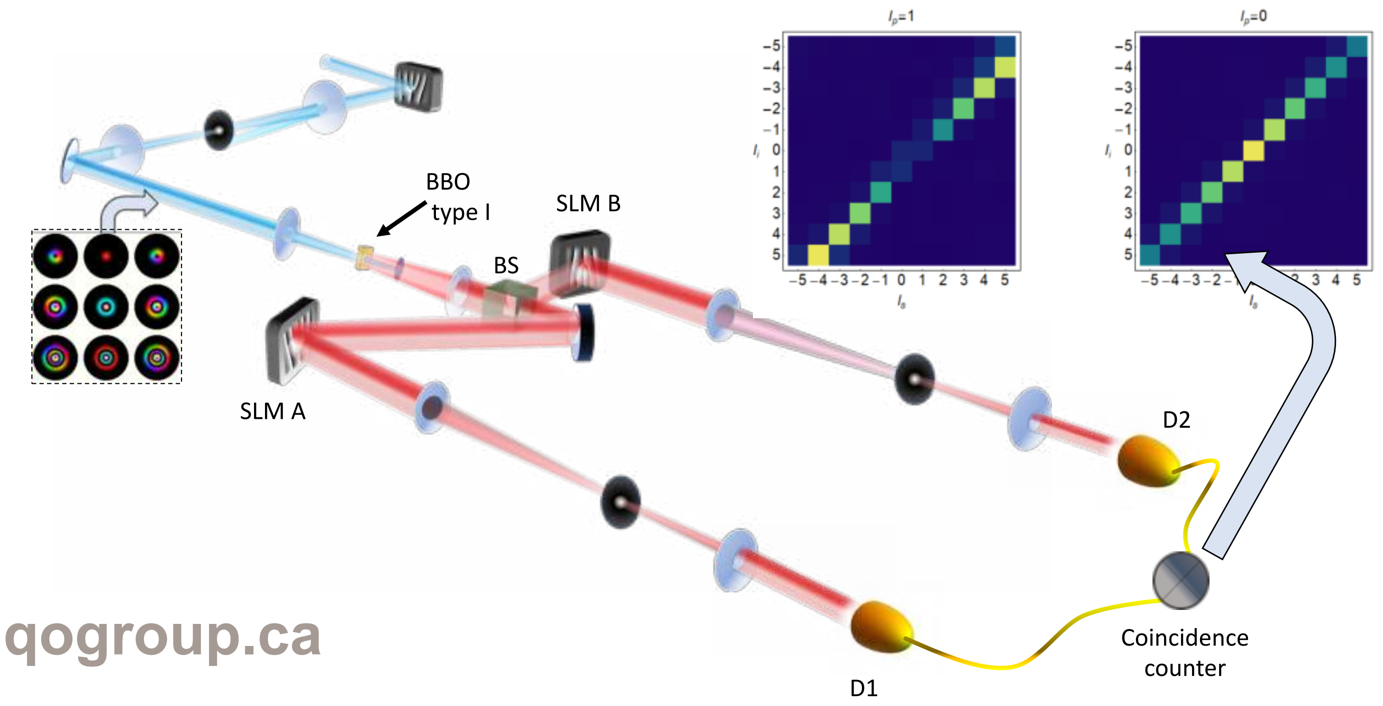
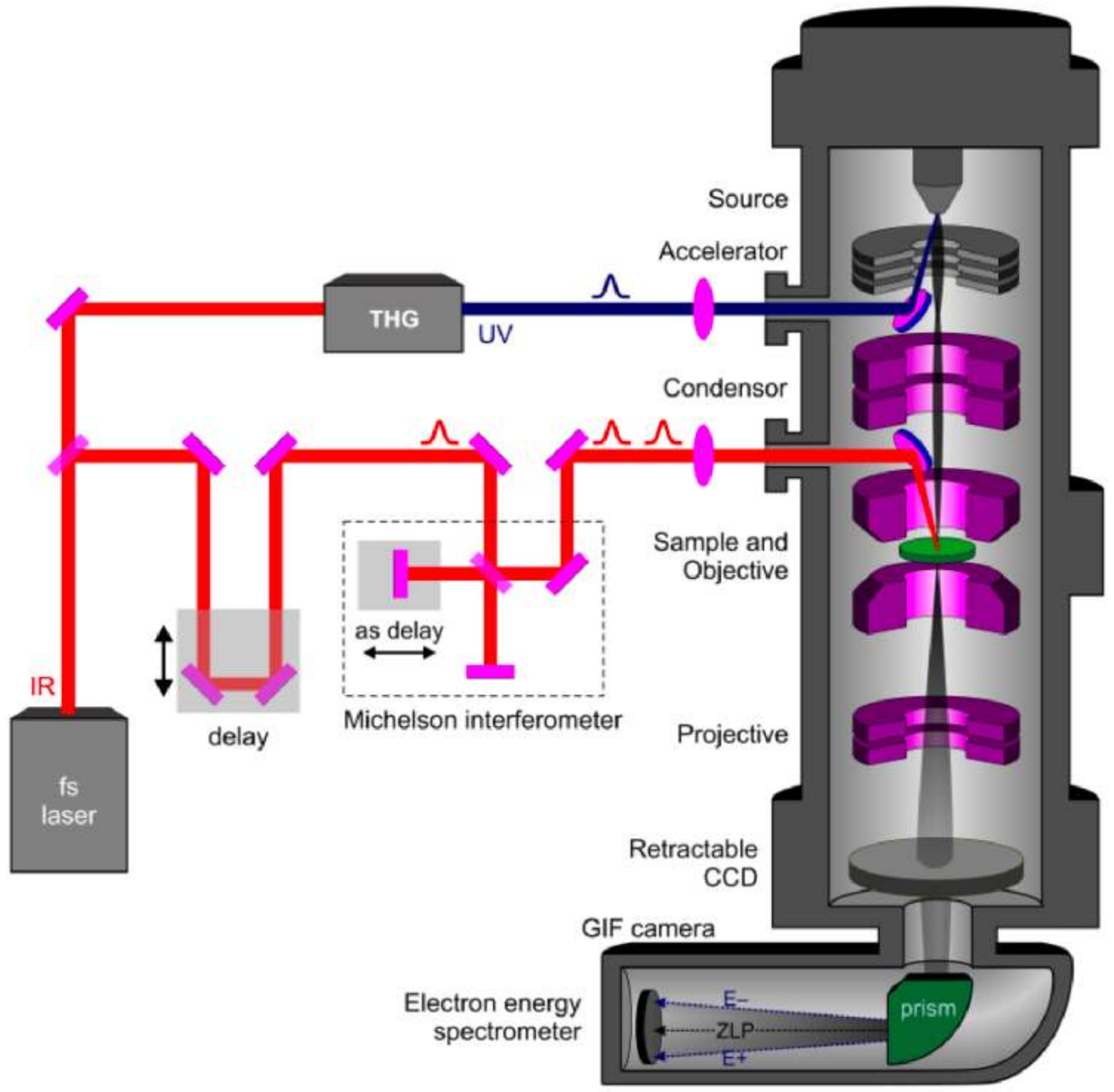
Summary

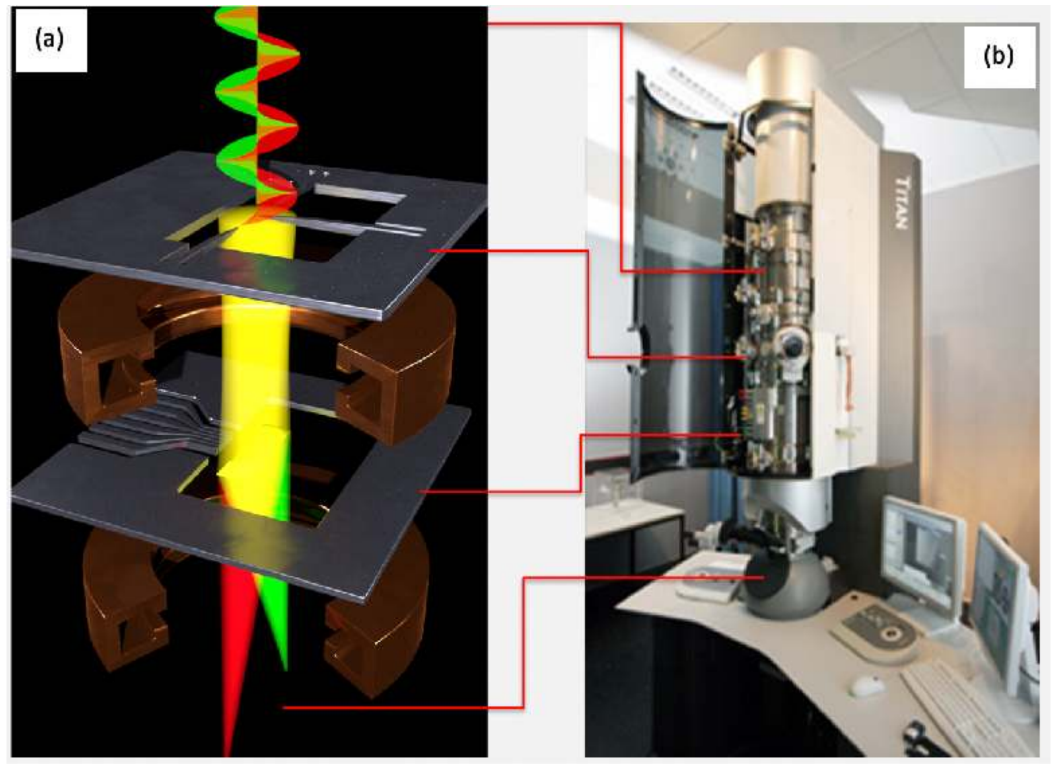
Fundamental Questions



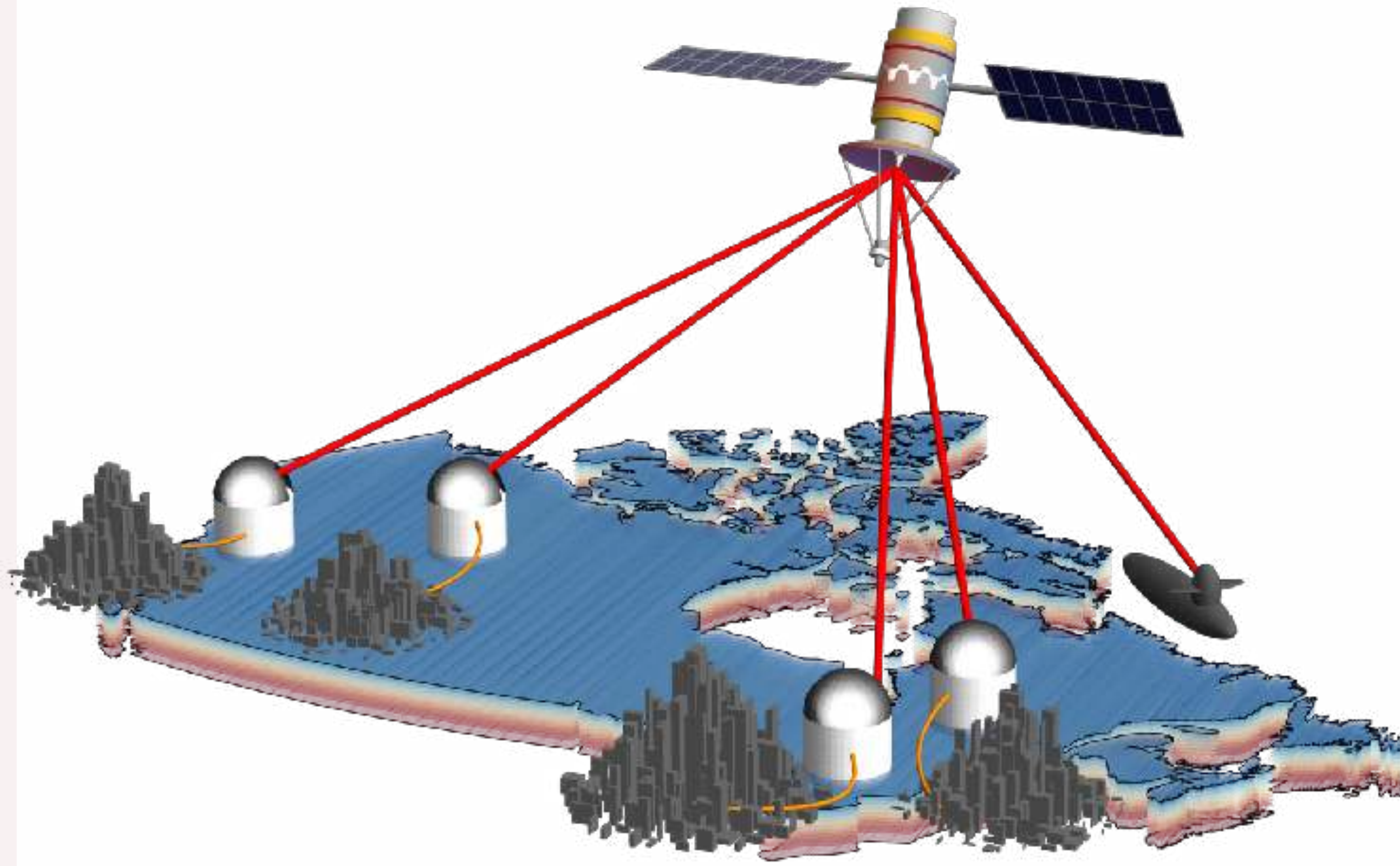


Extreme Quantum Microscope



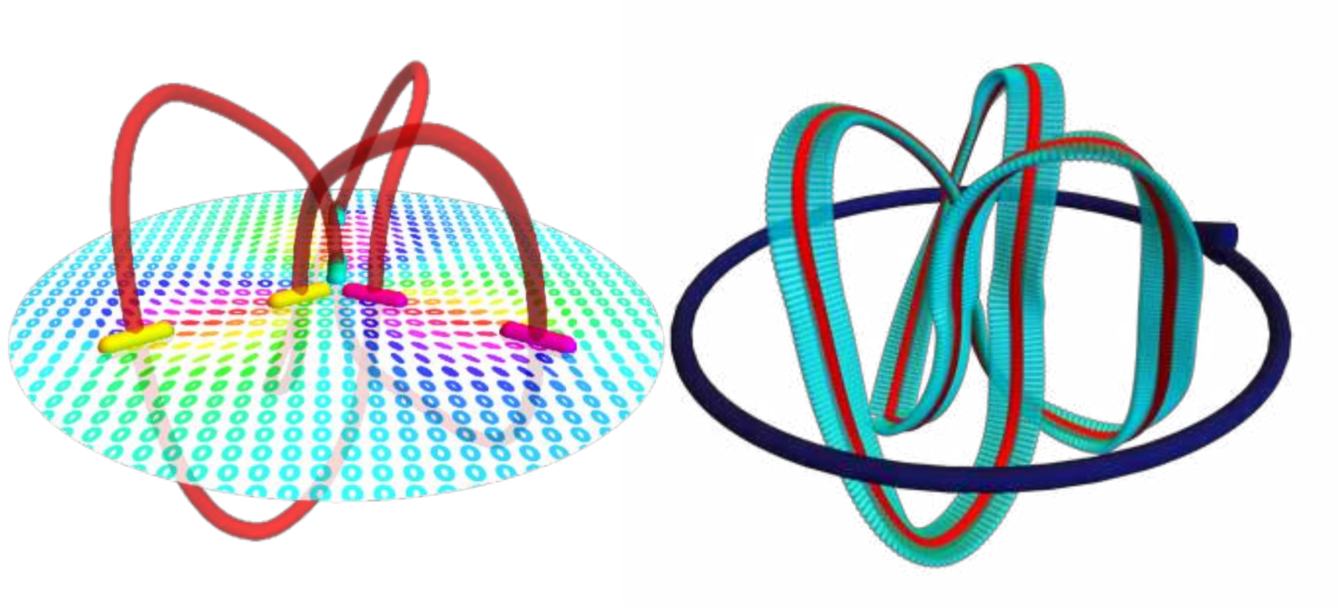


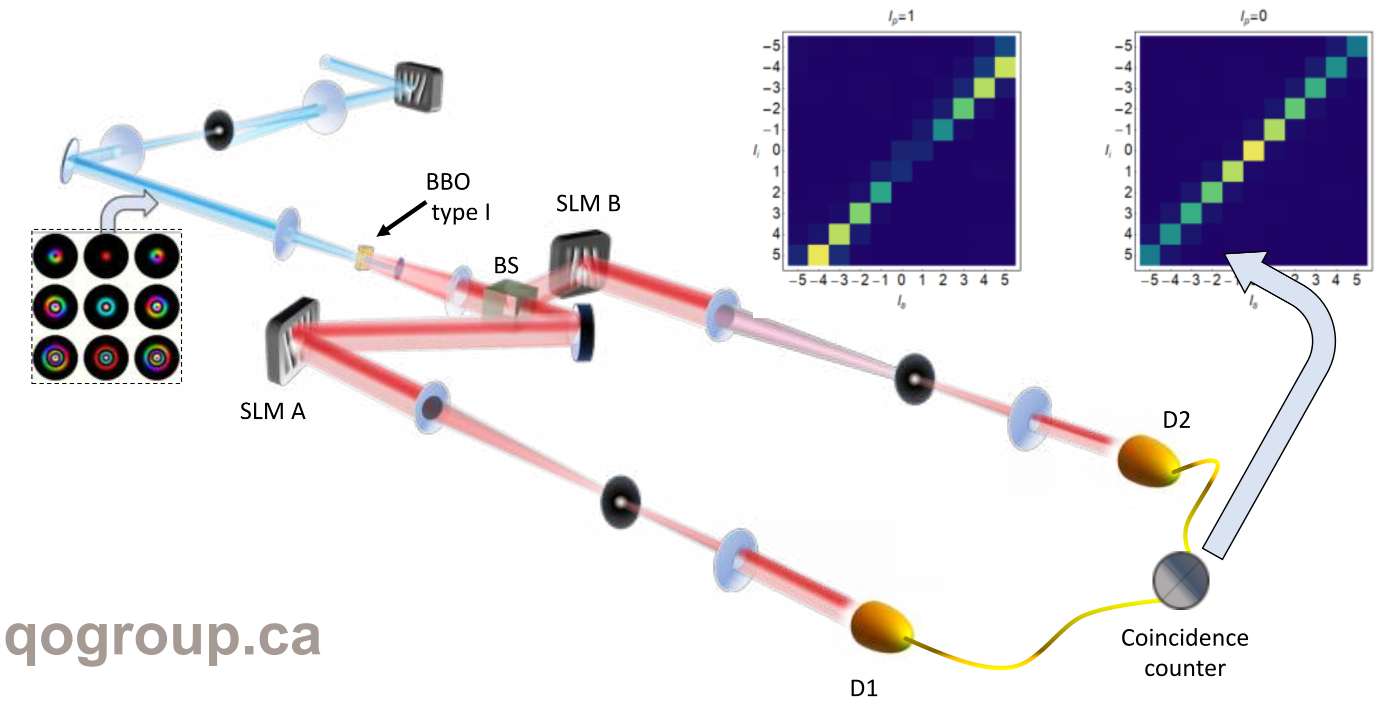
Quantum Internet Canada



Summary

Fundamental Questions





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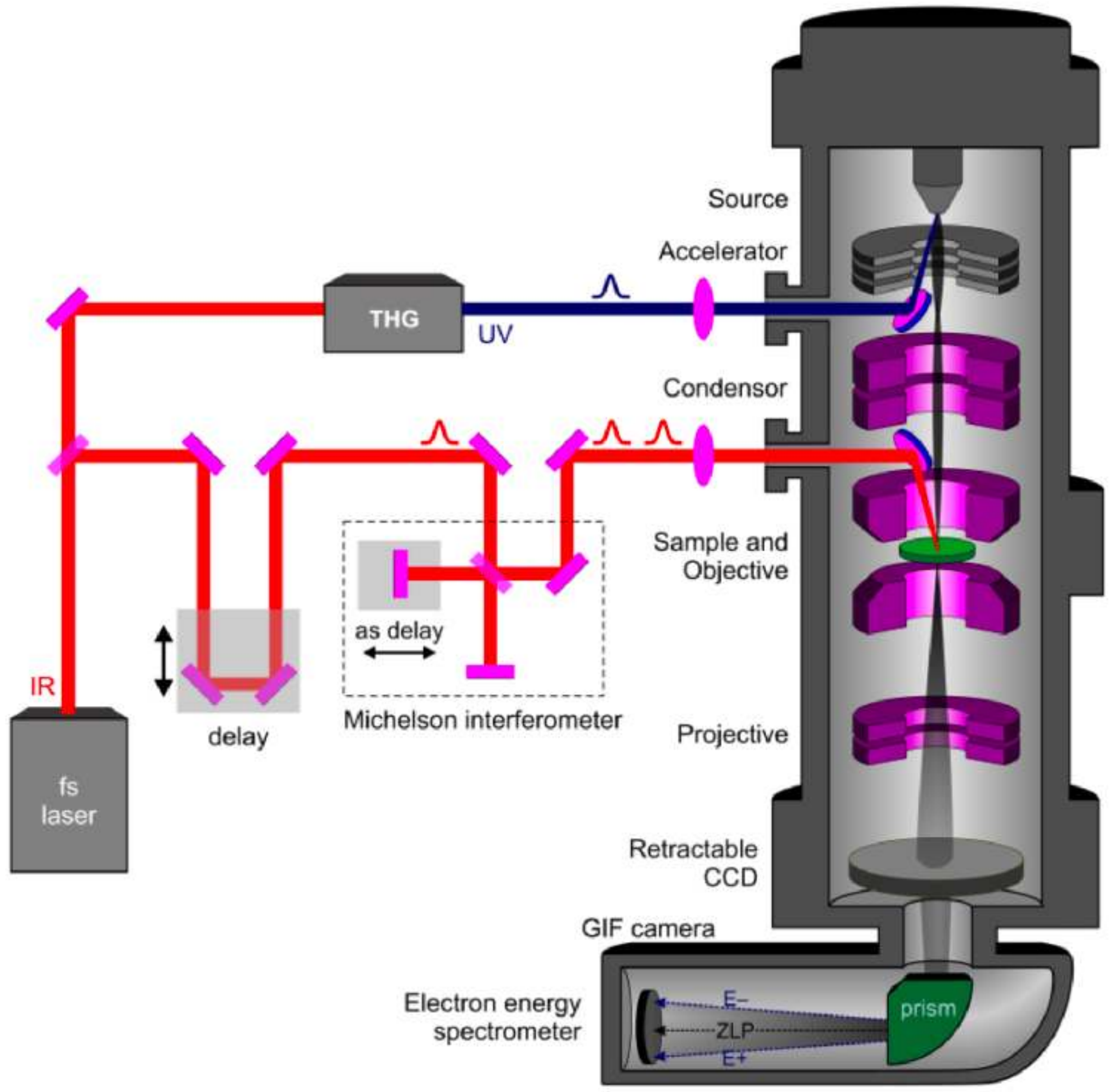

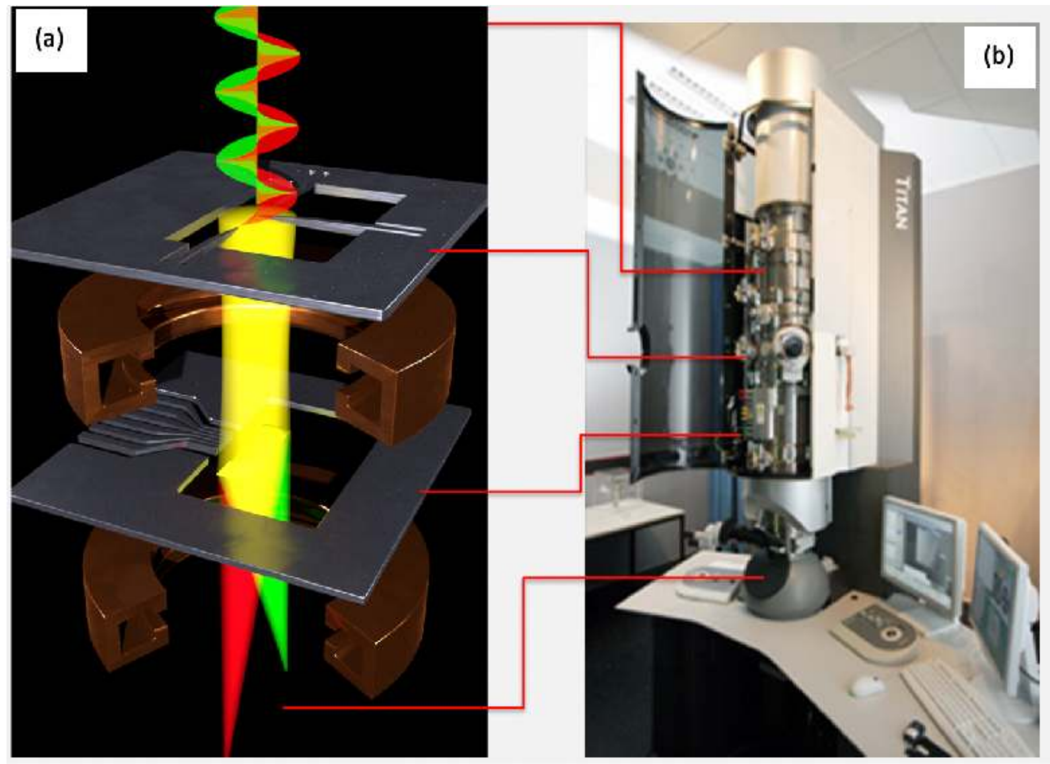

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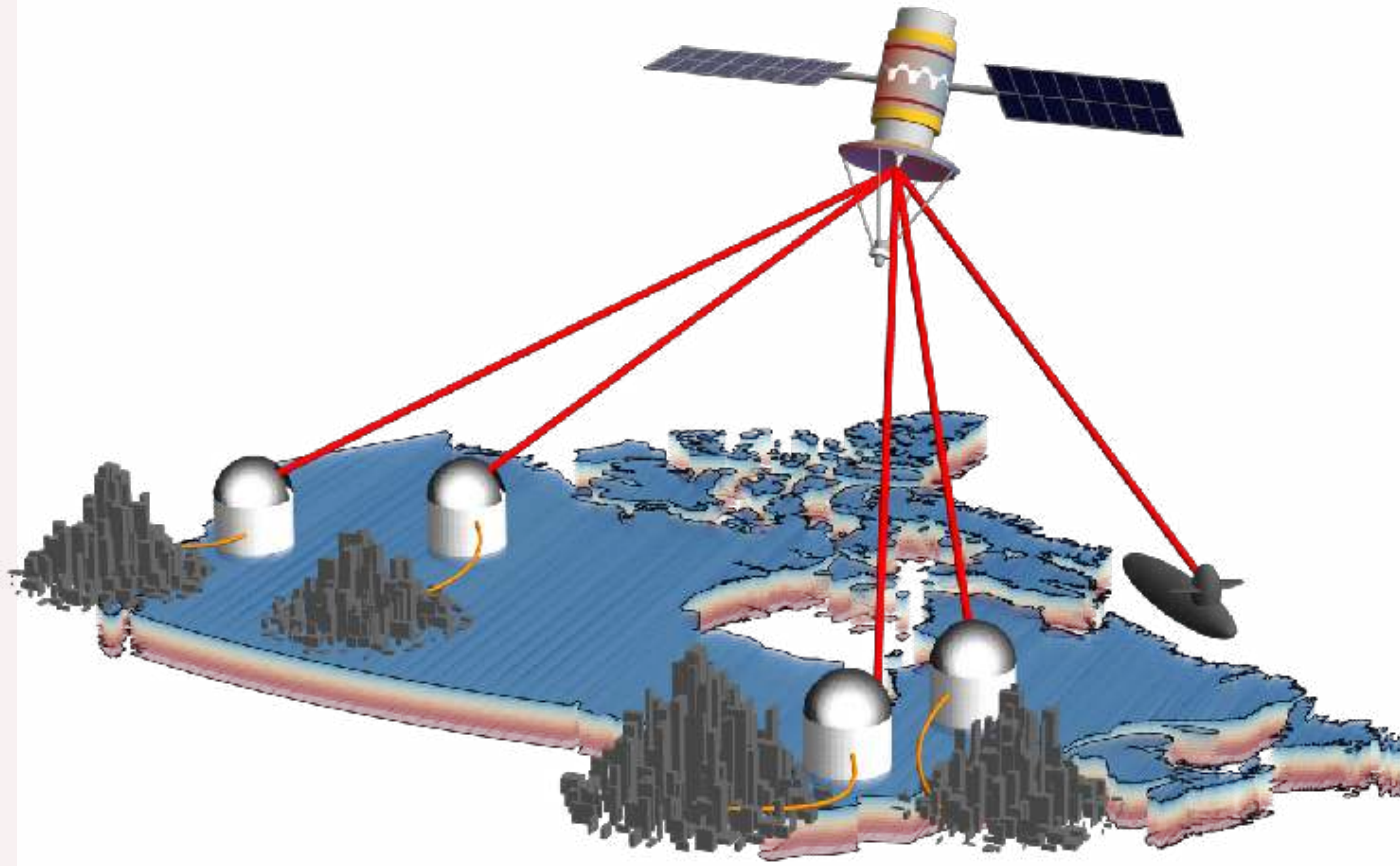
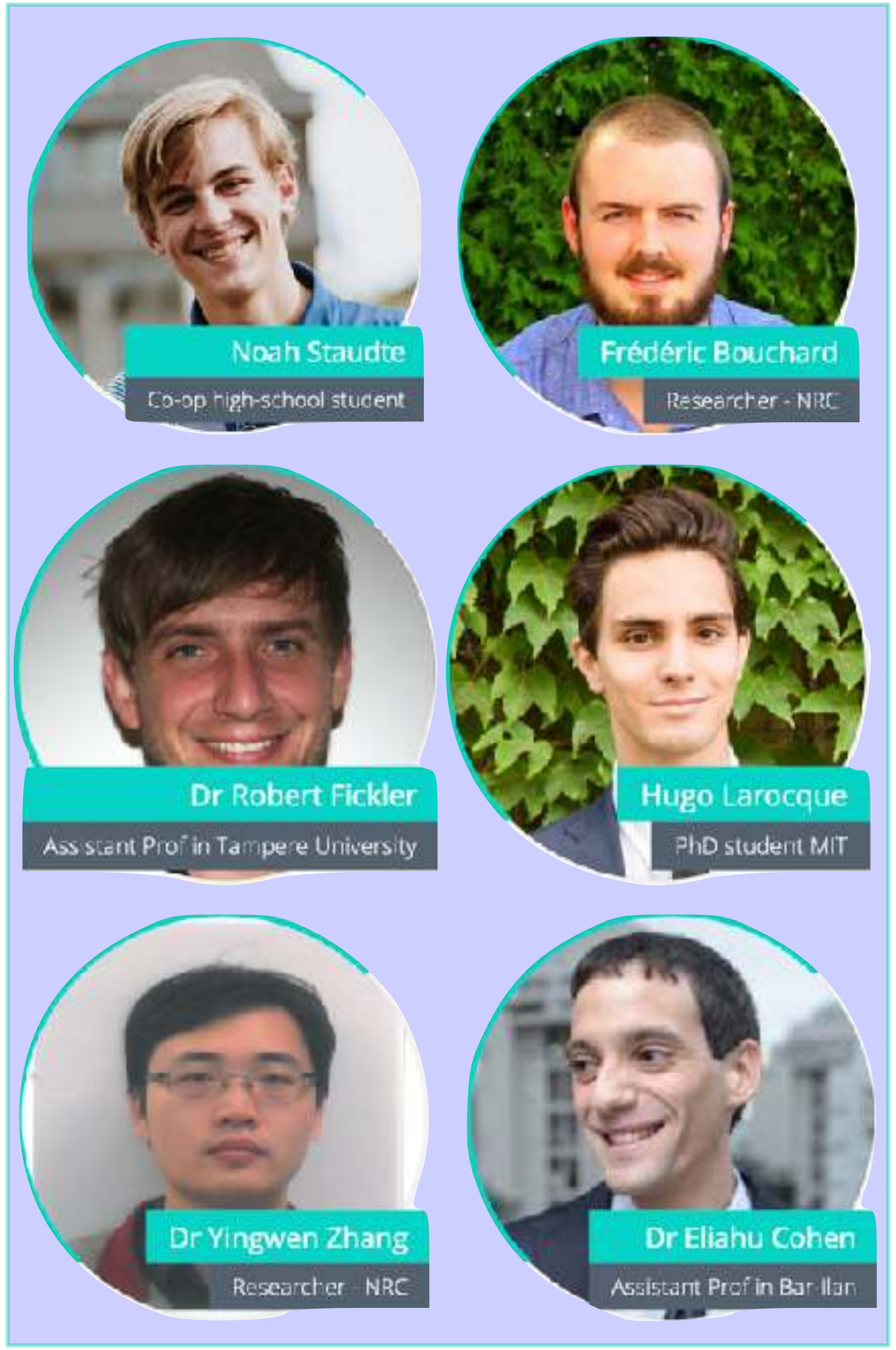


SQO team


Noah Staudte
Co-op high-school student
Frédéric Bouchard
Researcher - NRC
Dr Robert Fickler
Assistant Prof in Tampere University
Hugo Larocque
PhD student MIT
Dr Yingwen Zhang
Researcher - NRC
Dr Eliahu Cohen
Assistant Prof in Bar-Ilan

Collaborators

…, and many other members of these research teams

JCEP

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