Chiral Quantum Optics

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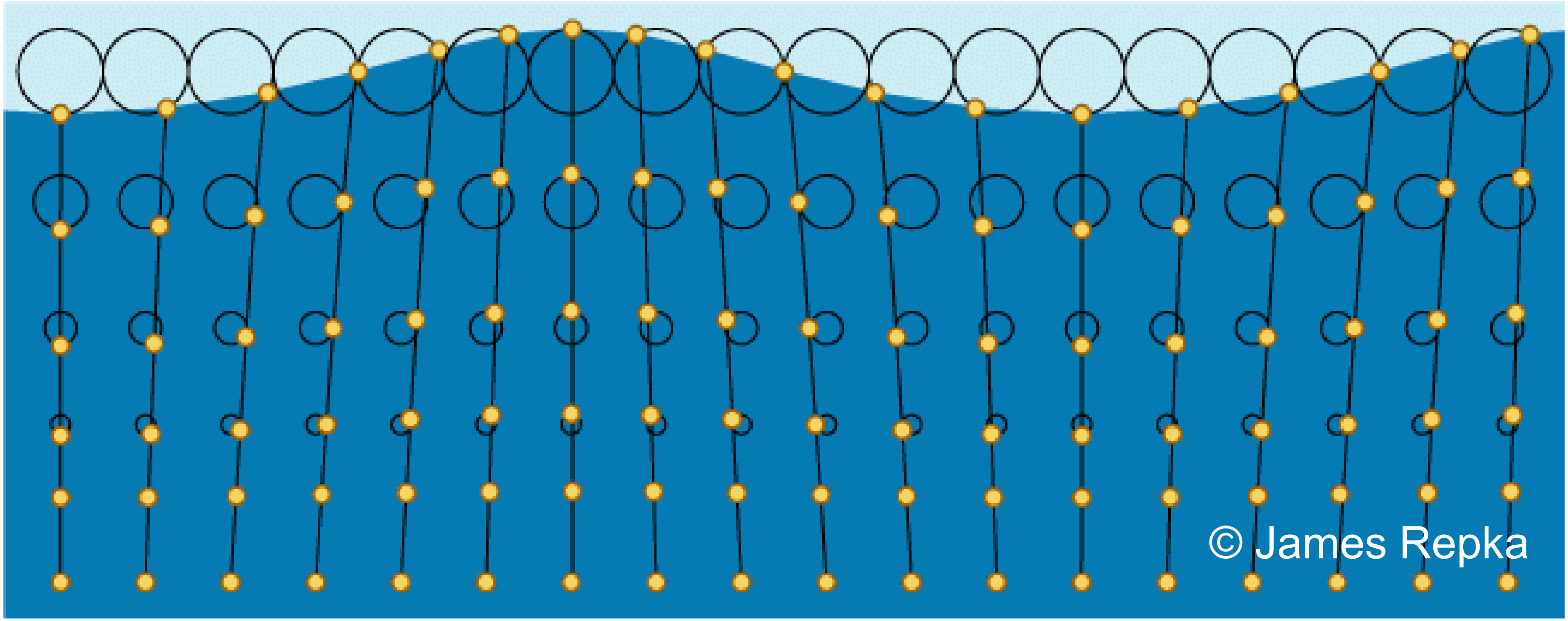
Intro: Surface Waves

- Amplitude diminishes with distance from surface
- Continuity equation: $\vec{\nabla} \cdot \vec{u} = 0$

⇒ Water moves in more-or-less circular orbits

⇒ Sense of circulation flips with direction of propagation



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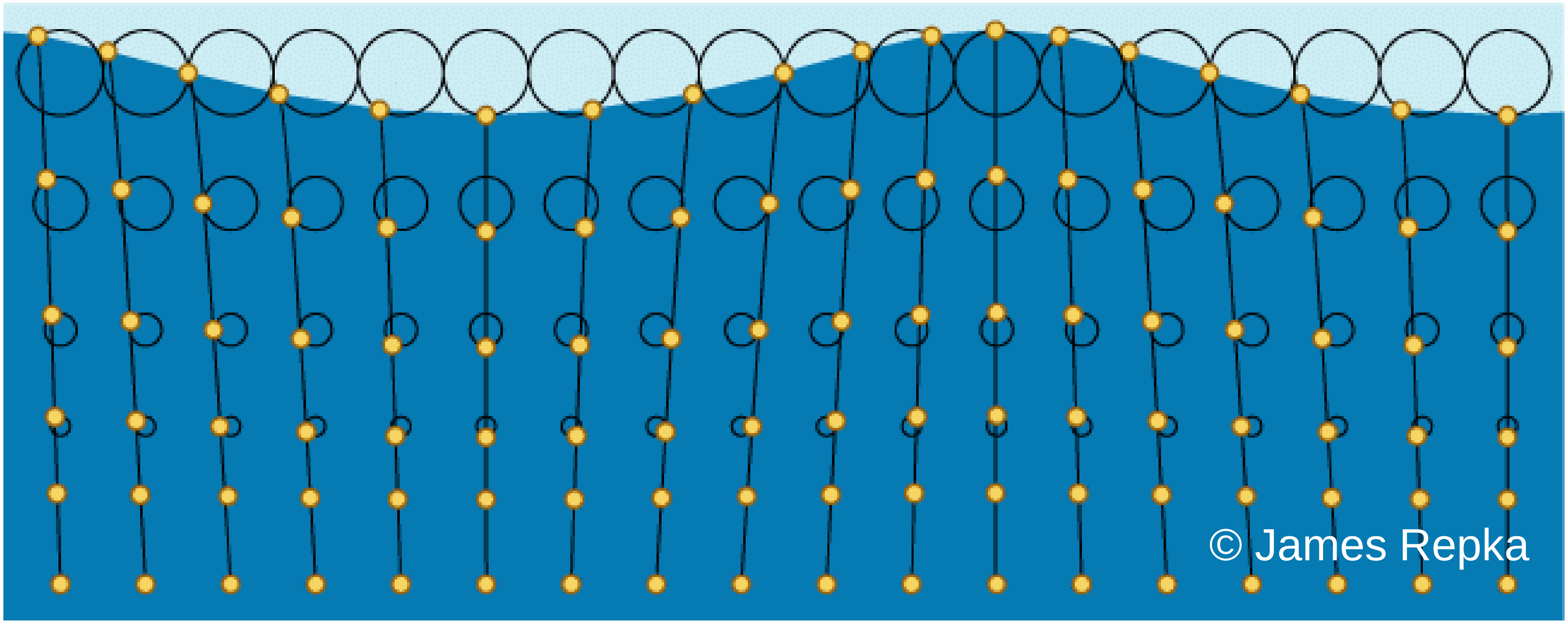
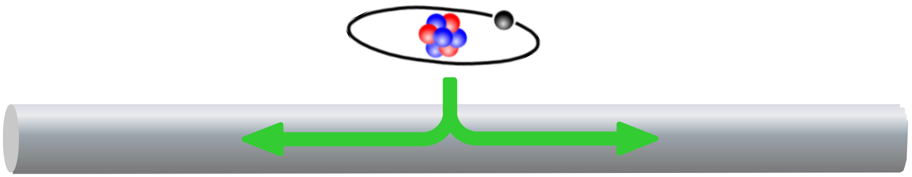


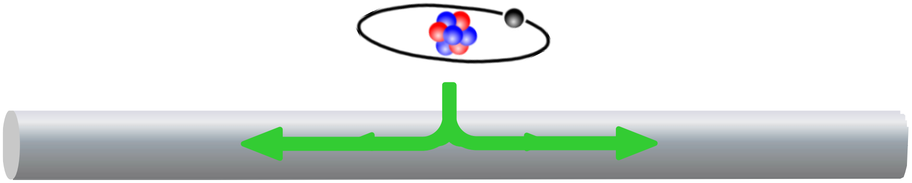
Intro: Chiral Coupling

Emitter coupled to surface wave surrounding nanophotonic waveguide

- Symmetric:



- Chiral:

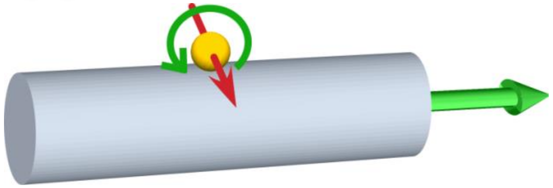


- See related experimental work by Capasso, Dayan, Fox, Kuipers, Lee, Leuchs, Lodahl, Martinez, Oulton, Rarity, Skolnick, and Zayats.

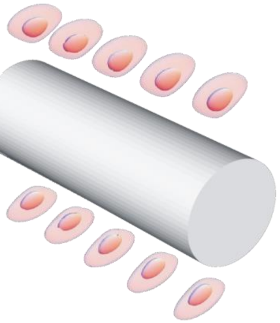
Overview

- Guided modes in optical nanofibers

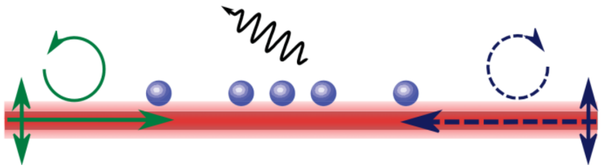
- Chiral nanophotonic waveguide interface



- Chiral atom-waveguide interface

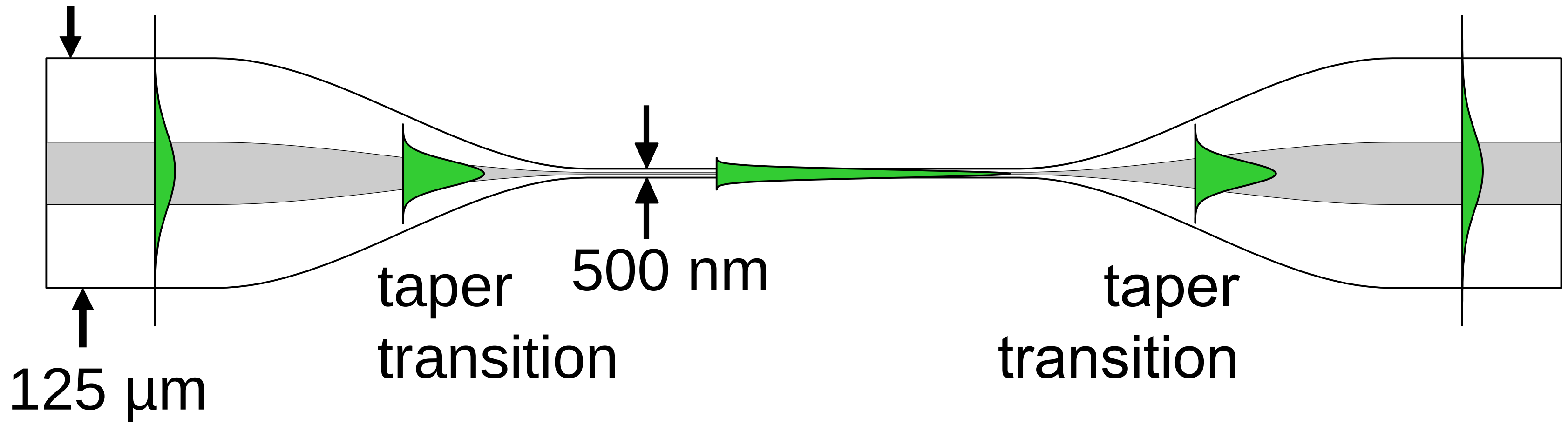


- Nonreciprocal nanophotonic devices



Nanofibers as the Waist of a Tapered Fiber

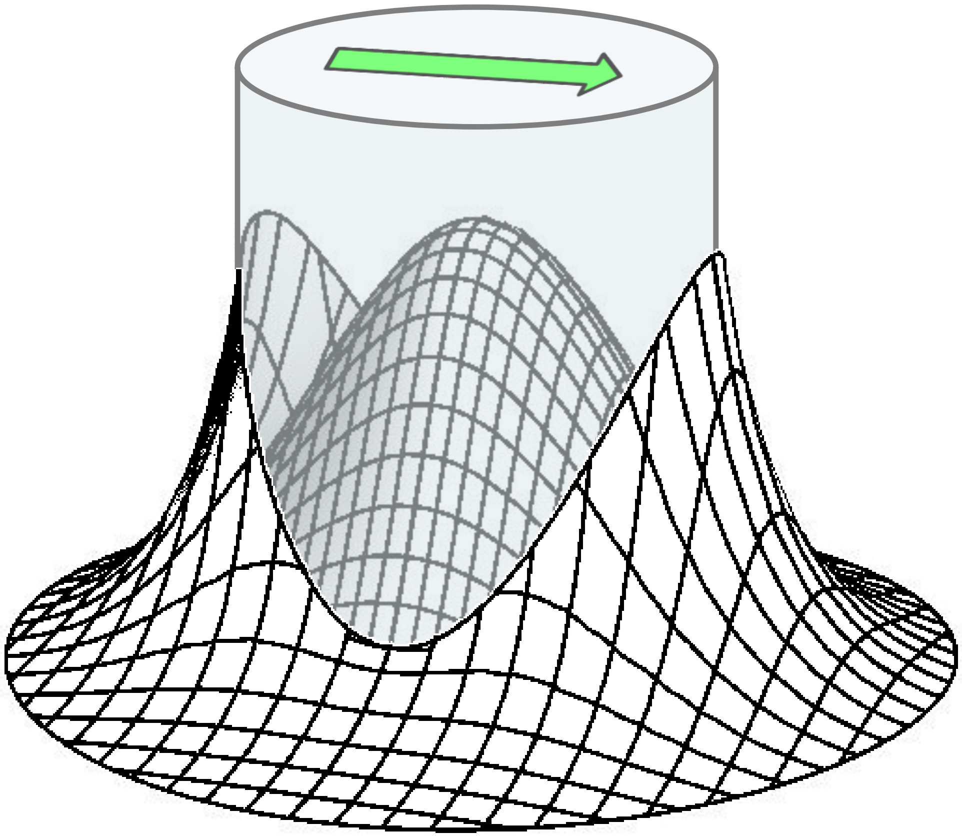
Efficient coupling of light into and out of the nanofiber



- Adiabatic mode transformation ⇒ up to 99% transmission
- Withstands >100 mW of transmitted optical power in vacuum

HE_{11} Mode: Intensity Distribution

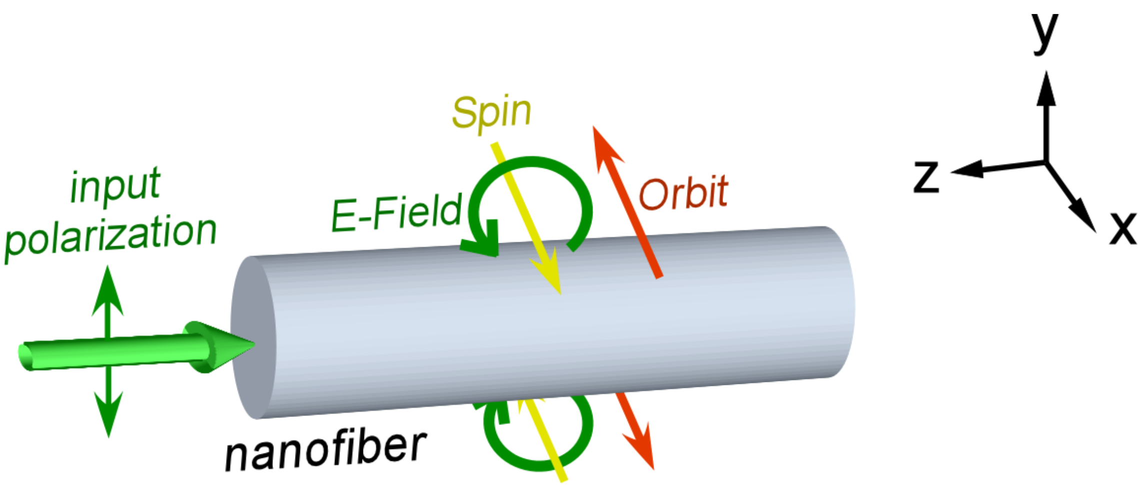
- Quasi linearly polarized HE_{11} mode.
- Parameters: $a = 250$ nm, $n_1 = 1.46$ (silica), $n_2 = 1$ (vacuum / air), and $\lambda = 852$ nm.



HE_{11} Mode: Spin-Momentum-Locking

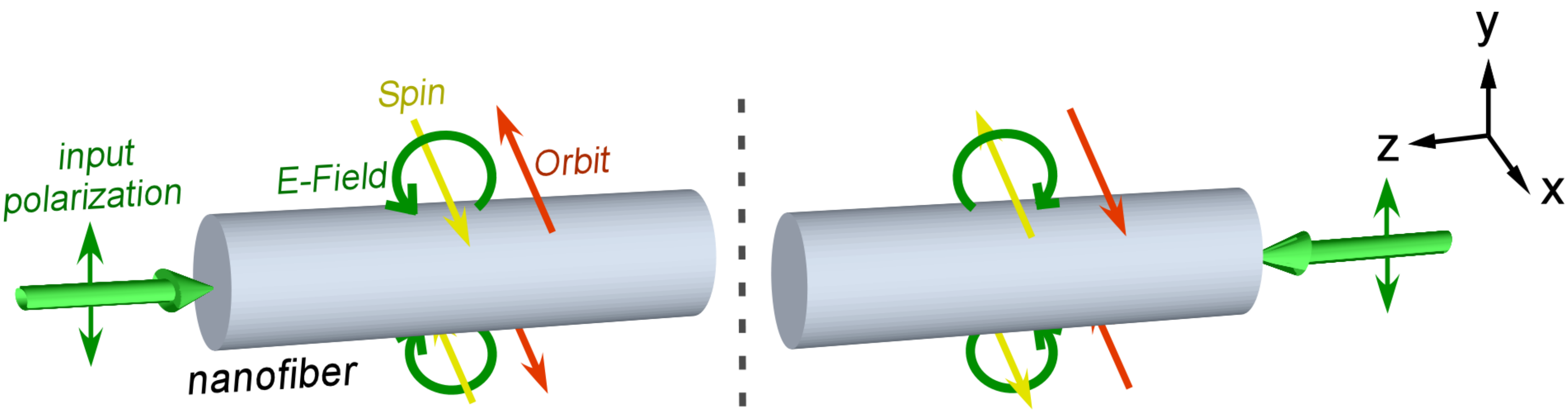
Fluid dynamics: continuity equation $\vec{\nabla} \cdot \vec{u} = 0$

Electromagnetism: Gauss‘ law, $\vec{\nabla} \cdot \vec{E} = 0$



⇒ Local ellipticity (or spin) depends on transverse position

HE_{11} Mode: Spin-Momentum-Locking

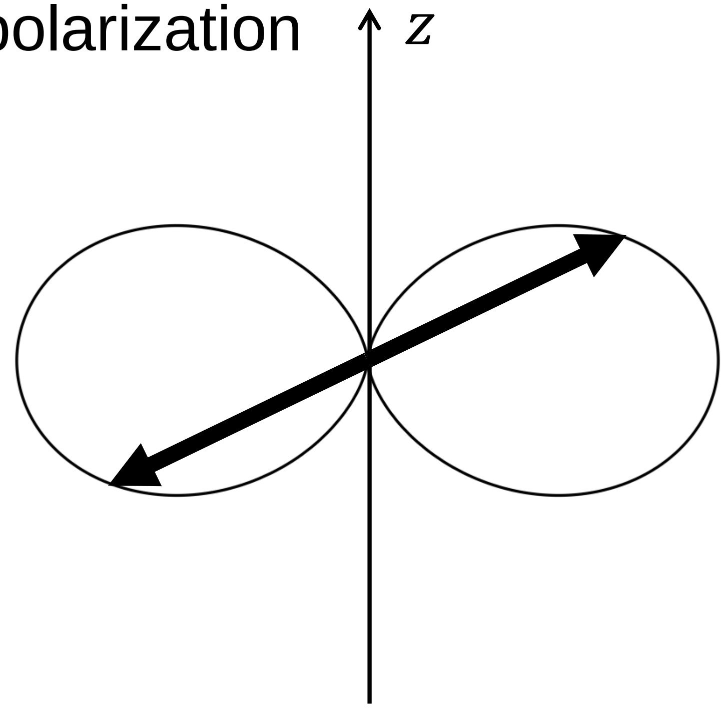


⇒ Local ellipticity (or spin) changes sign with direction of propagation

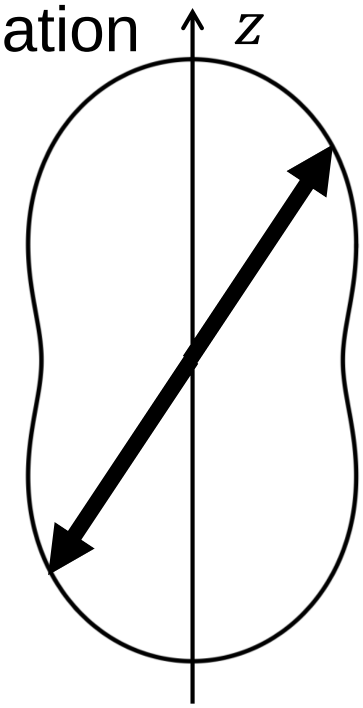
Dipolar Emission in Free Space

In free space, dipolar emission exhibits cylindrical symmetry w. r. t. quantization axis (z-axis) and is mirror-symmetric w. r. t. z=0 plane:

π-polarization



$\sigma^{\pm}$-polarization



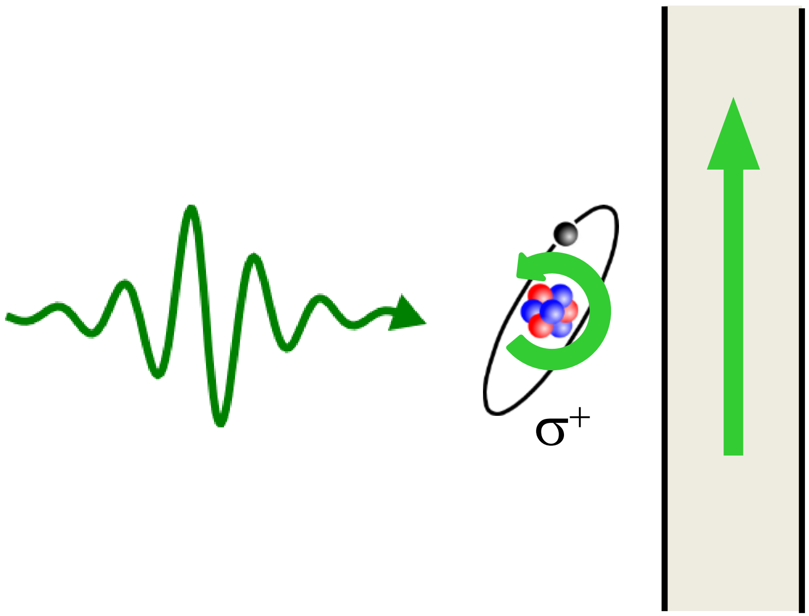
⇒ Emission in any given direction is the same as for opposite direction

Directional Dipolar Emission

Recipe

- Locate emitter on one side of the nanofiber
- Optical excitation…

  … emission of a σ^+-photon



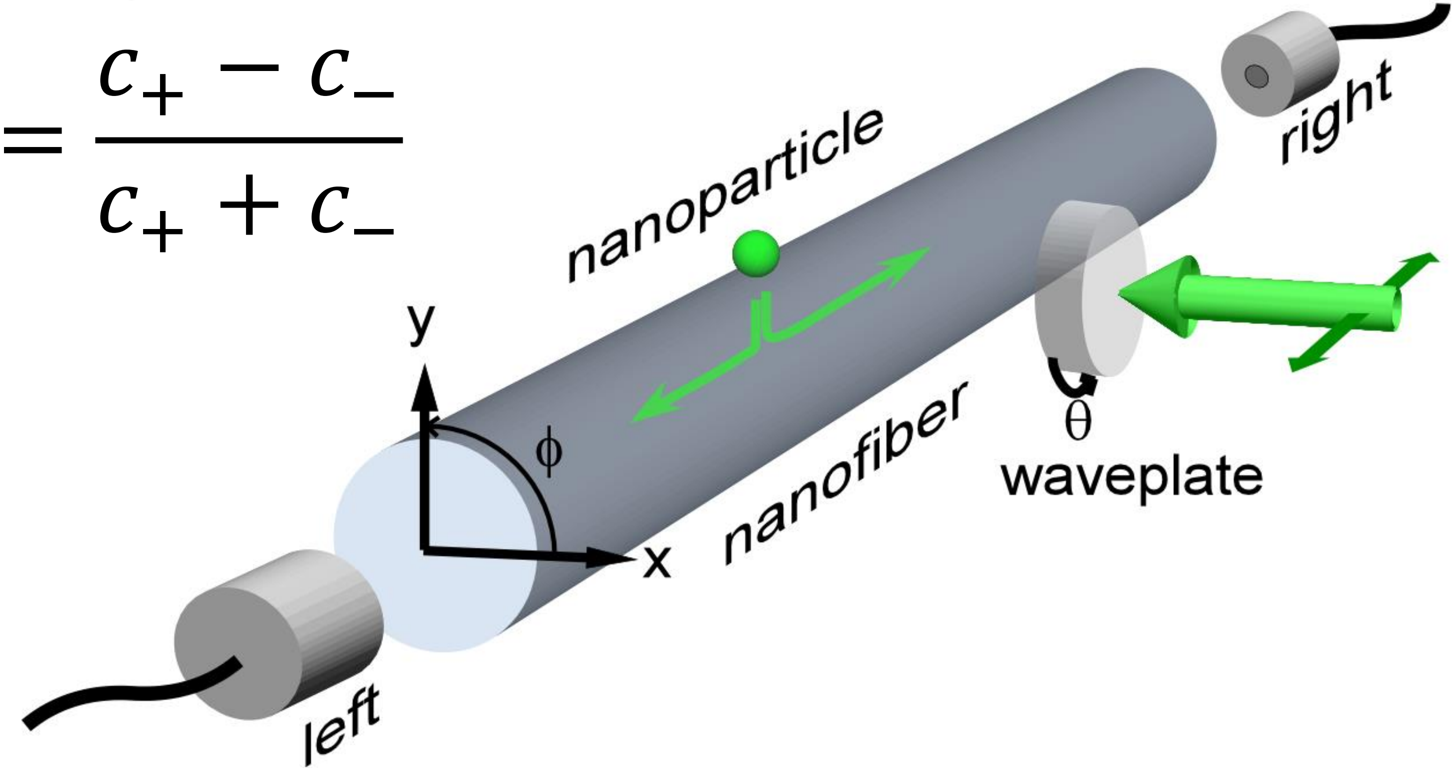
Experimental Set-Up

System: Gold nanoparticle (Ø=90 nm) on silica nanofiber (Ø=315 nm)

- Polarization of excitation light (σ^+, σ^-, linear) set by waveplate
- Azimuthal position of gold particle set by rotating nanofiber about axis

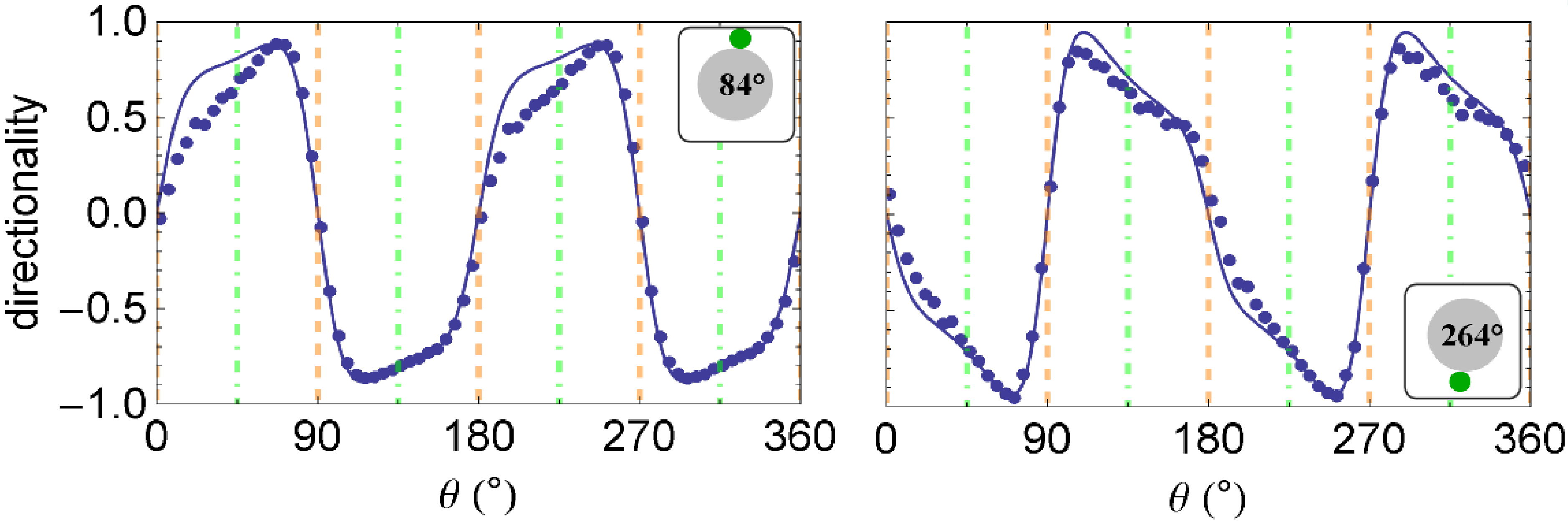
Directionality:

$$D = \frac{c_+ - c_-}{c_+ + c_-}$$



Petersen et al., Science **346**, 67 (2014)

Chiral Waveguide Coupling



- Maximum directionality:

$$D = 0.88 \qquad\qquad D = 0.95$$

- Corresponding ratio of left/right photon fluxes:

$$16 \div 1 \qquad\qquad 40 \div 1$$

Petersen et al., Science **346**, 67 (2014)

Overview

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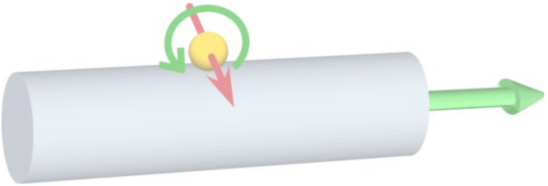
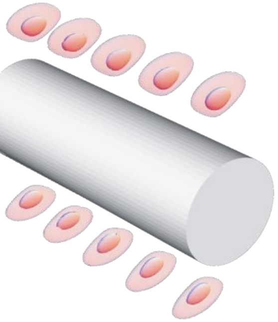
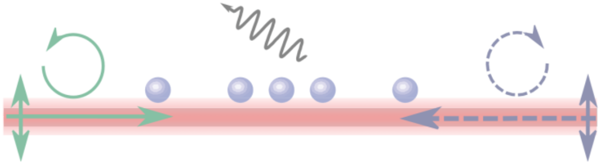


- **Chiral atom-waveguide interface**

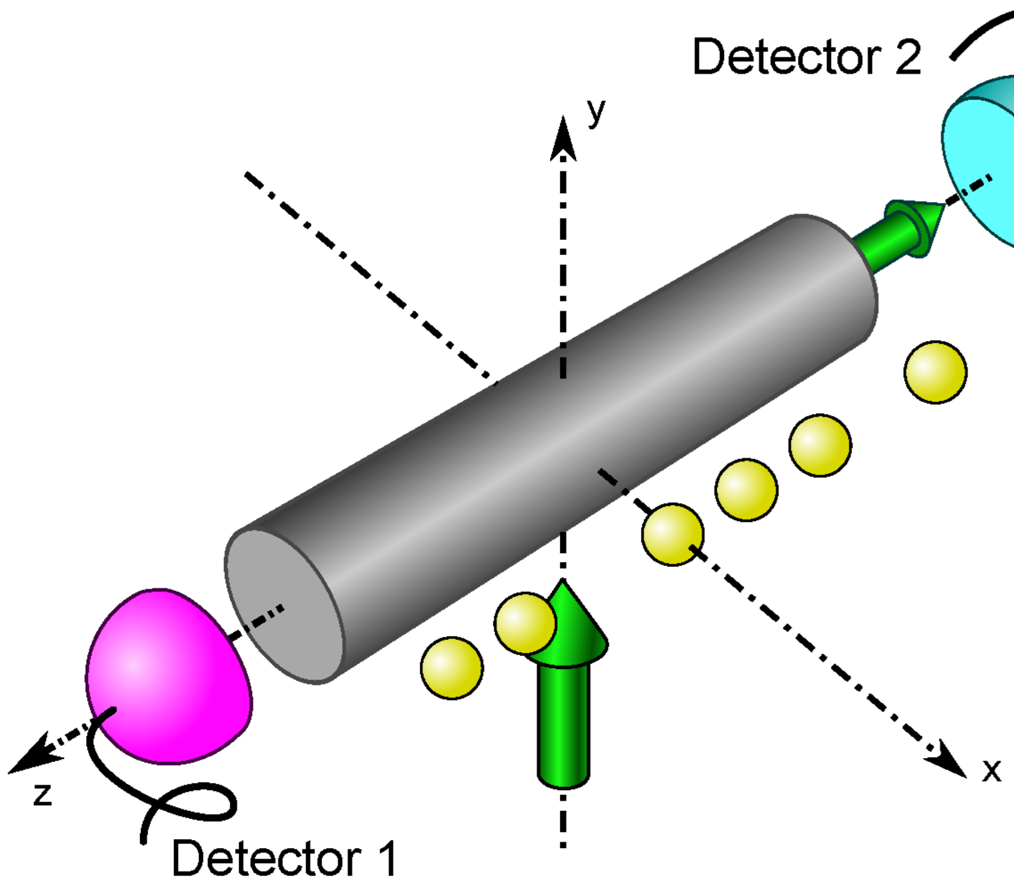


- Nonreciprocal nanophotonic devices



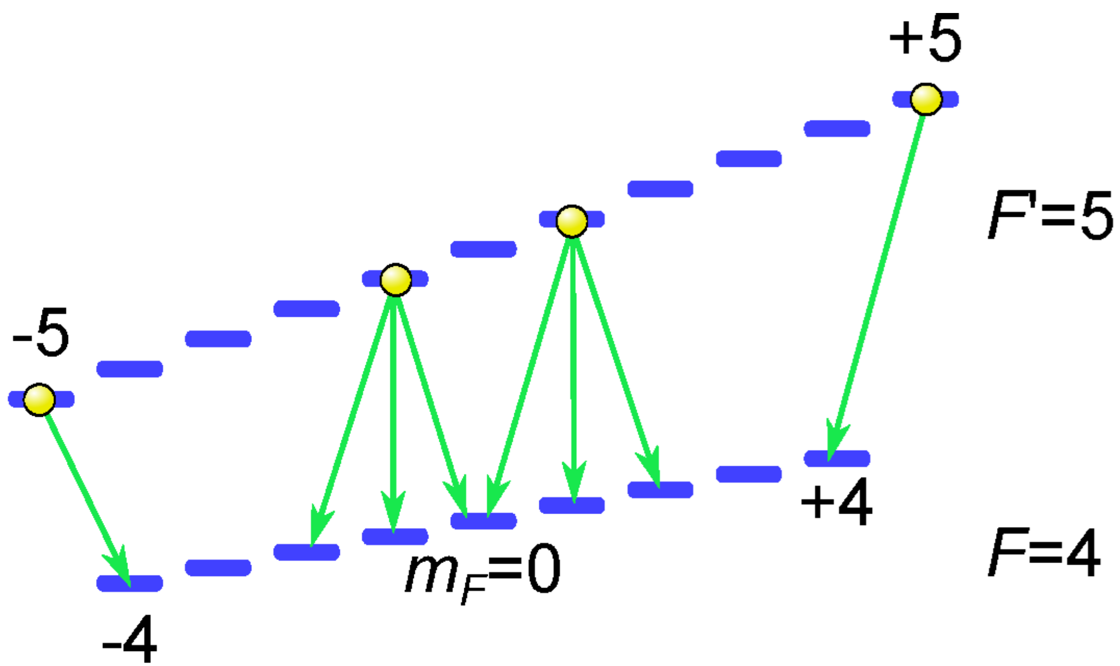
Experimental Set-Up

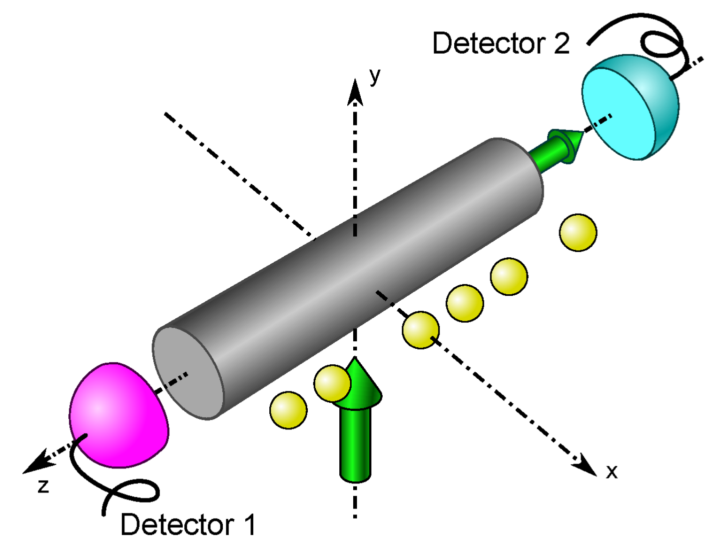
Nanofiber with cesium atoms on one side



R. Mitsch et al., Nat. Commun. **5**, 5713 (2014)

Cesium D2-Line Level Scheme

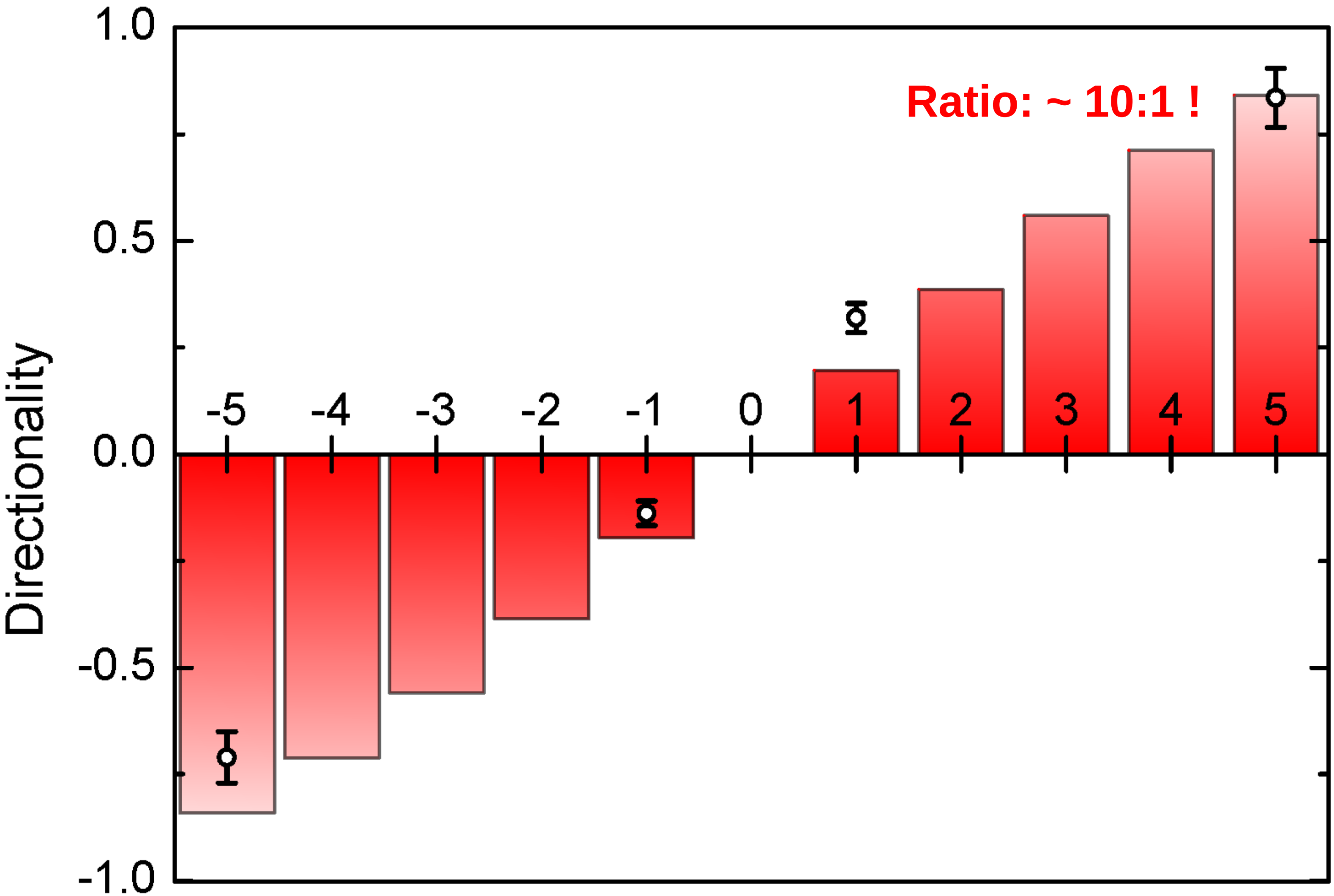




R. Mitsch et al., Nat. Commun. **5**, 5713 (2014)

Directional Atom-Waveguide Interface

Quantum state-controlled directional spontaneous emission



R. Mitsch et al., Nat. Commun. **5**, 5713 (2014)

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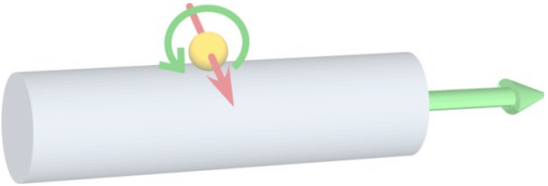

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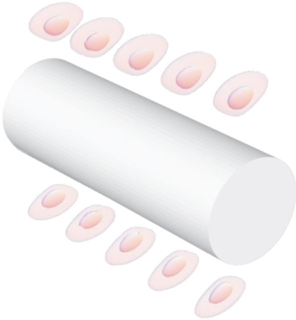

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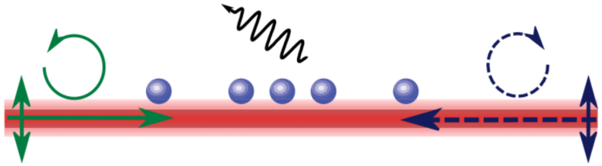
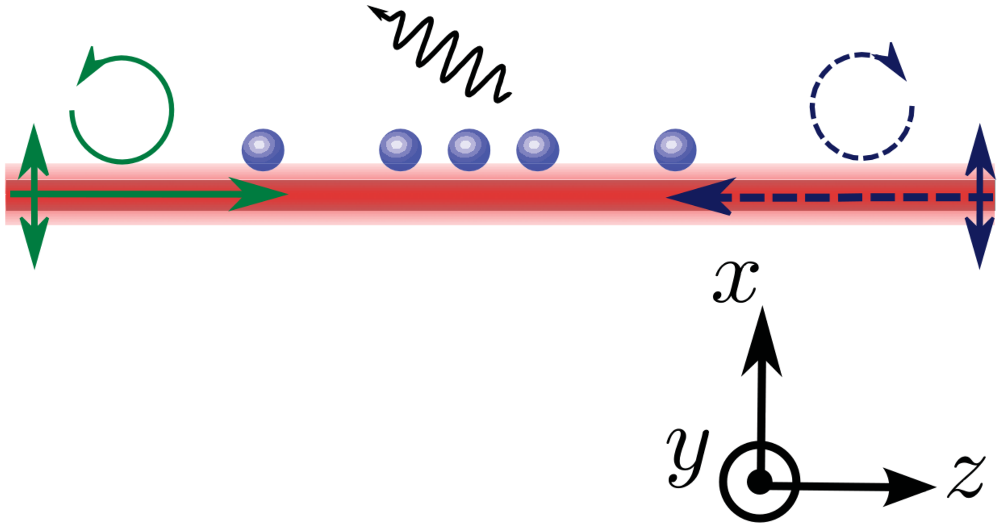


Ensemble-Based Optical Isolator

Nanofiber with spin-polarized atoms on one side



C. Sayrin et al., Phys. Rev. X **5**, 041036 (2015)

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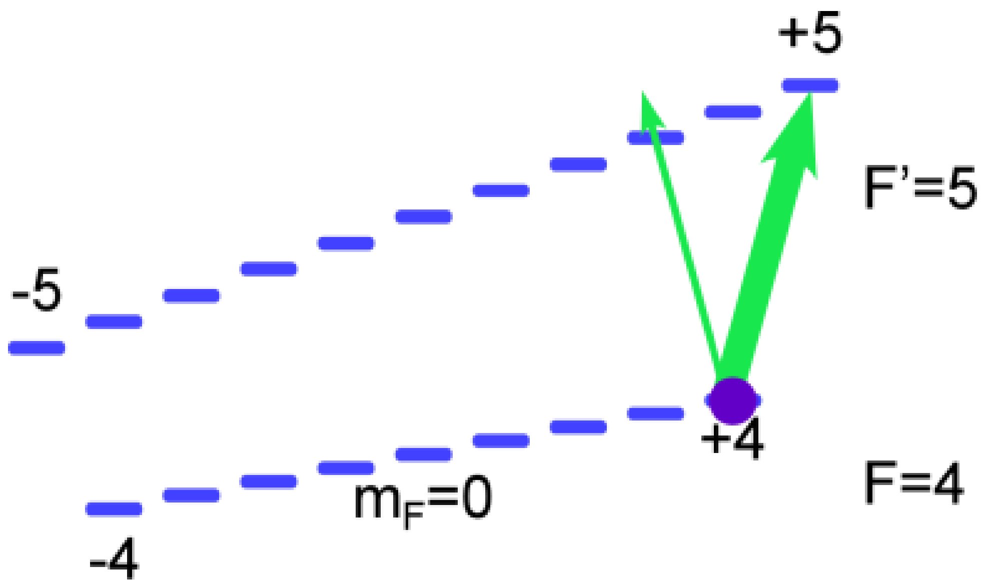

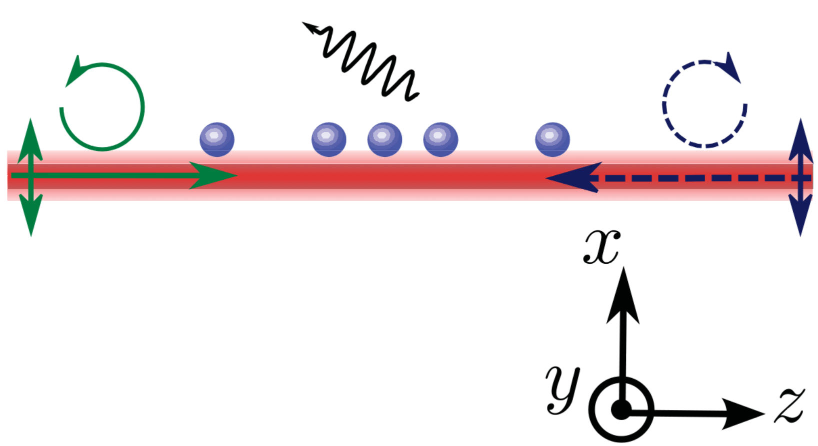

- Forward (backward) transmission of 78 % (13 %).
- Isolation of 8 dB.
- Data agrees with prediction for $\langle N \rangle = 27$ atoms.

C. Sayrin et al., Phys. Rev. X **5**, 041036 (2015)

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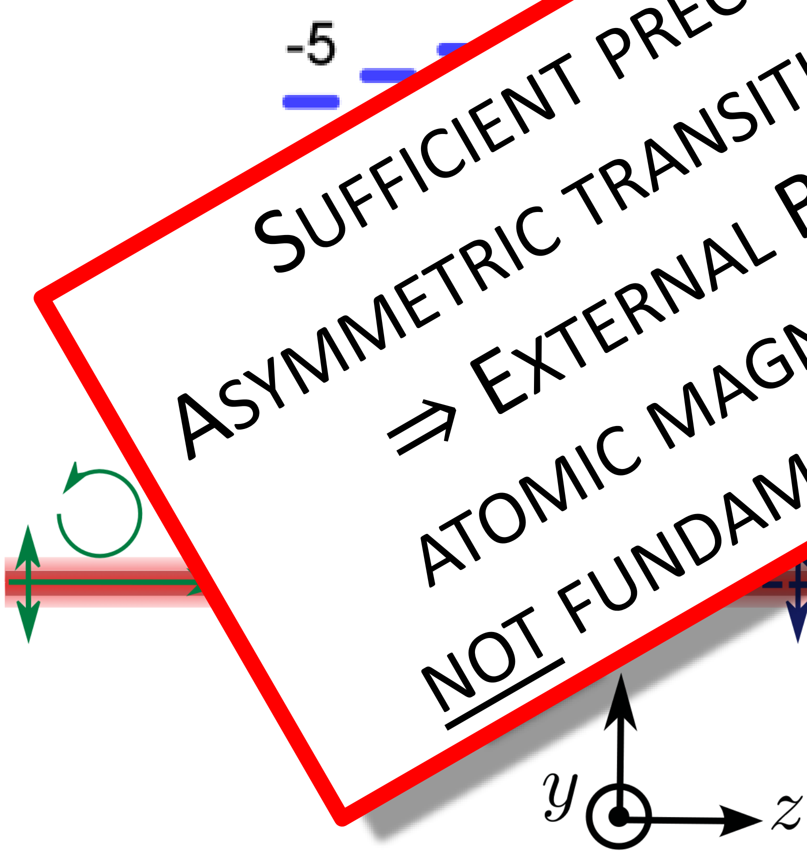

SUFFICIENT PRECONDITION:
ASYMMETRIC TRANSITION STRENGTHS
⇒ EXTERNAL B-FIELD AND
ATOMIC MAGNETIC MOMENT
<u>NOT</u> FUNDAMENTALLY REQUIRED

- orward (backward) transmission of 78 % (13 %).
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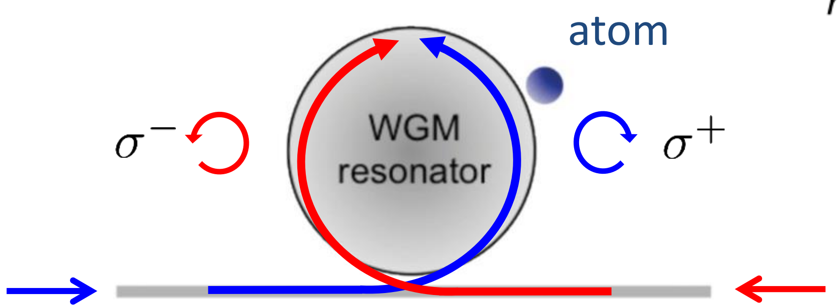
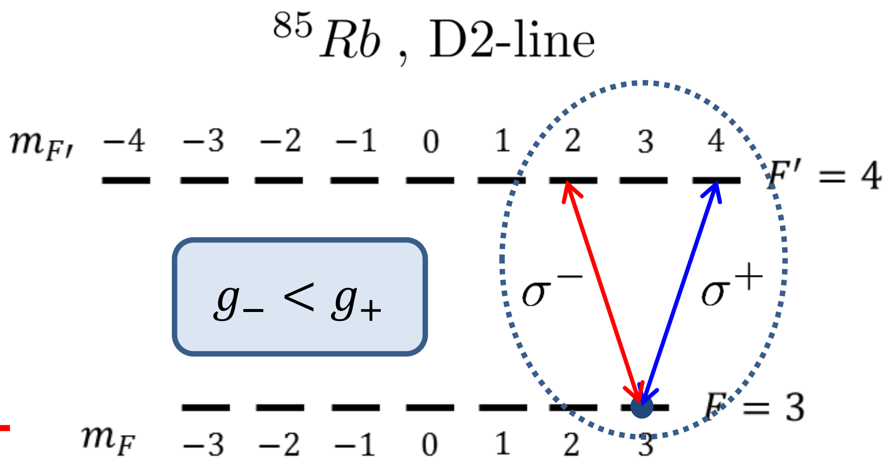
C. Sayrin et al., Phys. Rev. X **5**, 041036 (2015)

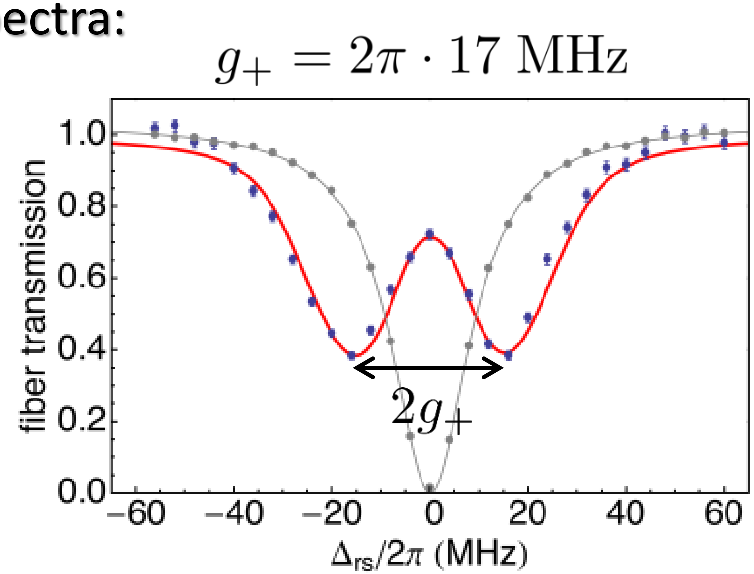
Single-Atom-Based Chiral Interface

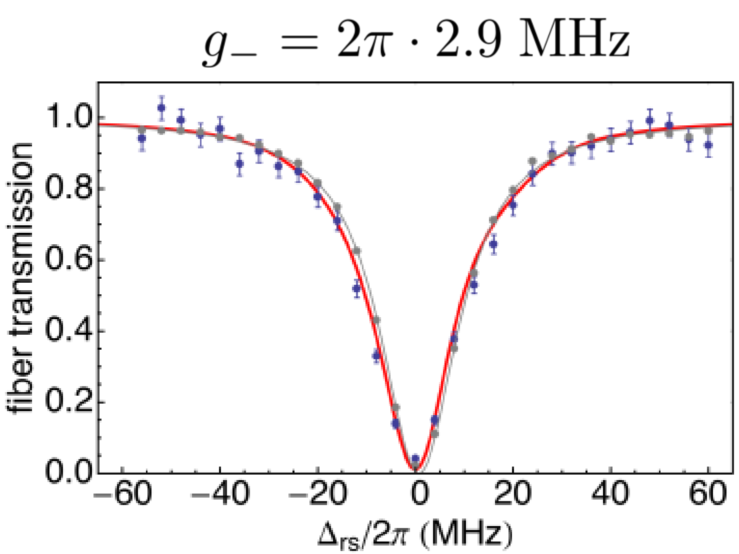
Resonator-enhanced atom:





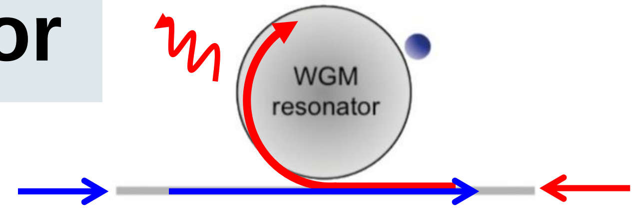
Spectra:



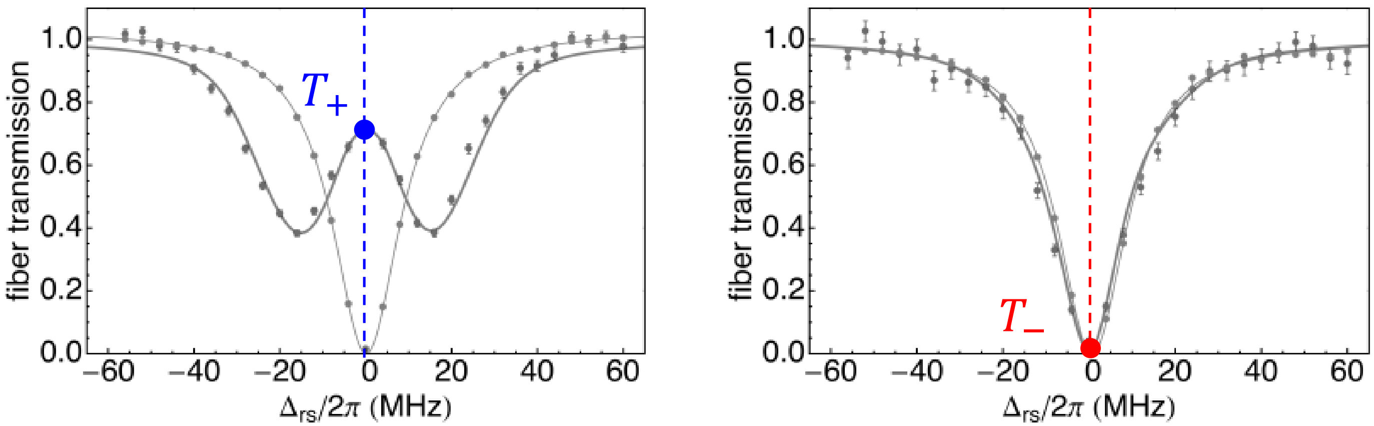


C. Junge et al., PRL **110**, 213604 (2013)

Single-Atom Optical Isolator



On-resonance transmission:



Realization of an **optical diode**

C. Sayrin et al., PRX **5**, 041036 (2015)

Isolation: $\mathcal{I} = 10 \log(\frac{T_+}{T_-}) = \mathbf{13}\ \mathrm{dB}$

Transmission: $T_{forward} = 72\%$

- controlling propagation direction ✓
- with a single atom ✓

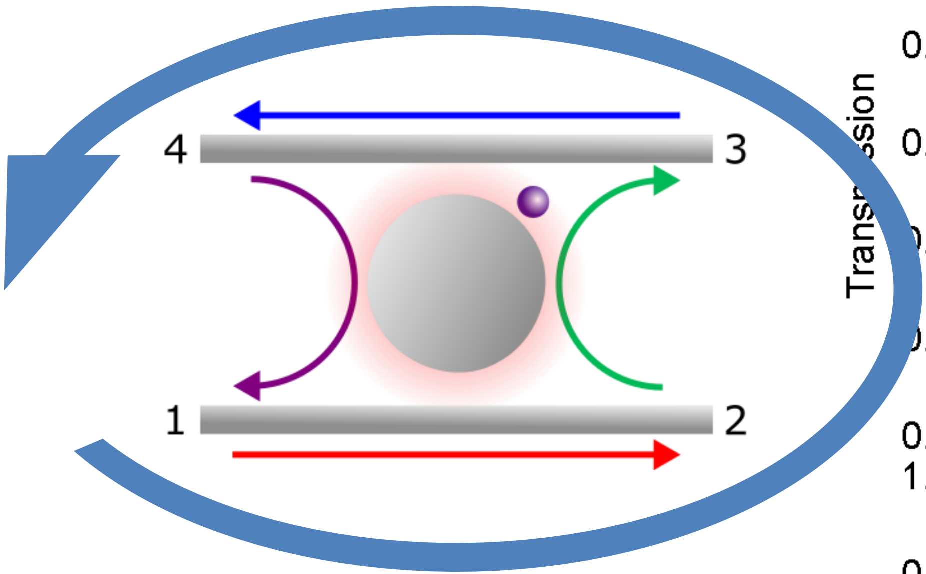
But: ✗

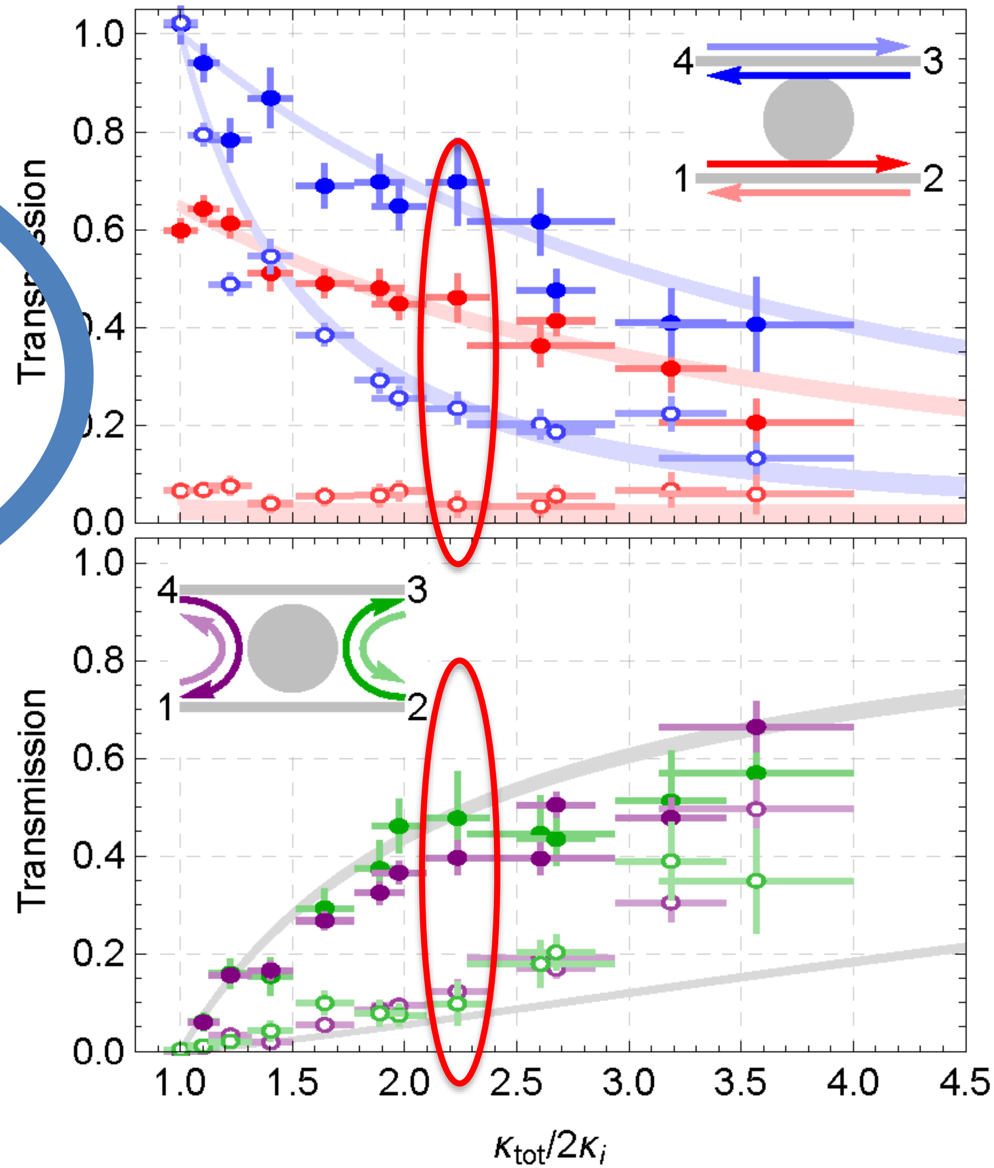
- device based on losses
  → no quantum functionality based on superposition

Quantum Optical Circulator

M. Scheucher et al., Science **354**, 1577 (2016)

4-port device:





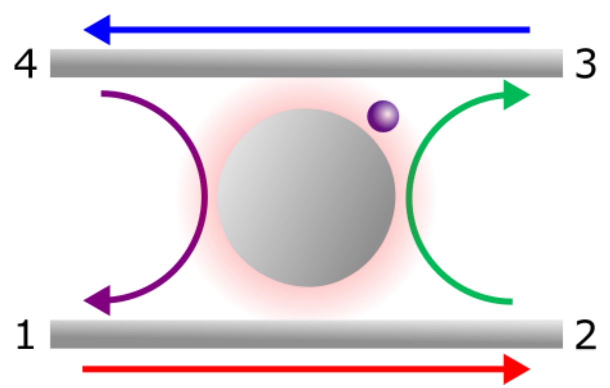
Principle of an **optical circulator**

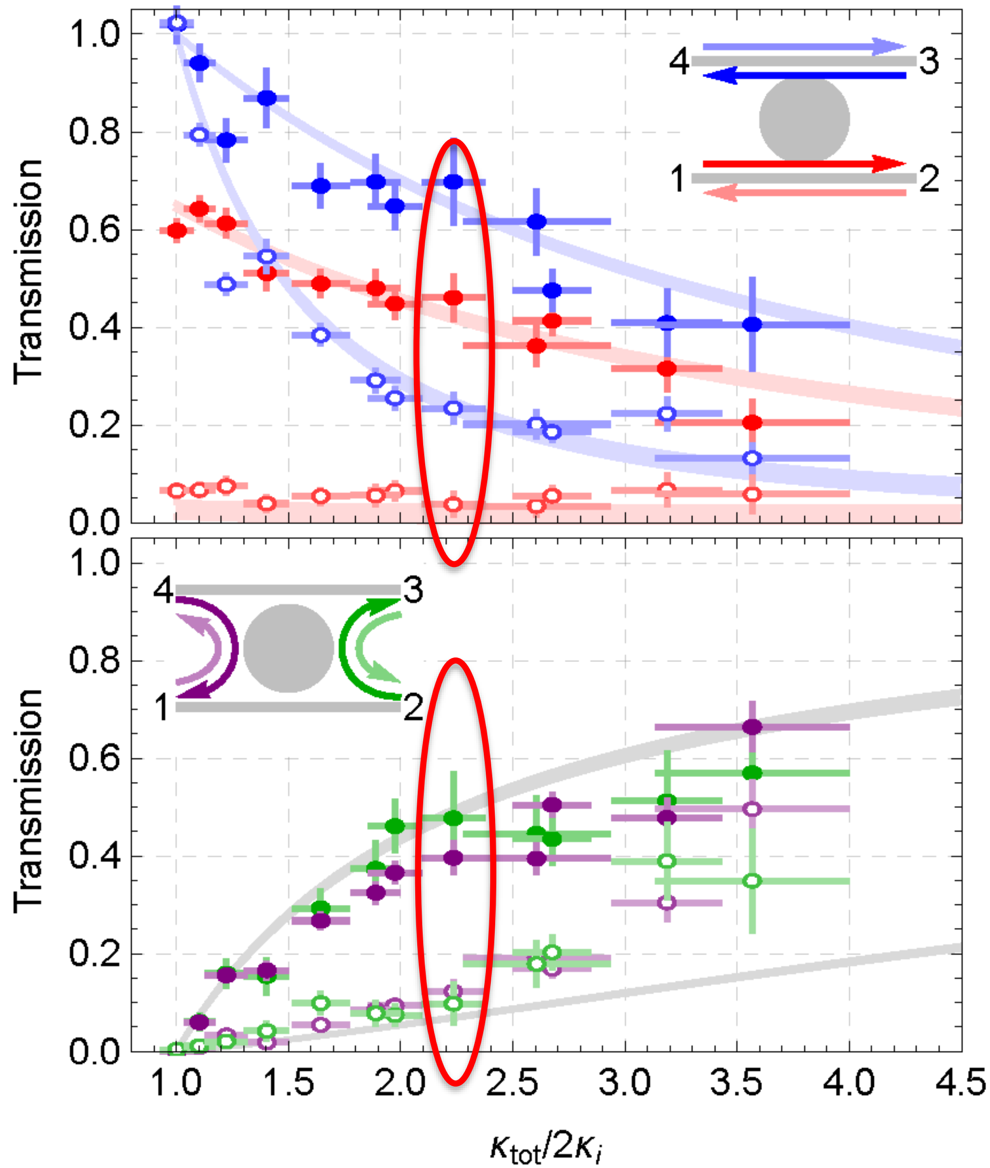
K. Xia et al., Phys. Rev. A **90**, 043802 (2014)

Quantum Optical Circulator

M. Scheucher et al., Science **354**, 1577 (2016)

4-port device:





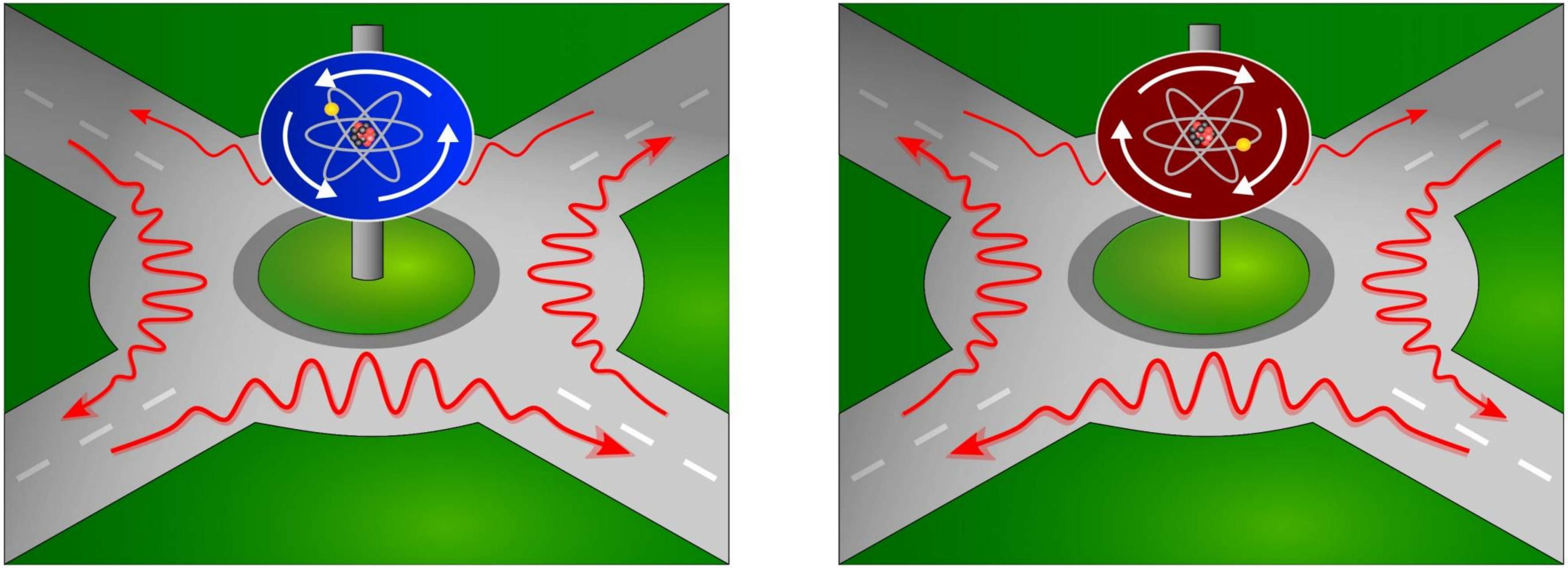
Isolation: $\mathcal{I} =$ (10.9 ± 2.5, 6.9 ± 1.9, 4.7 ± 0.7, 5.1 ± 0.8) dB

Photon survival: 70.6 ± 0.4 %

Spin state-controlled routing

Quantum Optical Circulator

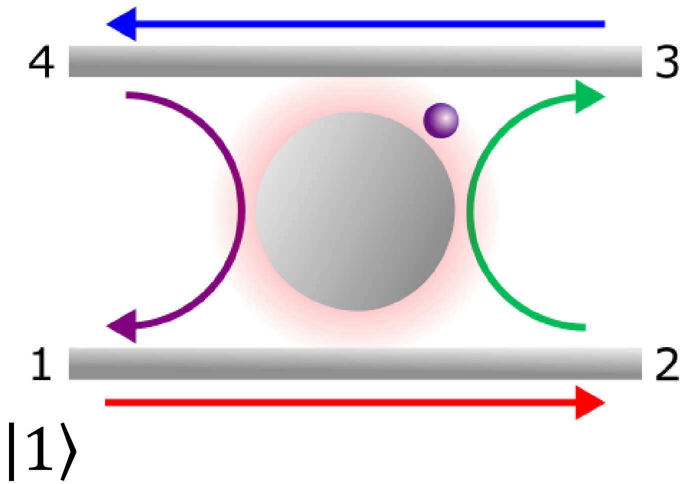
M. Scheucher et al., Science **354**, 1577 (2016)



Spin state-controlled routing

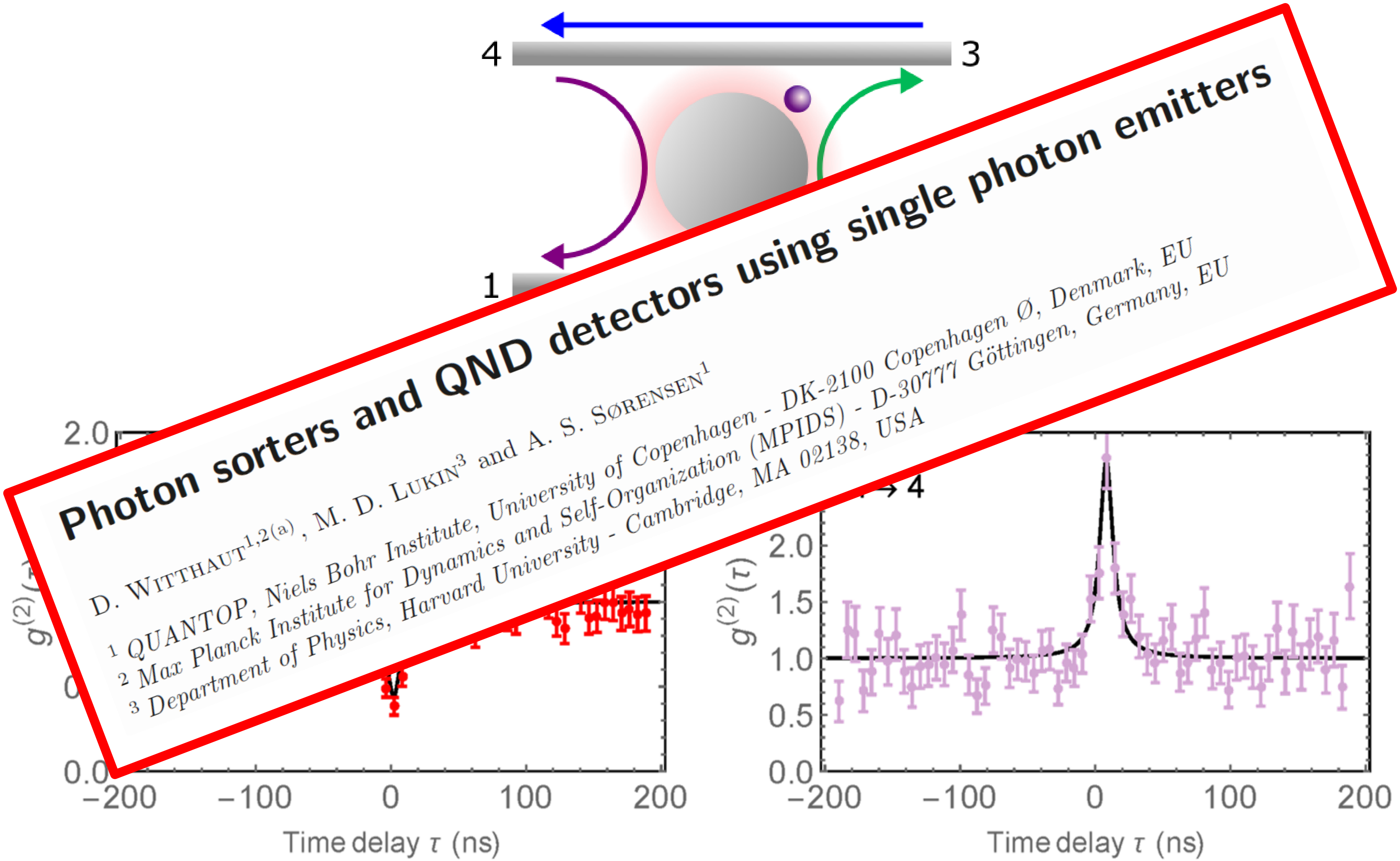
Optical Circulator – Photon-Number Routing

M. Scheucher et al., Science **354**, 1577 (2016)



Optical Circulator – Photon-Number Routing

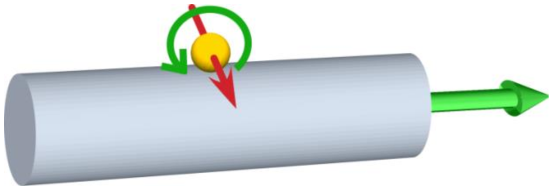
M. Scheucher et al., Science **354**, 1577 (2016)



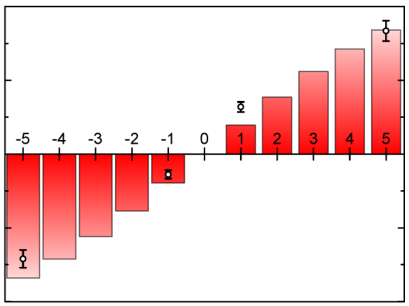
Summary

- **Guided modes in optical nanofibers**
  - Non-transversal polarization
  - Local polarization ⇔ propagation direction

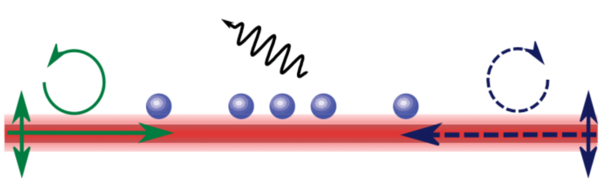
- **Directional emission of a gold nanoparticle**
  - Waveguide interface for single particle
  - Directionality of up to 95% demonstrated



- **Directional atom-waveguide interface**
  - Atomic state determines directionality
  - Ratio of ~ 10:1



- **Nonreciprocal nanophotonic waveguide**
  - Nanoscale quantum optical analogues of microwave ferrite resonance isolators and circulators.

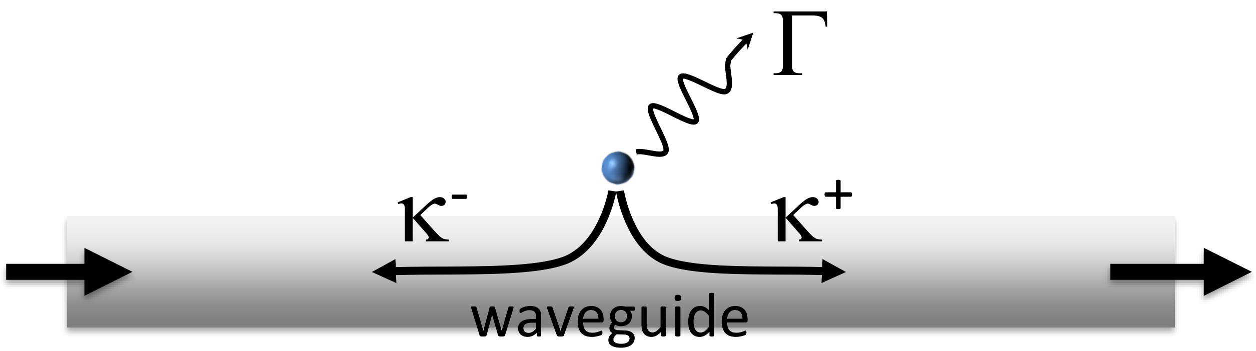


Perspectives

Optical signal processing and routing of light in integrated (quantum) optical environment.

Revisit “one-dimensional atom” $\Rightarrow$ qualitatively new effects

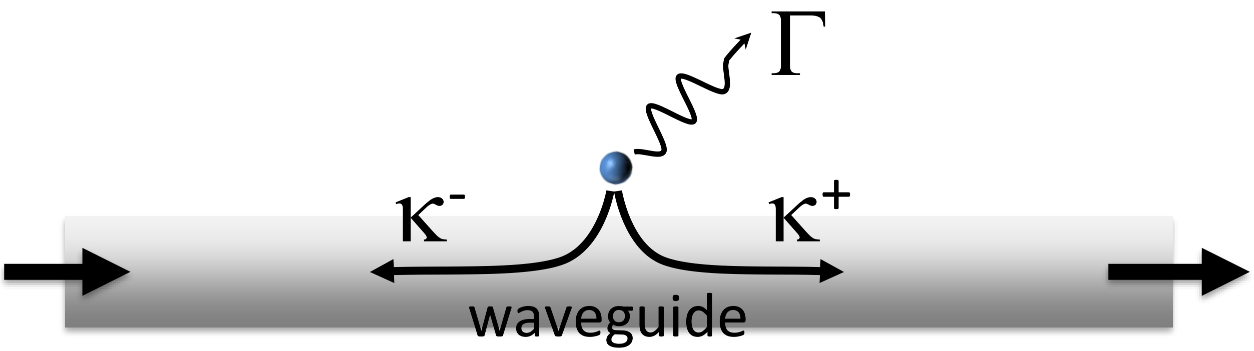
One Dimensional Atom Physics



Chiral interaction modifies absorption and transmission:

- Critical symmetric coupling: $\kappa^+ = \kappa^- = \Gamma$
  ⇒ <u>max. absorption of 50%</u>
- Critical chiral coupling: $\kappa^+ = \Gamma$ and $\kappa^- = 0$
  ⇒ <u>perfect absorber</u>

One Dimensional Atom Physics

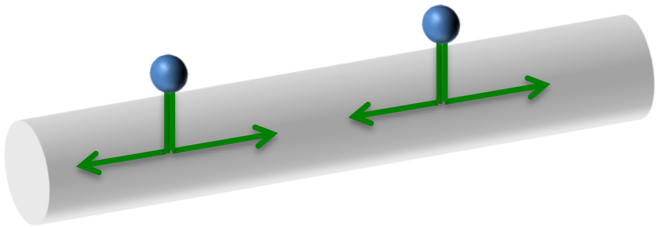


Chiral interaction modifies absorption and transmission:

- Ultra-strong symmetric coupling: $\kappa^+ = \kappa^- \gg \Gamma$
  ⇒ <u>perfect mirror</u>
- Ultra-strong chiral coupling: $\kappa^+ \gg \Gamma$ and $\kappa^- = 0$
  ⇒ <u>perfectly transparent nonreciprocal π-phase shifter</u>

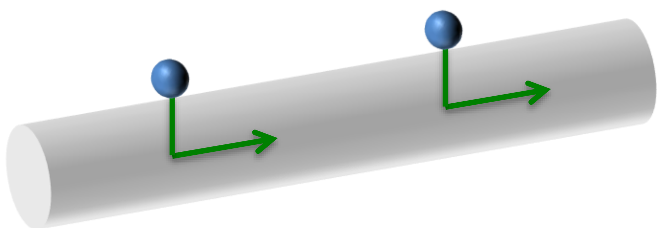
Collective Emission

- Symmetric coupling:



⇒ interference
⇒ super- / sub-radiance

- Chiral coupling:



⇒ directional emission
⇒ no back-action to “the left”
⇒ no super- / sub-radiance

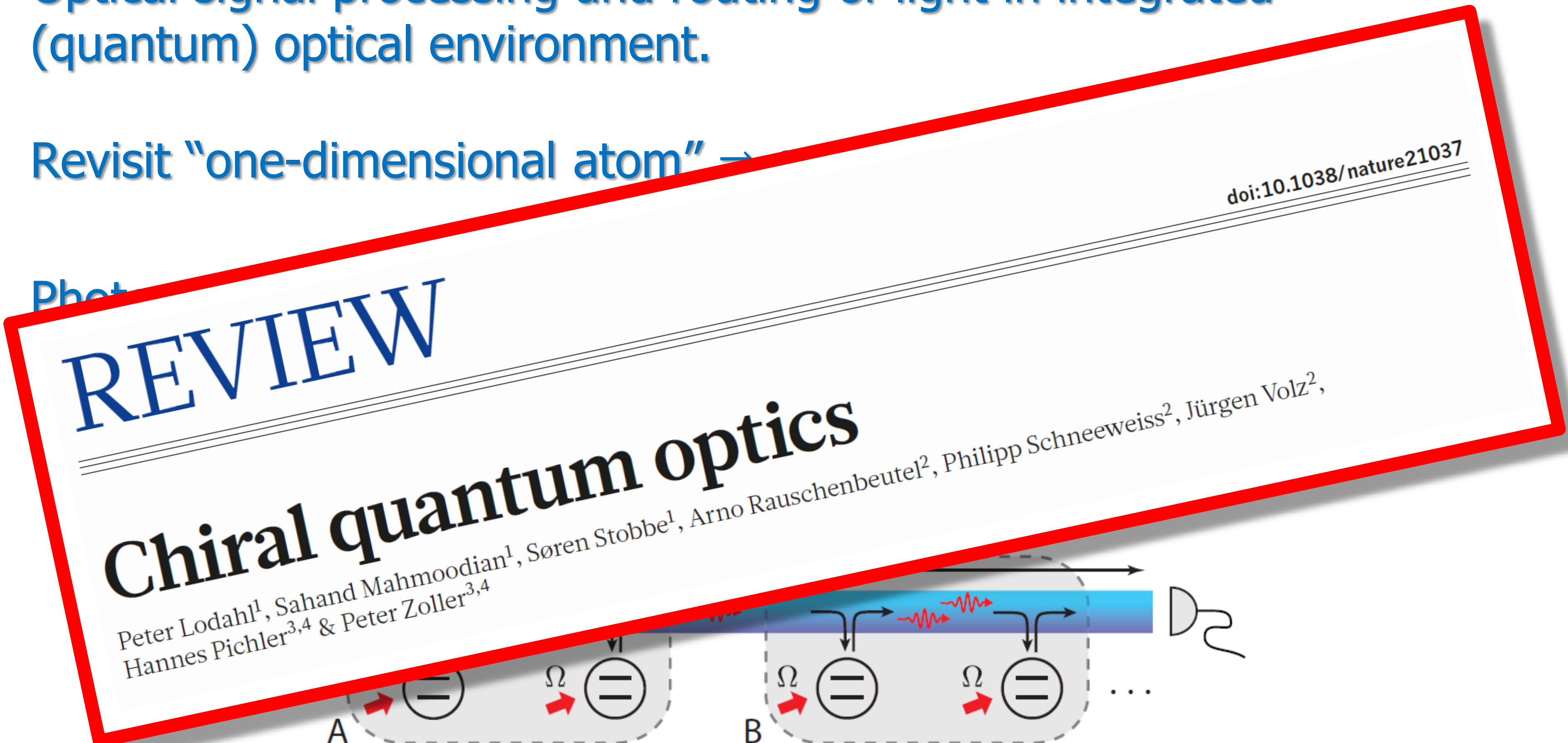
Fam Le Kien and A.R., Phys. Rev. A **95**, 023838 (2017)

Perspectives

Optical signal processing and routing of light in integrated (quantum) optical environment.

Revisit "one-dimensional atom" → …

Phot…



Stannigel et al., New. J. Phys. **14**, 063014 (2012)

Acknowledgements

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Nanofiber-Based Atom–Light Interface**:** Bernhard Albrecht, Rudolf Mitsch, Clément Sayrin, Philipp Schneeweiß

Single-Atom Cavity QED with WGMs**:** Adèle Hilico, Christian Junge, Danny O'Shea, Michael Scheucher, Elisa Will, Jürgen Volz

Funding

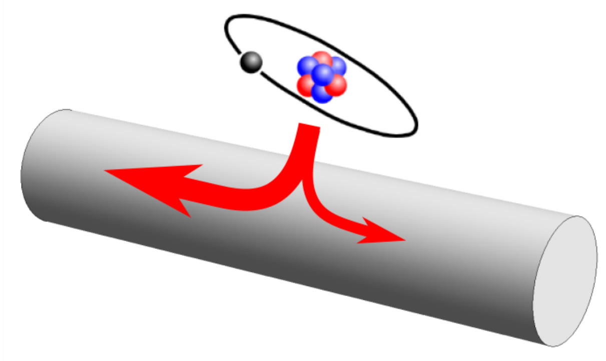
FWF : SFB FoQuS NEXT lite CoQuS

: erc MARIE CURIE ACTIONS siqs

VCQ Vienna Center for Quantum Science and Technology

Studienstiftung des deutschen Volkes

Thank you for your attention!

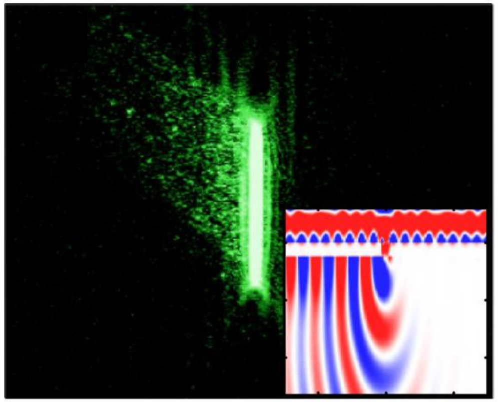


Nature **541**, 473 (2017)

Intro: Chiral Coupling

- Chiral coupling in different physical situations.

  - Surface plasmon polaritons:



Lee et al., Phys. Rev. Lett. **108**, 213907 (2012)

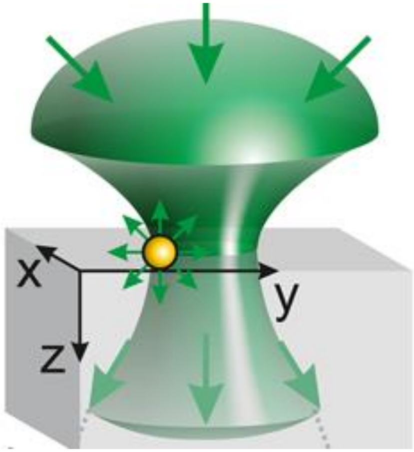
Rodríguez-Fortuño et al., Science **340**, 328 (2013)

J. Lin, et al., Science **340**, 331 (2013)

Intro: Chiral Coupling

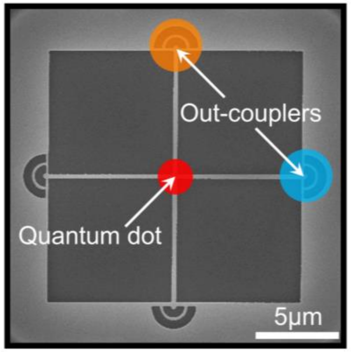
- Chiral coupling in different physical situations.

- Dielectric interface & 2d waveguides



Neugebauer et al., Nano Lett. **14**, 2546 (2014)

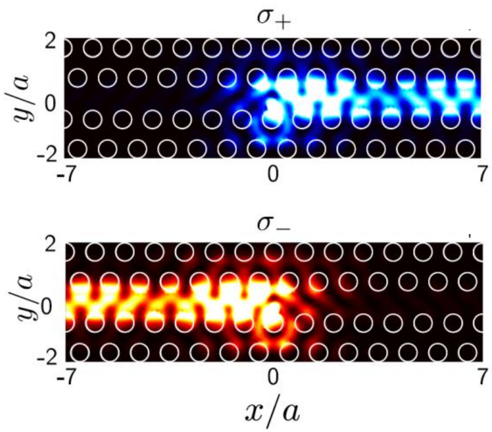
- Dielectric 1d waveguides:



Luxmoore et al., Phys. Rev. Lett. **110**, 037402 (2013)

Rodríguez-Fortuño et al., ACS Photonics **1**, 762 (2014)

- Photonic crystal waveguides:

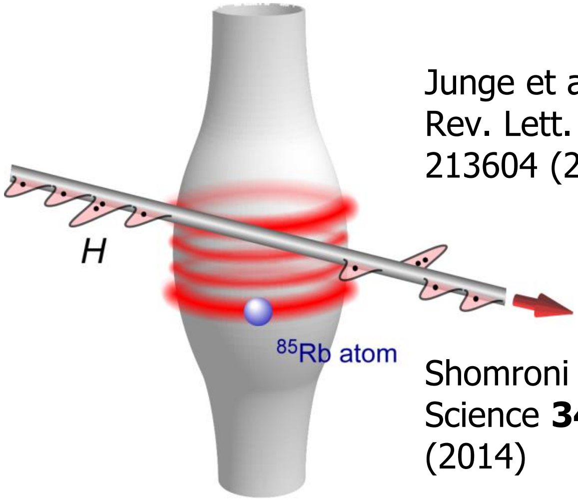


le Feber et al., Nat. Commun. **6**, 6695 (2014)

Söllner et al., Nat. Nanotech. **10**, 159 (2015)

Young et al., Phys. Rev. Lett. **115**, 153901 (2015)

- Cavity QED with WGMs:

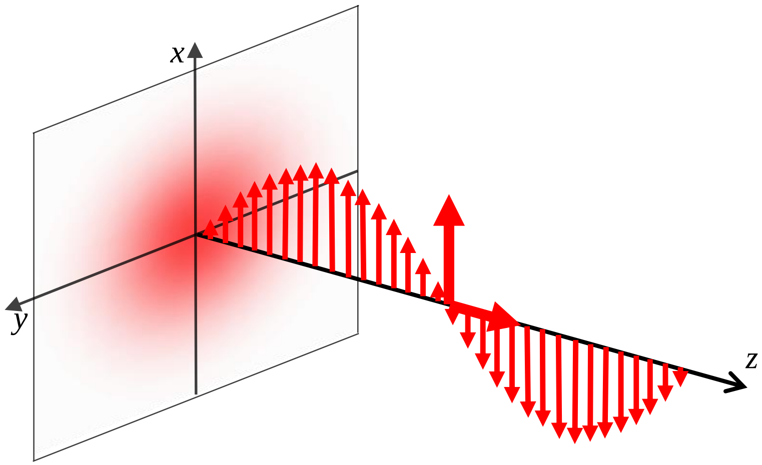


Junge et al., Phys. Rev. Lett. **110**, 213604 (2013)

Shomroni et al., Science **345**, 903 (2014)

Introduction – Non-transversal Polarization

- Non-transversal polarization
  - Electric field oscillating in direction of propagation



$$\vec{\nabla} \cdot \vec{E} = 0$$

Introduction – Non-transversal Polarization

- Non-transversal polarization
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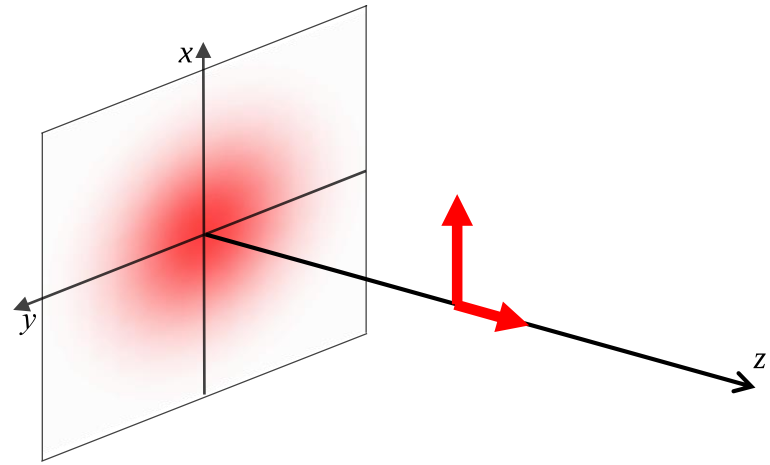

- Origin of longitudinal field
  - Non-zero transversal divergence
  - E. g., if transversal E-field points along the field gradient
  - ➔ Longitudinal field component

$$\underbrace{\partial_x E_x + \partial_y E_y}_{\vec{\nabla}_{trans} \cdot \vec{E}_{trans}} + \underbrace{\partial_z E_z}_{\approx i \frac{2\pi}{\lambda} E_z} = 0$$

Introduction – Non-transversal Polarization

- Non-transversal polarization
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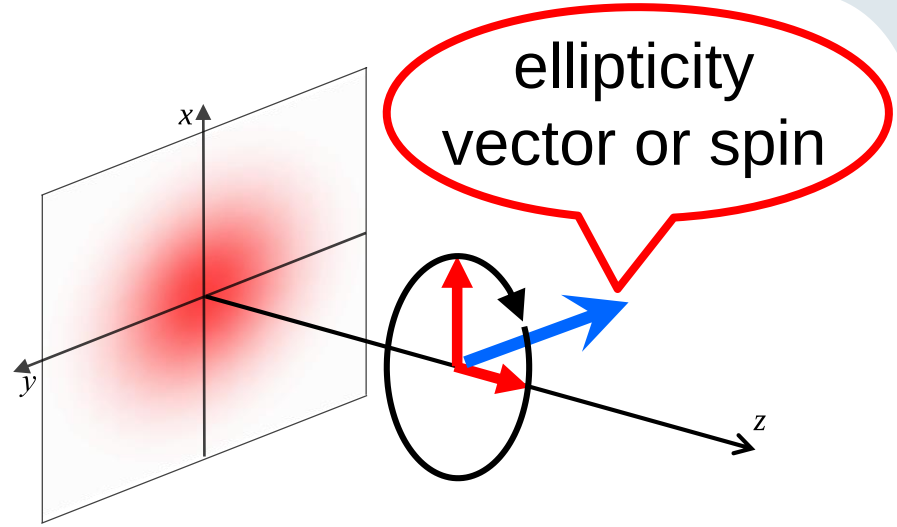


- Origin of longitudinal field
  - Non-zero transversal divergence
  - E. g., if transversal E-field points along the field gradient

  ➔ Longitudinal field component

$$E_z = i\frac{\lambda}{2\pi}\left(\vec{\nabla}_{trans}\cdot\vec{E}_{trans}\right)$$

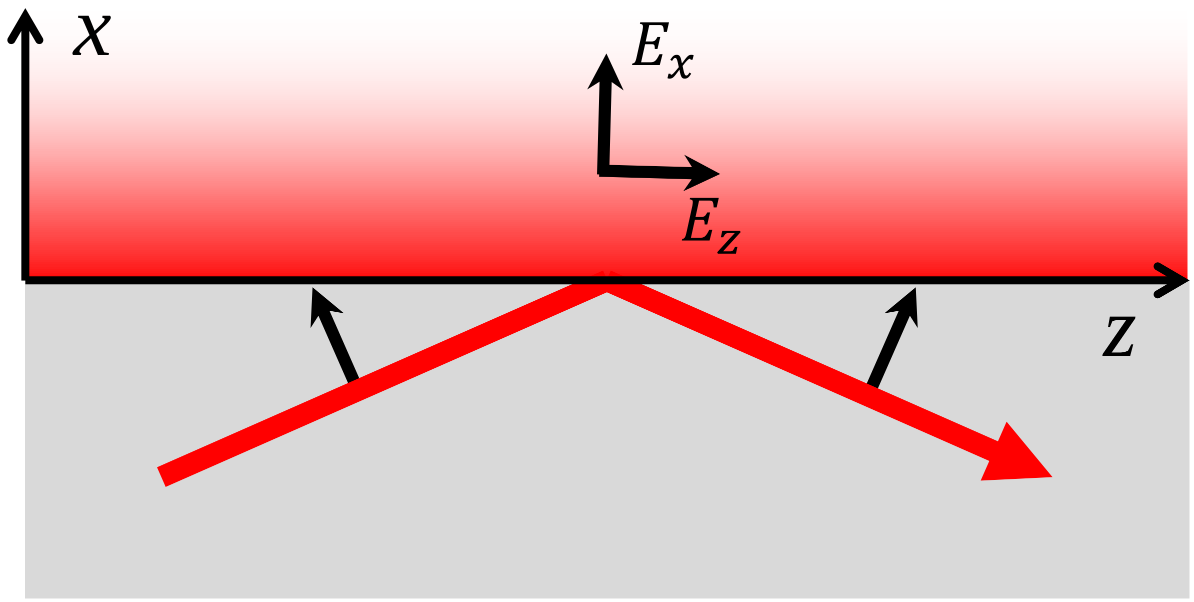
oscillates 90° out of phase!!

➡ Significant longitudinal field if gradient is significant on wavelength scale

Intro: Spin–Momentum Locking of Light

- p-polarized evanescent wave propagating in $+z$-direction:

$$\vec{E} = \begin{pmatrix} E_x \\ 0 \\ E_z \end{pmatrix} e^{ikz} e^{-\beta x}$$

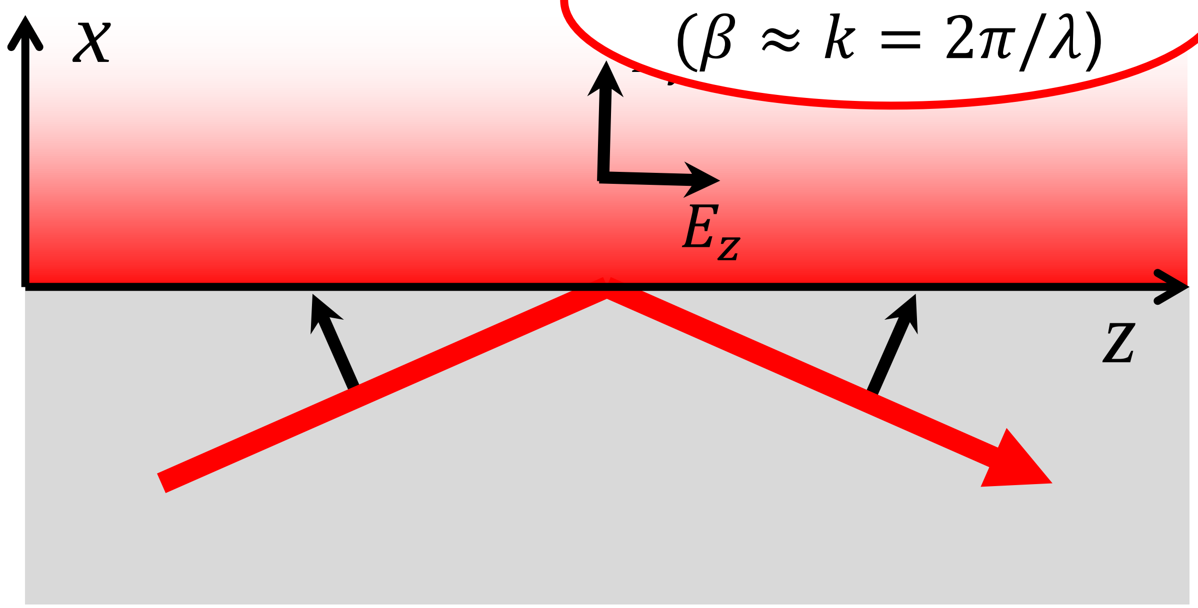


Intro: Spin–Momentum Locking of Light

- Application of Gauss' law, $\vec{\nabla} \cdot \vec{E} = 0$, yields

$$E_z = -i\frac{\beta}{k}E_x$$

on the order of 1
$(\beta \approx k = 2\pi/\lambda)$



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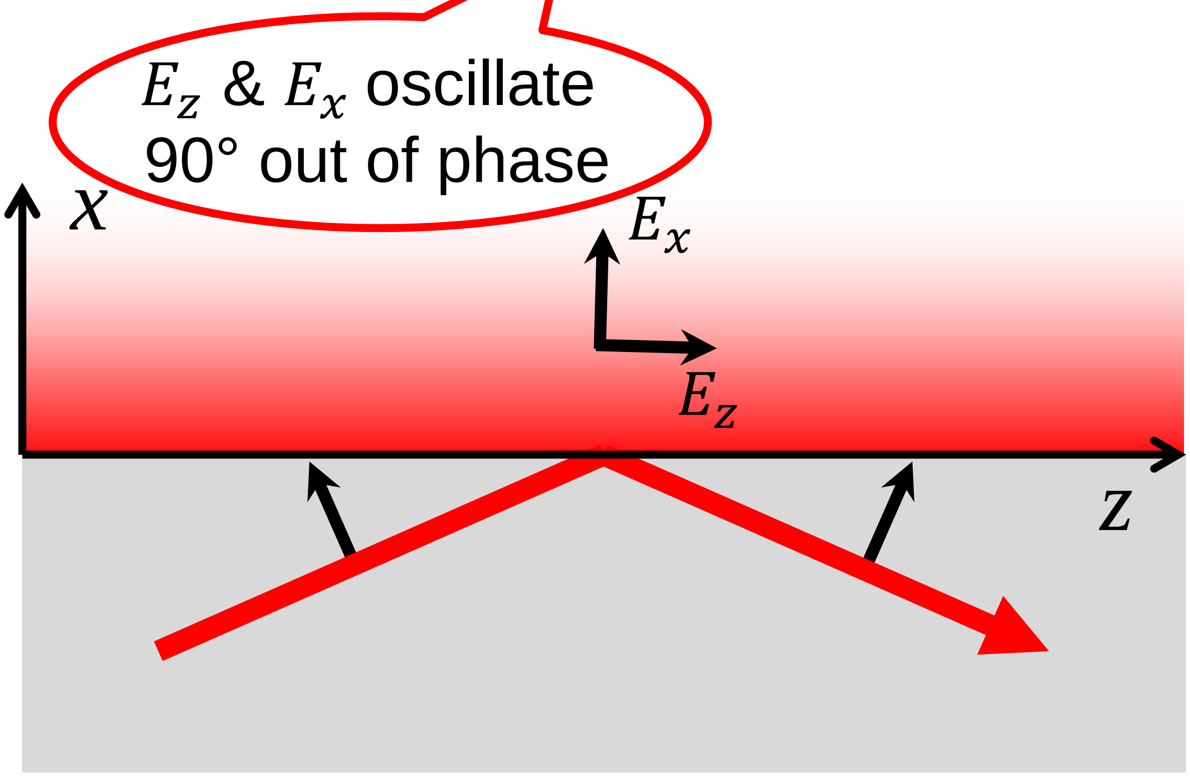

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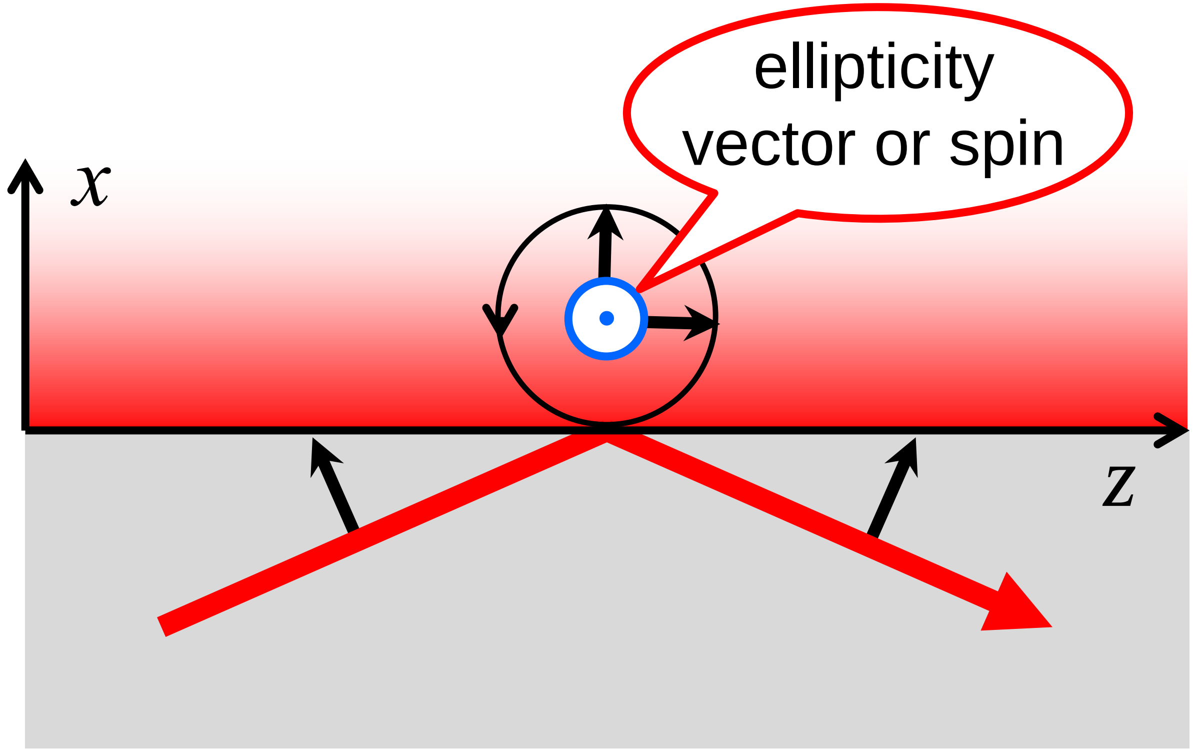
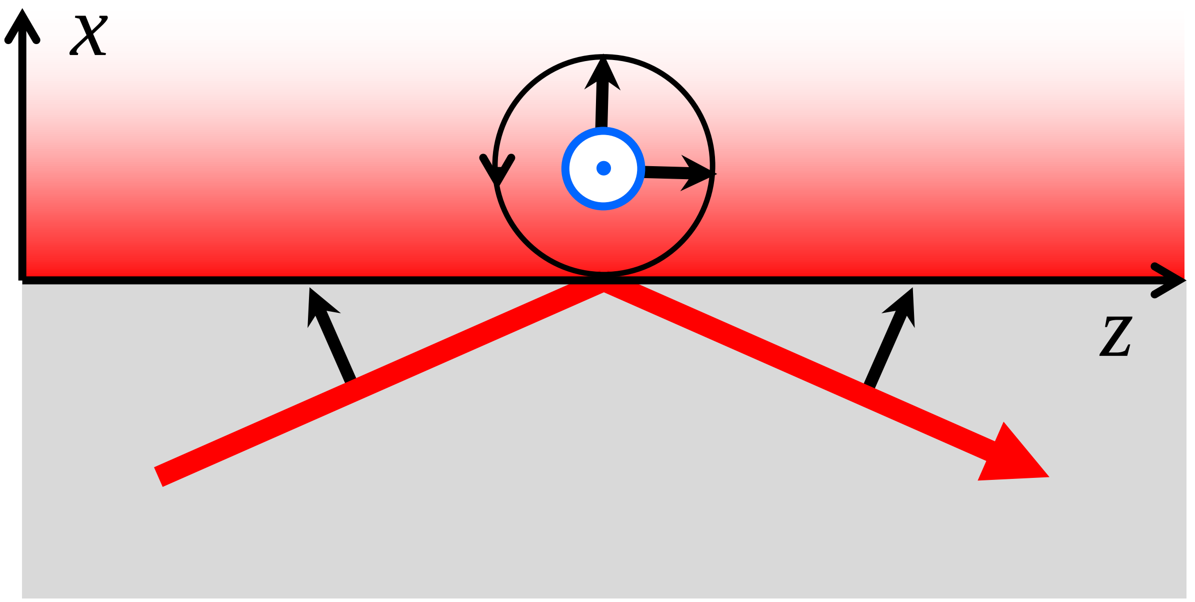


Intro: Spin–Momentum Locking of Light

- Local ellipticity (spin) flips sign with direction of propagation:

$$e^{ikz} \to e^{-ikz} \quad \Rightarrow \quad E_z \approx -iE_x \to +iE_x$$



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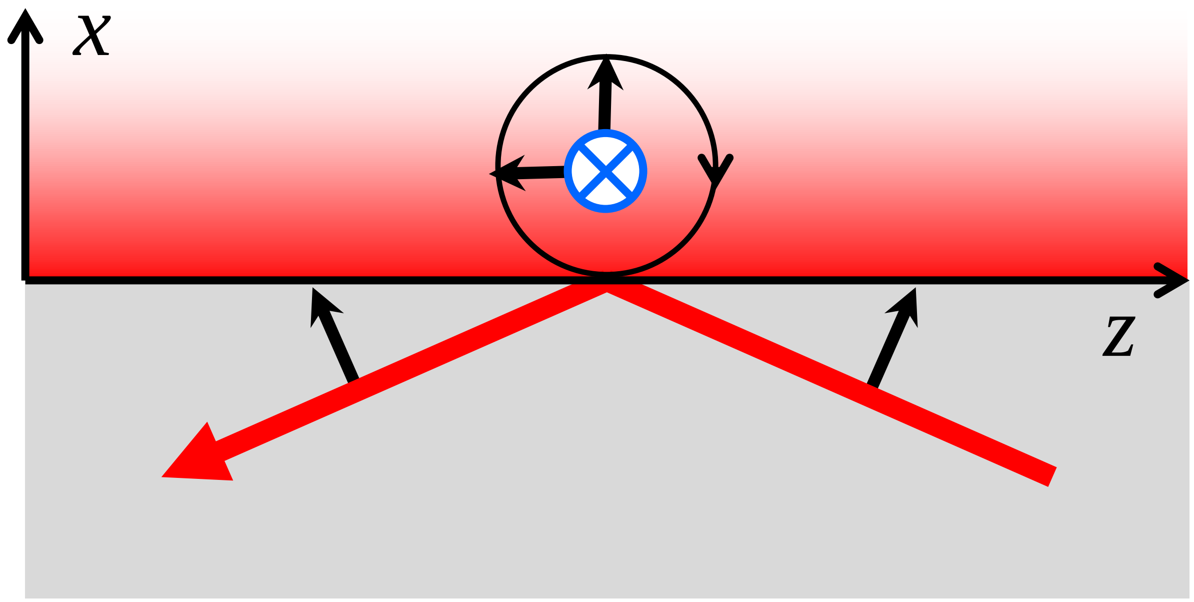
see reviews by A. Aiello *et al*. & K. Y. Bliokh *et al*. in Nat. Photon. (2015)

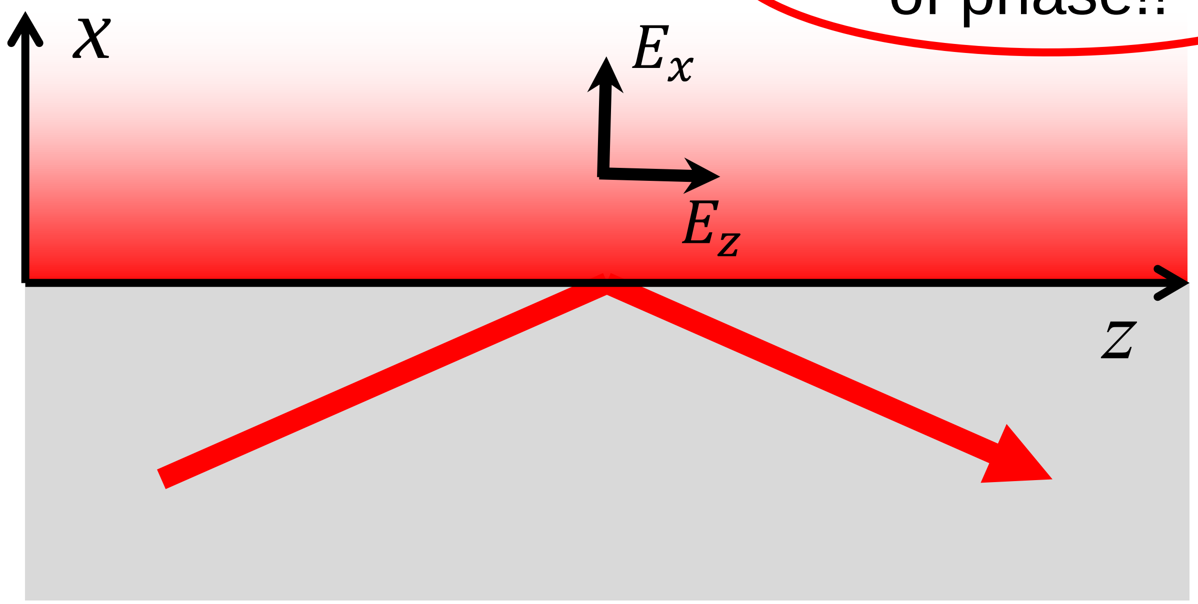


Spin–Momentum Locking of Light

- For grazing incidence and silica / air interface, we have:

$$\beta/k = 0{,}73 \qquad \text{and thus} \qquad E_z \approx -iE_x$$

oscillates 90° out of phase!!



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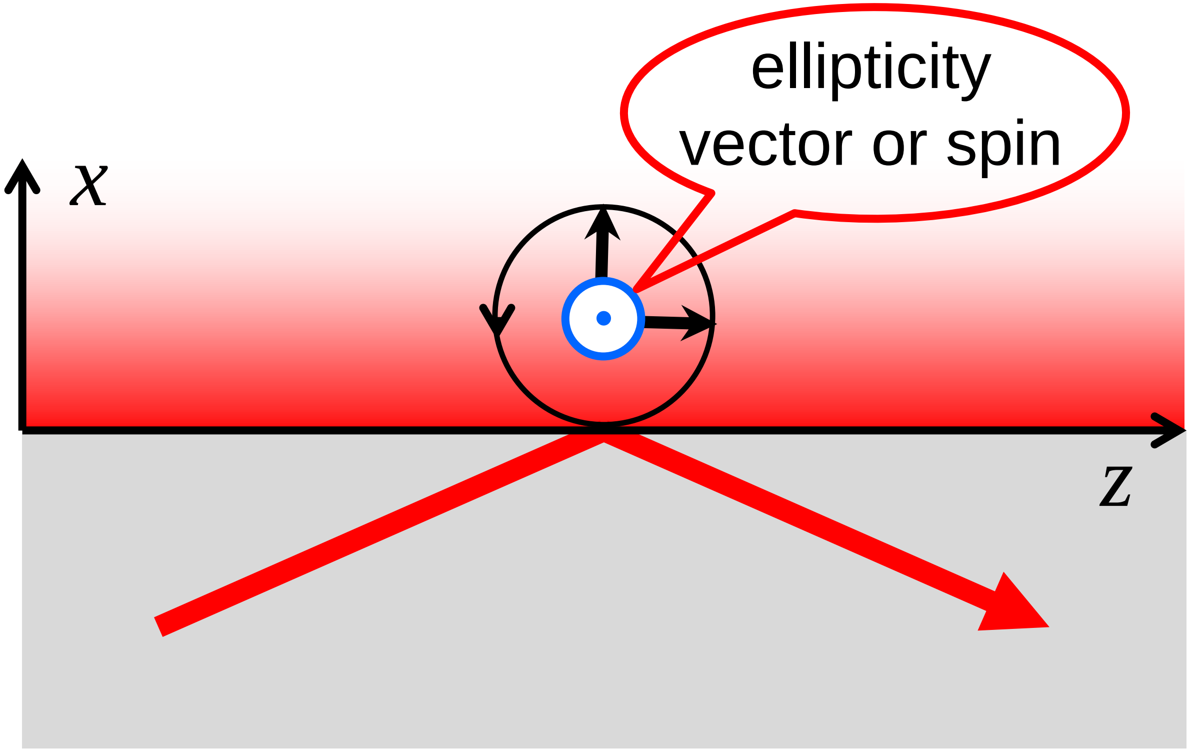
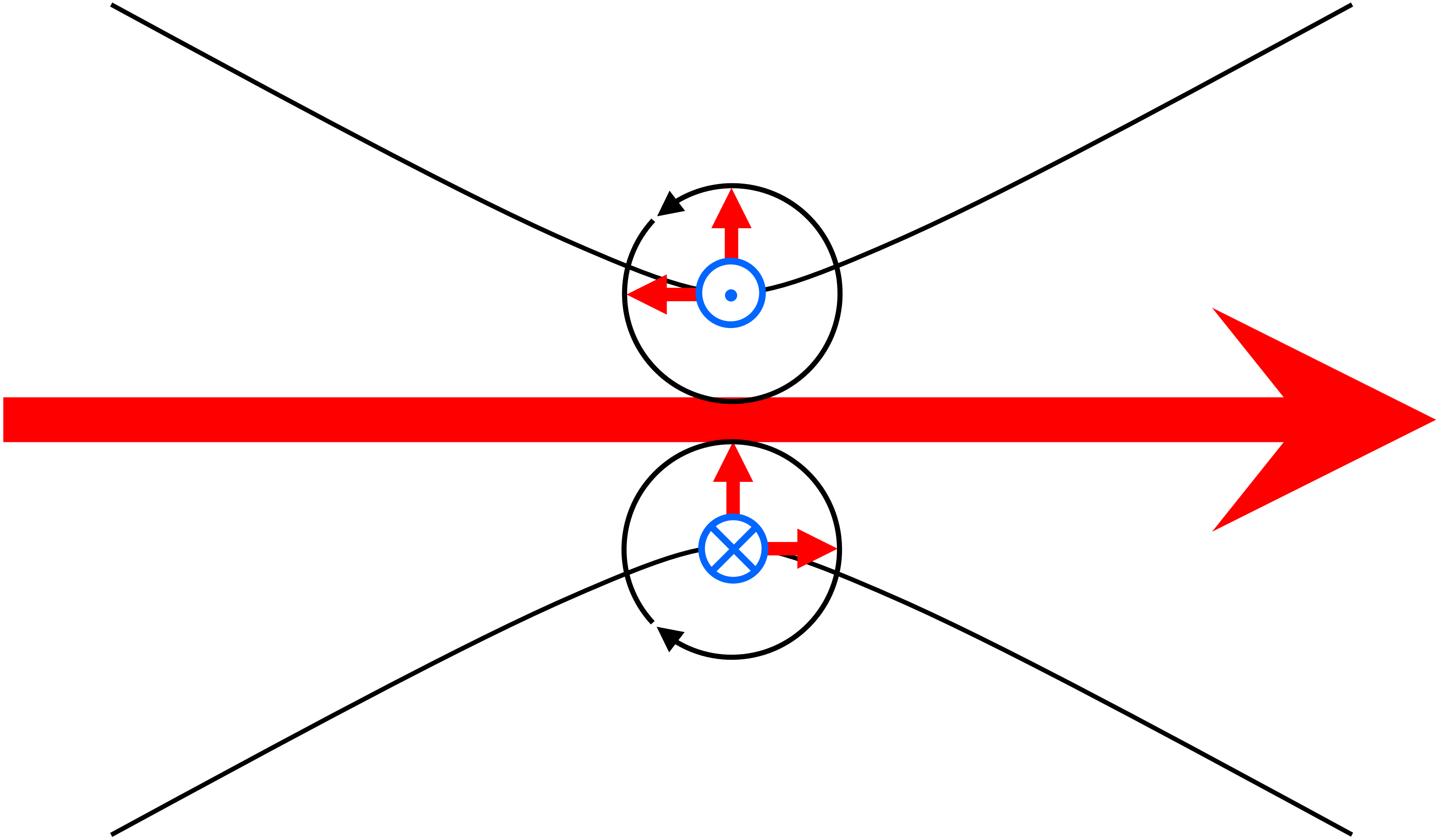


Introduction – Spin-Orbit Interaction of Light

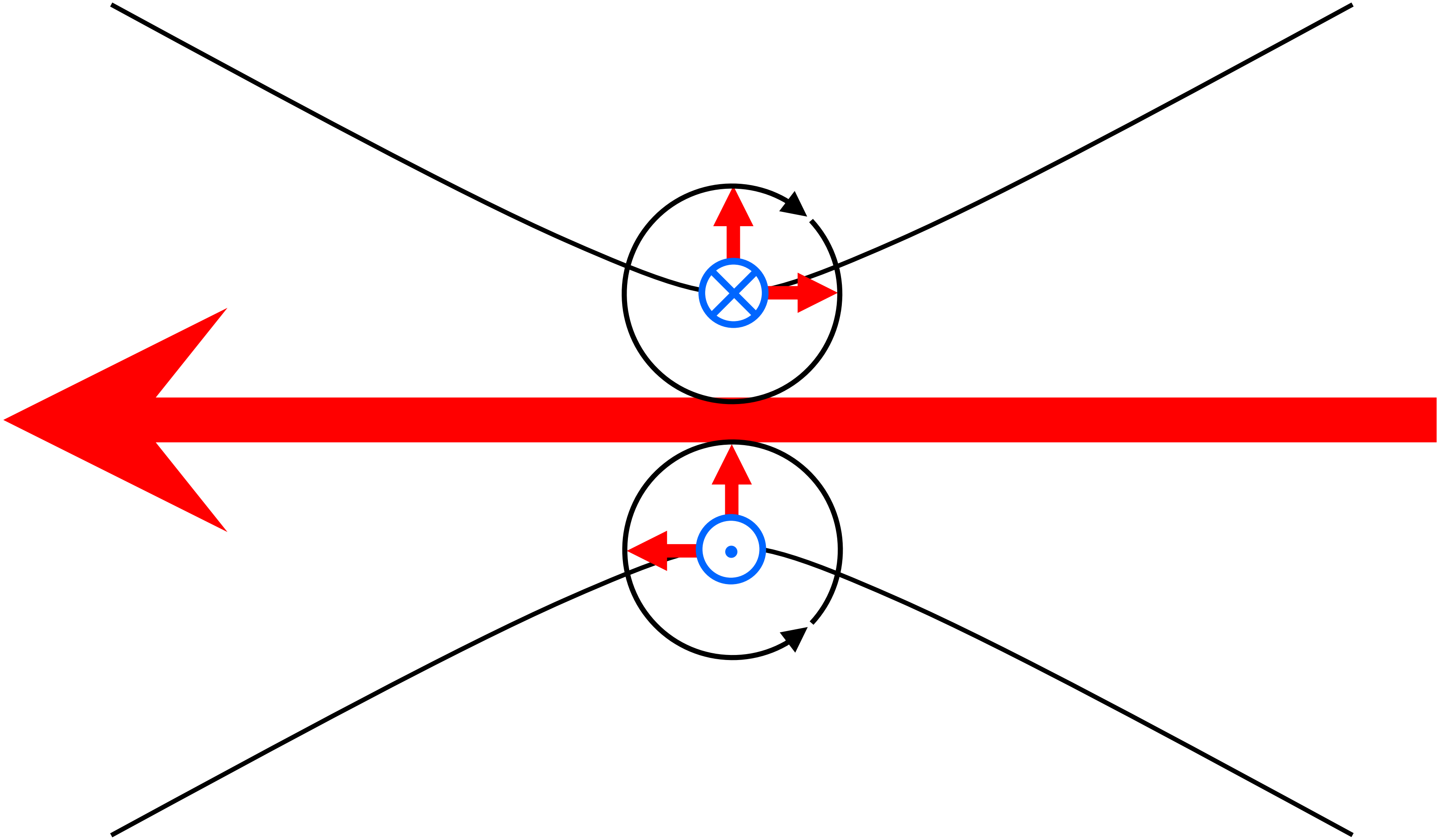
- Linearly polarized propagating focused Gaussian mode



⇒ Local ellipticity (or spin) depends on transverse position

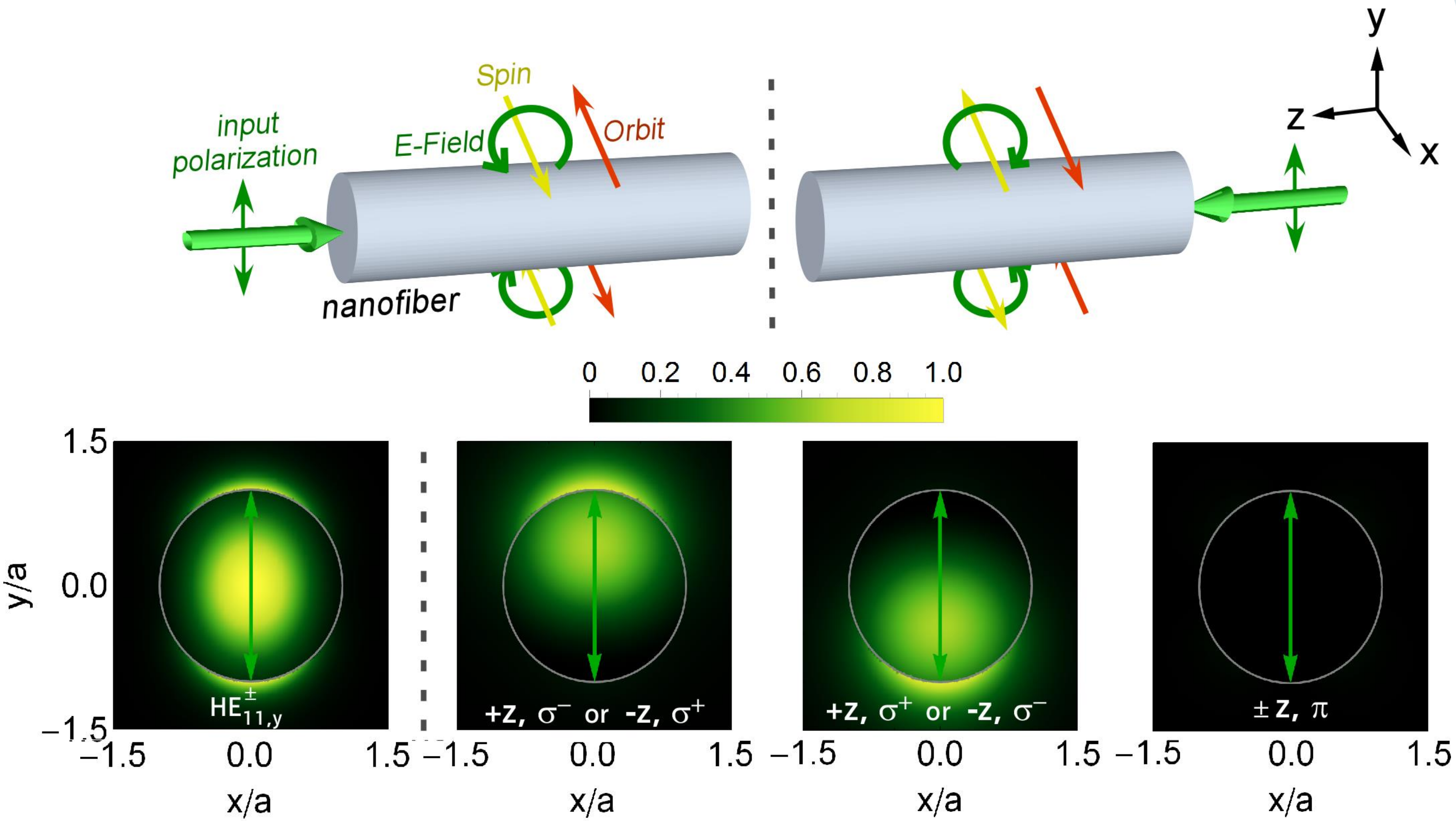
Introduction – Spin-Orbit Interaction of Light

- Linearly polarized propagating focused Gaussian mode



⇒ Local ellipticity (or spin) changes sign with direction of propagation

HE_{11} Mode: Polarization Properties

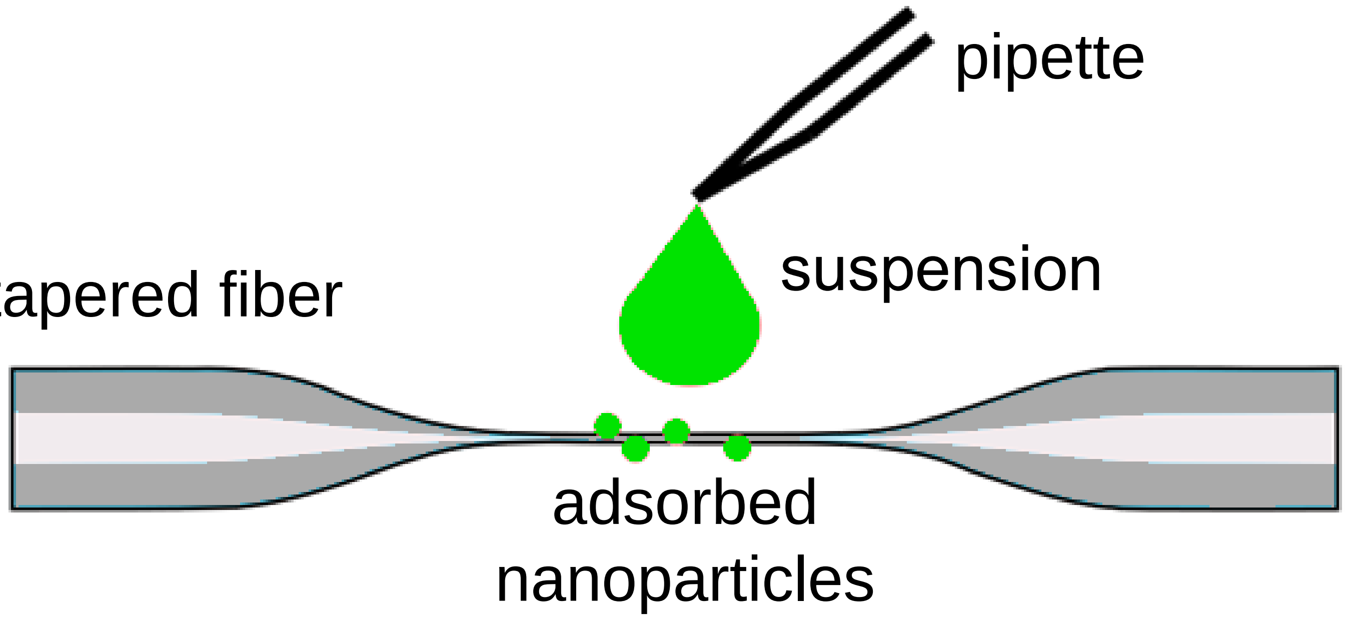


⇒ Local ellipticity (or spin) changes sign with direction of propagation

Sample Preparation

Touch nanofiber with drop of suspension of gold nanoparticles

- Presence of single gold nanoparticle detected via absorption spectroscopy



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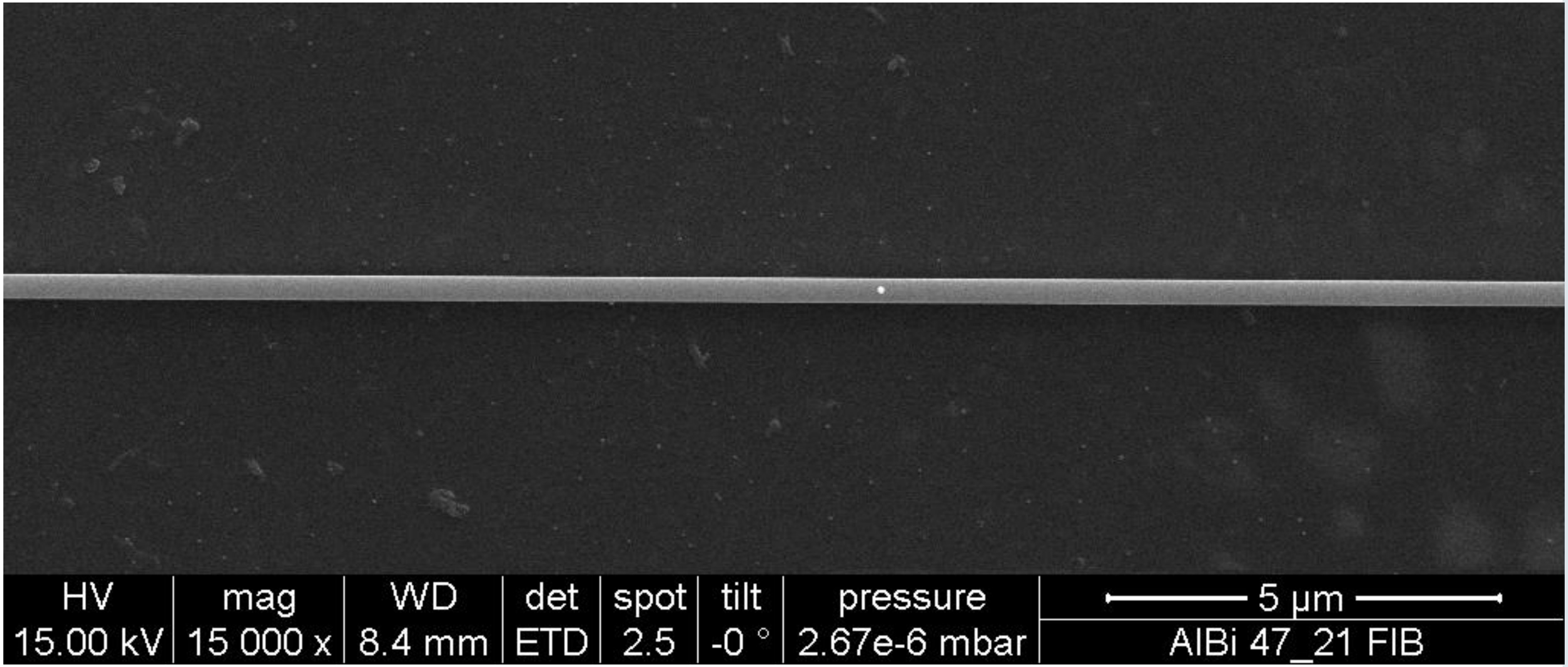

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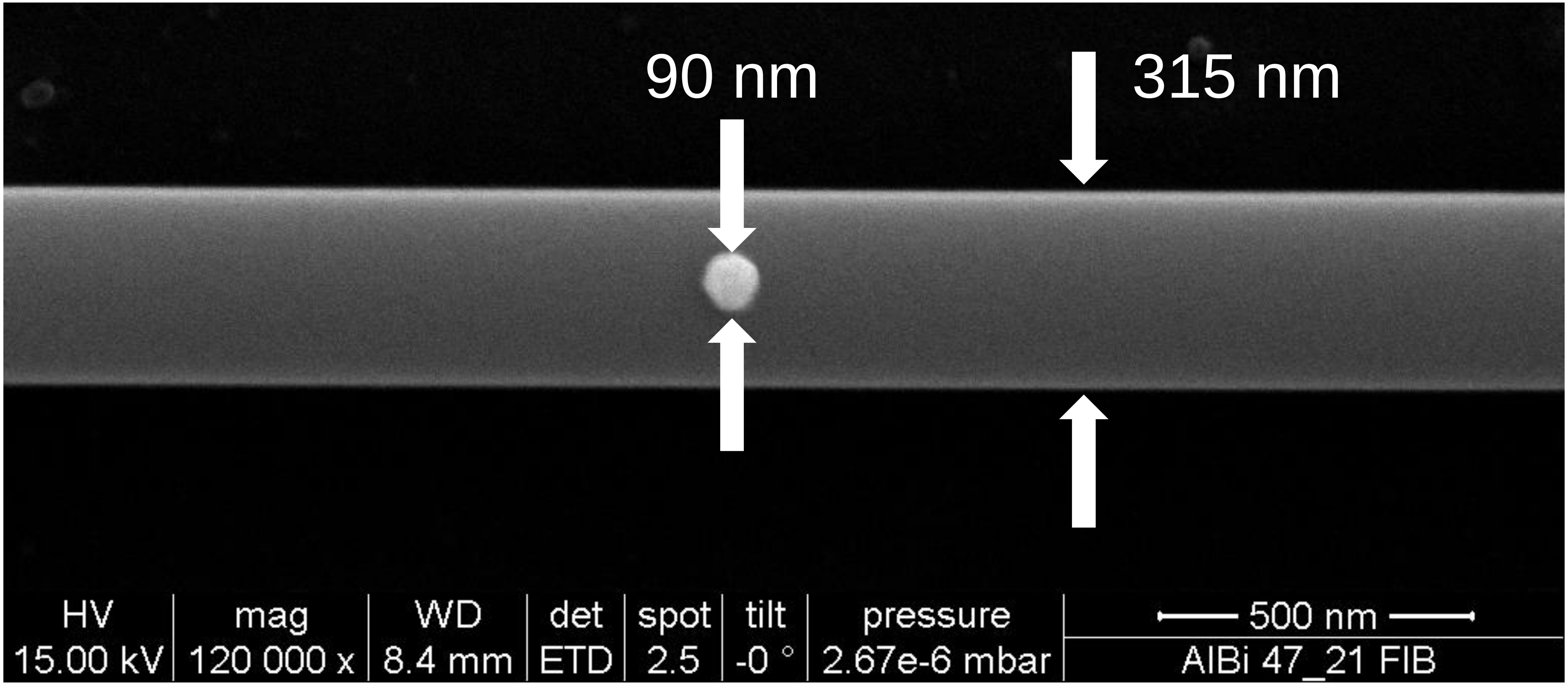
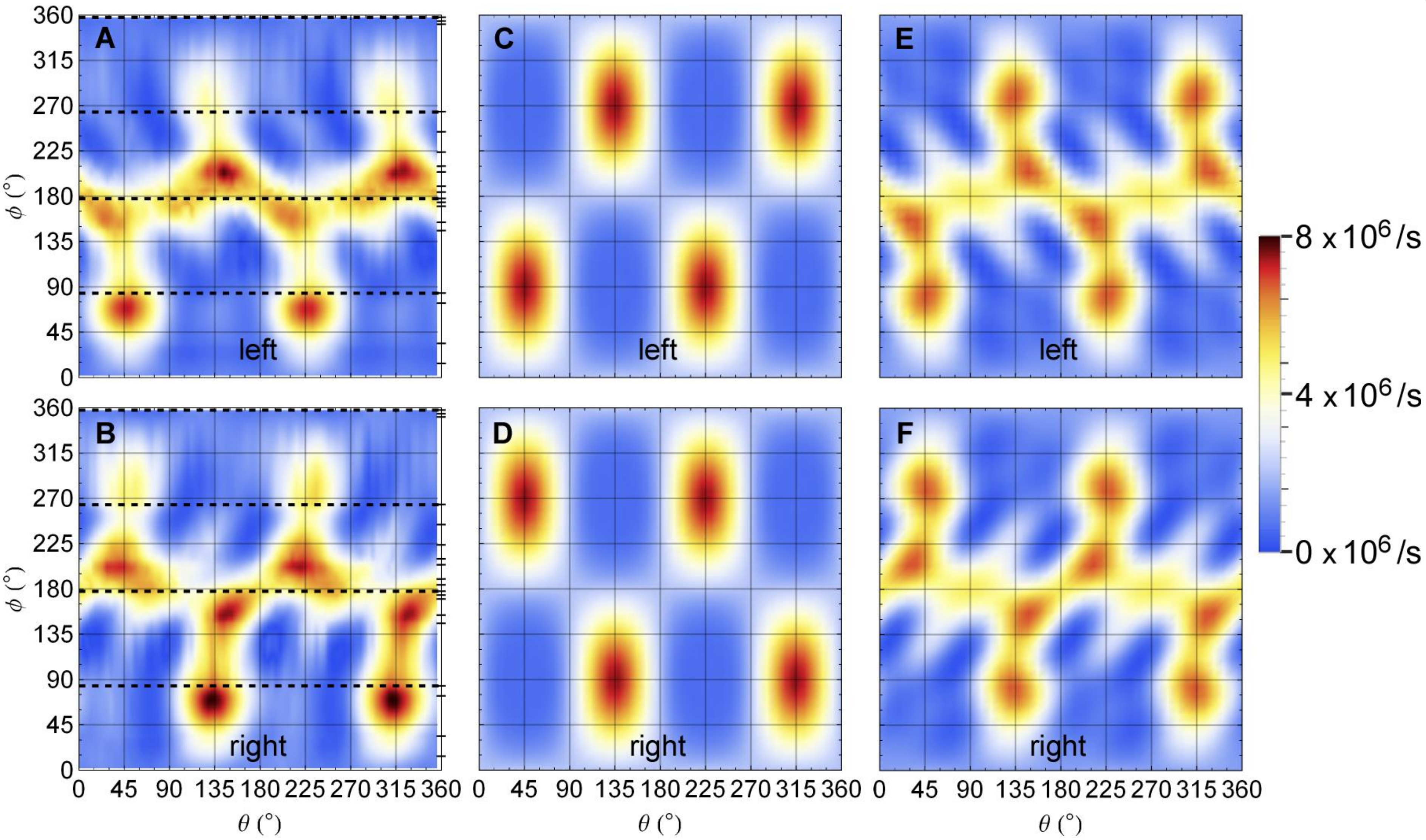
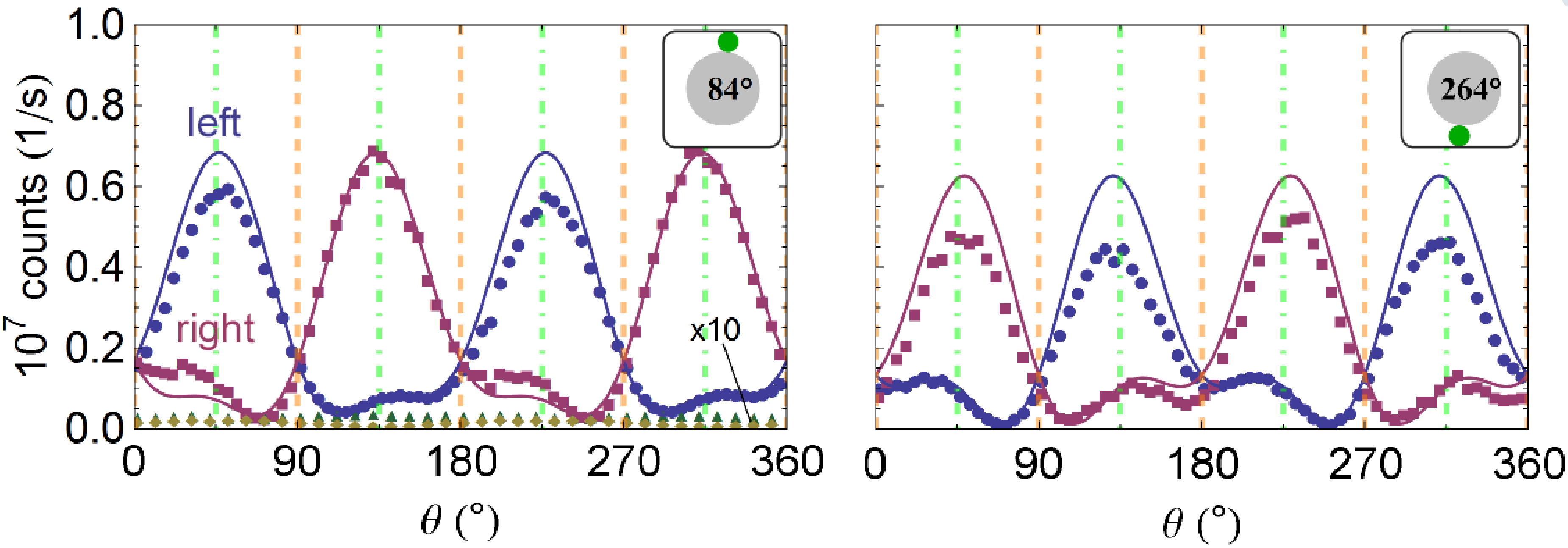


Chiral Waveguide Coupling



Petersen et al., Science **346**, 67 (2014)

Chiral Waveguide Coupling

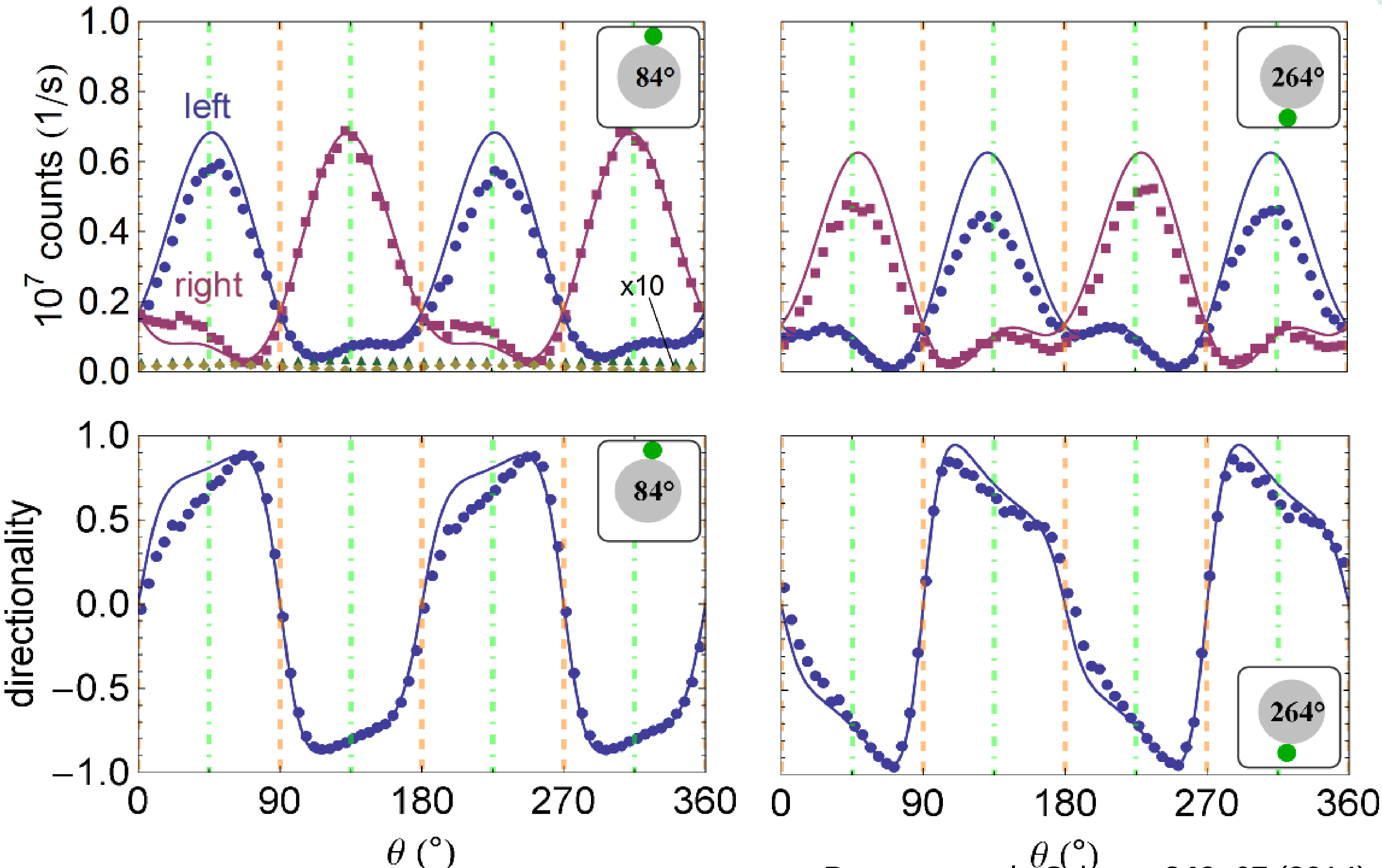


Calculate directionality from above data:

$$D = \frac{c_+ - c_-}{c_+ + c_-}$$

Petersen et al., Science **346**, 67 (2014)

Chiral Waveguide Coupling



Petersen et al., Science **346**, 67 (2014)

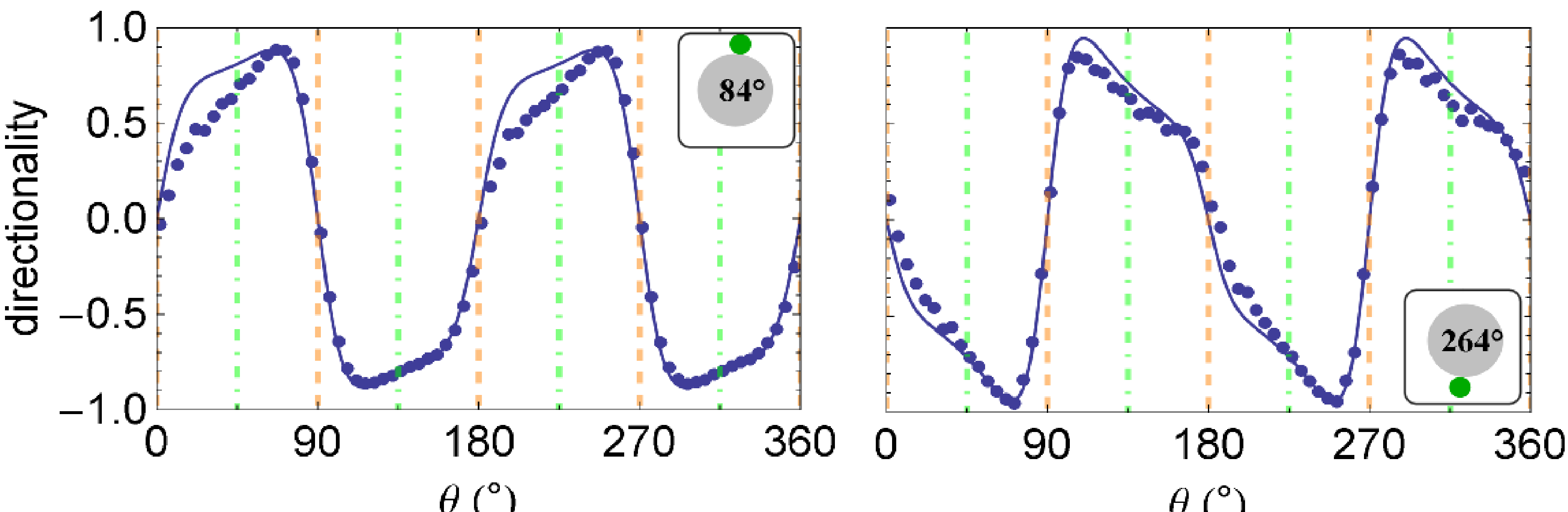
Chiral Waveguide Coupling

- Maximum directionality:

$$D = 0.88 \qquad\qquad D = 0.95$$

- Corresponding ratio of left/right photon fluxes:

$$16 \div 1 \qquad\qquad 40 \div 1$$

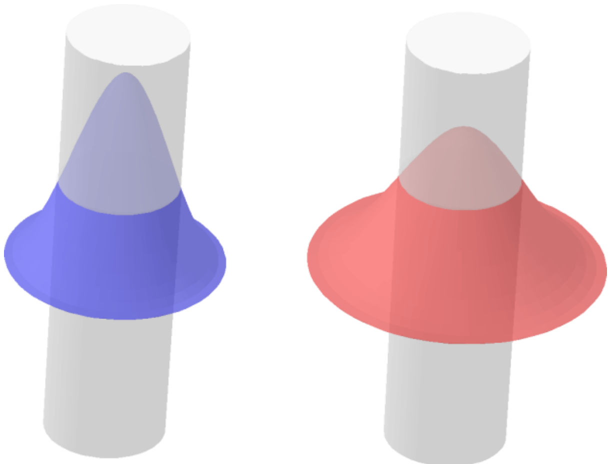


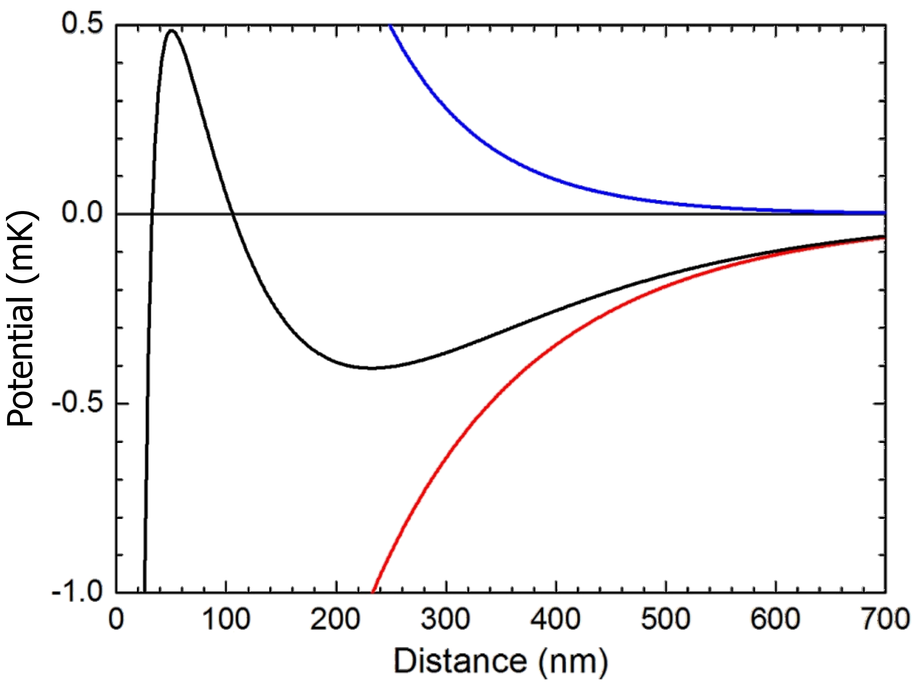
Petersen et al., Science **346**, 67 (2014)

Two-Color Nanofiber-Based Atom Trap

Radial confinement

- Evanescent field exerts a dipole force on the atoms
- "Blue light" is more tightly bound to the nanofiber than "red light"





Fam Le Kien et al., PRA **70**, 063403 (2004)

Two-Color Nanofiber-Based Atom Trap

Axial confinement

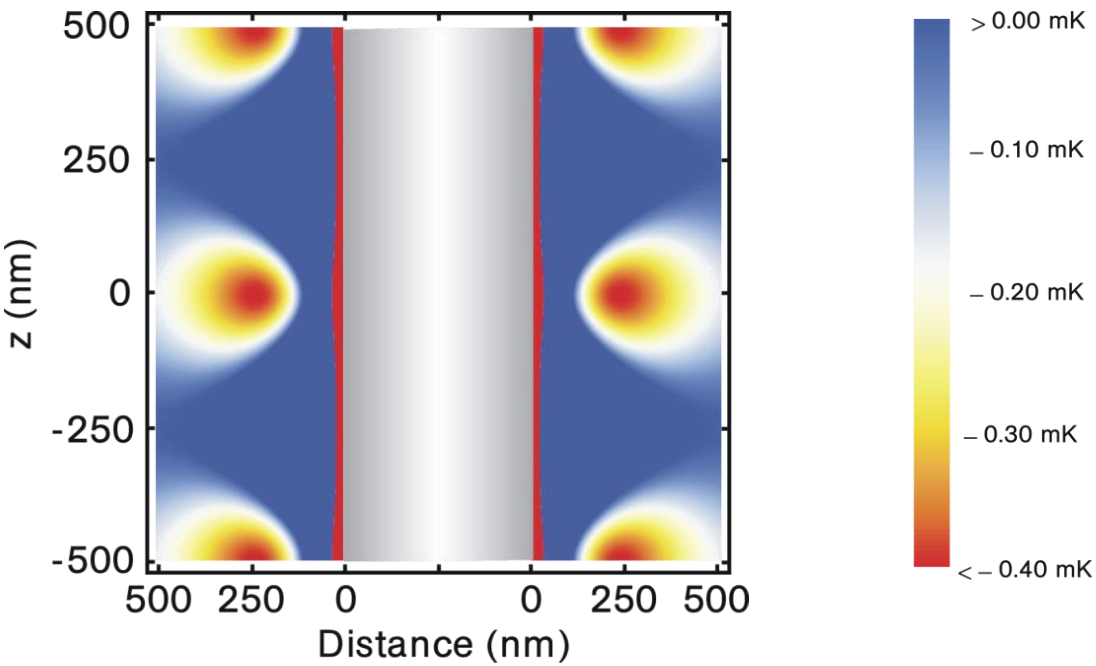
Two counter-propagating red-detuned beams

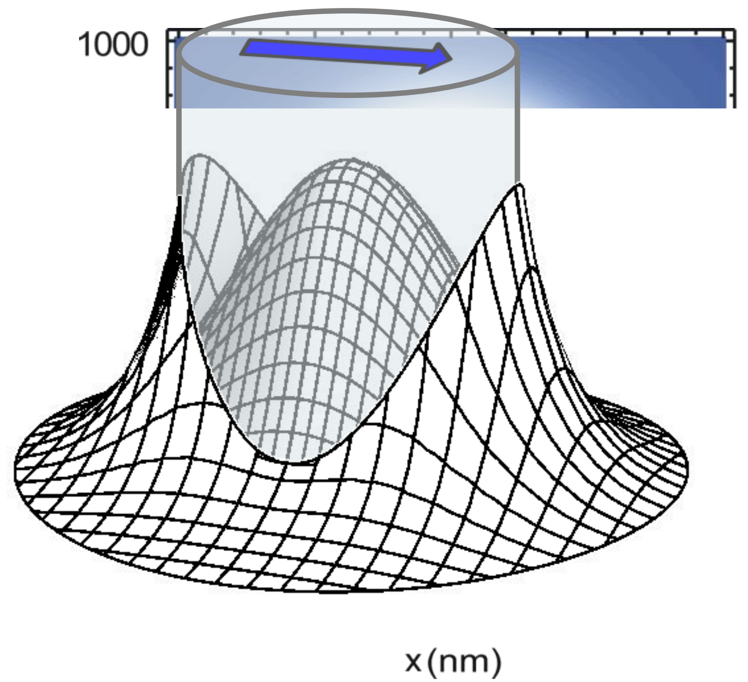
→ standing wave
500 nm between trapping sites

Azimuthal confinement

Linear polarizations

→ breaking of the rotational symmetry

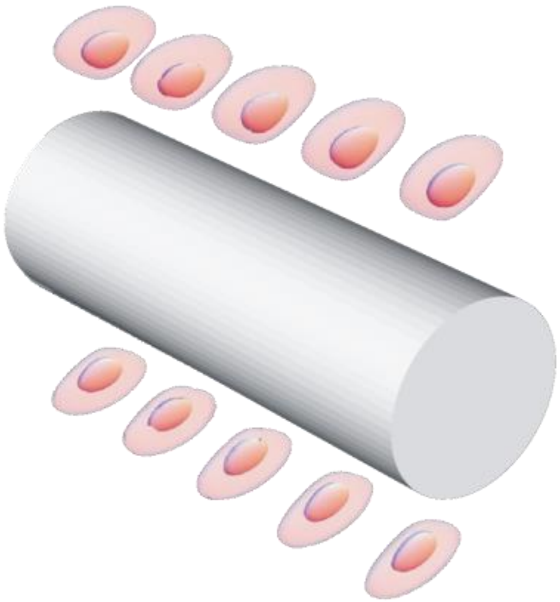




Two-Color Nanofiber-Based Atom Trap

Two arrays of trapping sites

- Nanofiber diameter: 500 nm
- At most one Cs atom per trapping site
- Filling factor: ~ 0.5



Trap parameters

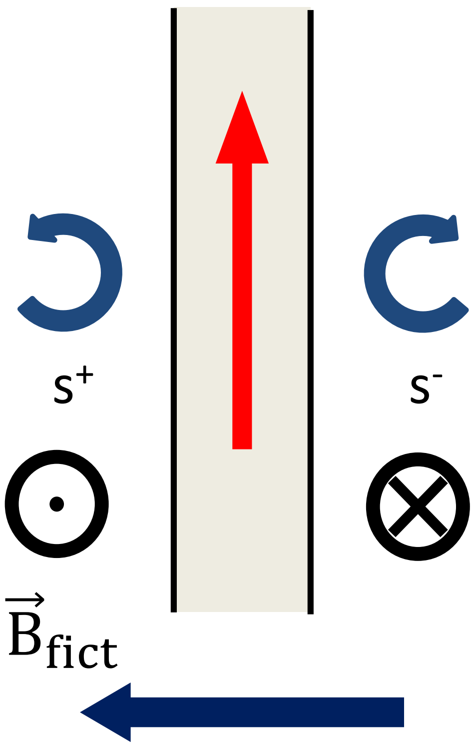
- Atom-surface distance: 230 nm
- Trap frequencies: (200, 315, 140) kHz
- Atoms are localized to a volume $\ll \lambda^3$

More nanofiber-based atom traps (past, present, and future):
Caltech, Niels Bohr Institute, JQI / University of Maryland, LKB Paris, Waseda University, OIST Japan, Univ. of Arizona, Swansea University, Univ. of Queensland, Univ. of Auckland, Univ. of Rochester…

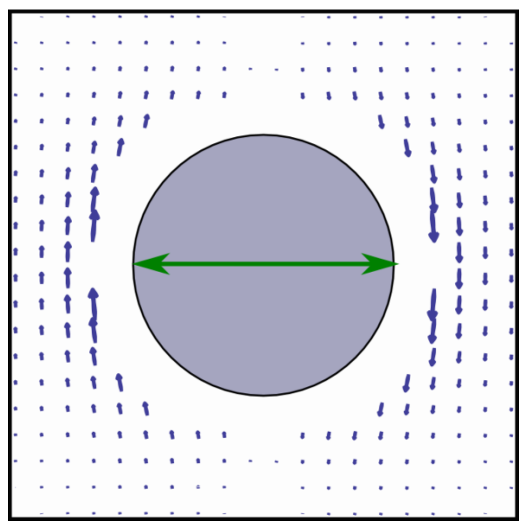
E. Vetsch et al., PRL **104**, 203603 (2010)
E. Vetsch et al., IEEE J of Quant Elec. **18**, 1763 (2012)

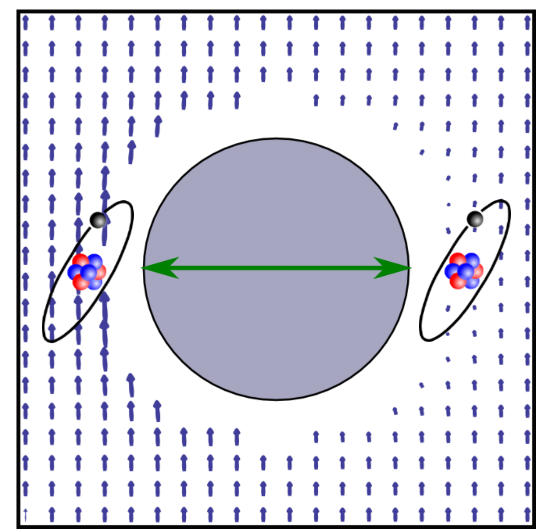
Side-Selective Removal of Atoms

Side-dependent light-induced magnetic field



- Detuned light-field ⇒ light shift
  Elliptical polarization ⇒ fictitious magnetic field
- Opposite sign on the two sides of the nanofiber
- Total magnetic field = side-dependent



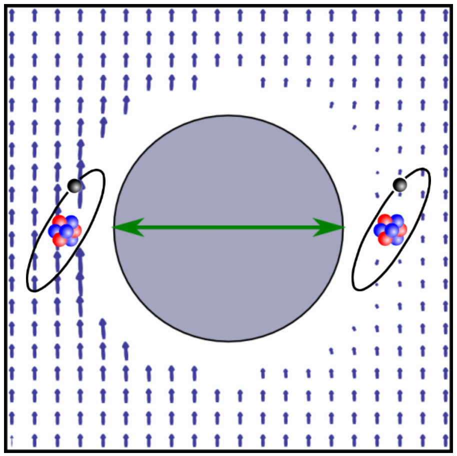


- Two sides can be spectrally discerned!

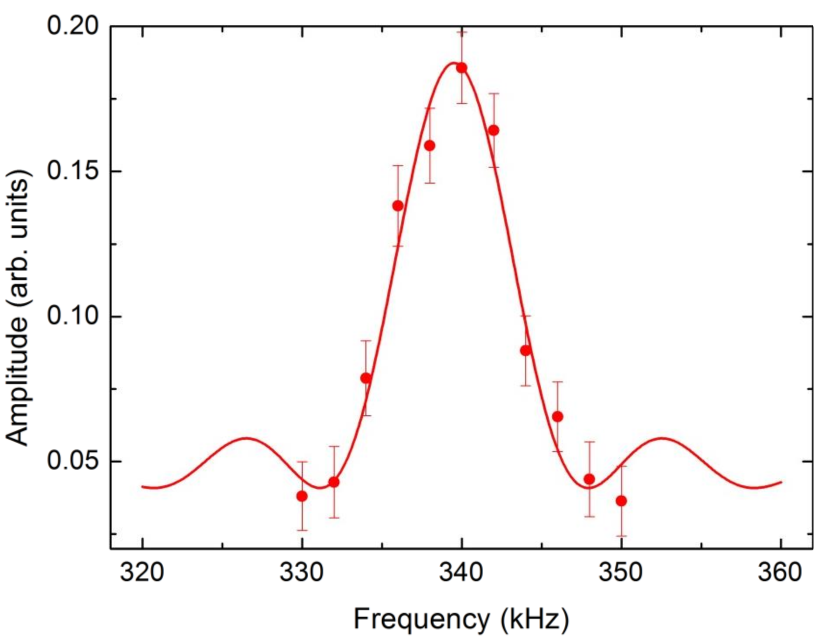
R. Mitsch et al., Phys. Rev. A **89**, 063829 (2014)

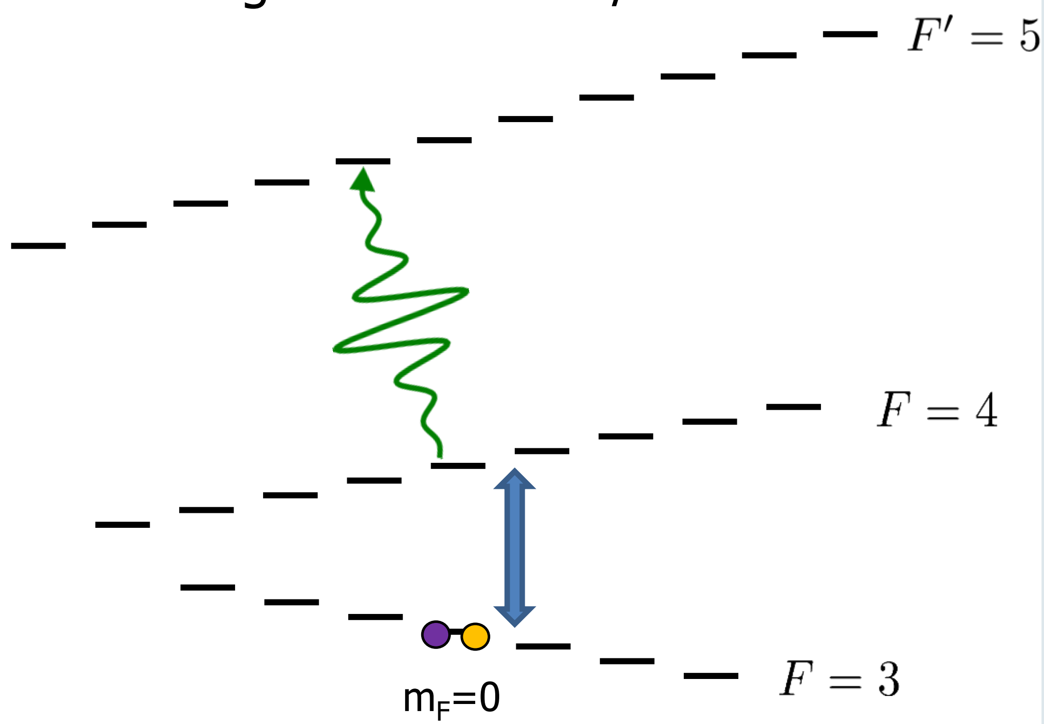
Side-Selective Removal of Atoms

Discerning and selectively manipulating the trapped atoms



- Microwave radiation: transfer between hyperfine ground states
- Atoms on only one side brought to $F = 4$
- Fictitious B-field gradient ~ 70 T/m





R. Mitsch et al., Phys. Rev. A **89**, 063829 (2014)

Formulae

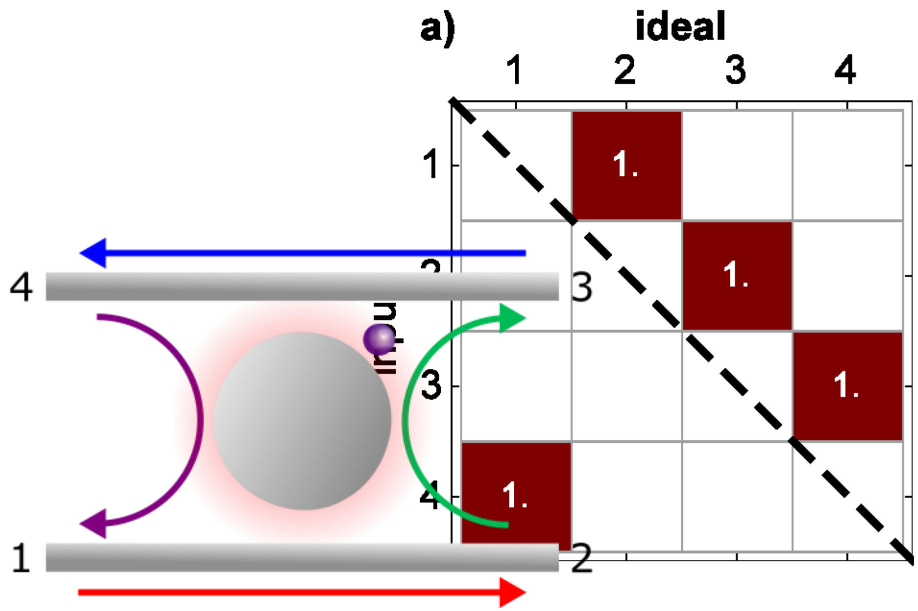
- Coupling strengths of atom to fiber modes: $\beta_{\pm} = \frac{\kappa_{\pm}}{\kappa_{+}+\kappa_{-}+\gamma}$

- Amplitude transmission (reflection) of fiber-guided light: $t_{\pm} = 1 - 2\beta_{\pm}$ ($r_{\pm} = 2\sqrt{\beta_{+}\beta_{-}}$).

- Symmetric coupling ($\kappa_{+} = \kappa_{-}$):
  $\Rightarrow \beta_{+} = \beta_{-} = 1/2$ in the limit of perfect coupling ($\gamma = 0$)
  $\Rightarrow t_{\pm}^{2} = 0$ and $r_{\pm}^{2} = 1$, i.e., perfect mirror

- Absorption: $\eta_{\pm} = 1 - t_{\pm}^{2} - r_{\pm}^{2}$
  $\Rightarrow$ maximal for $\beta_{+} = \beta_{-} = \frac{1}{4}$
  $\Rightarrow$ max. absorption of $\eta_{\pm} = 0.5$

Transmission Matrix



M. Scheucher et al., Science **354**, 1577 (2016)

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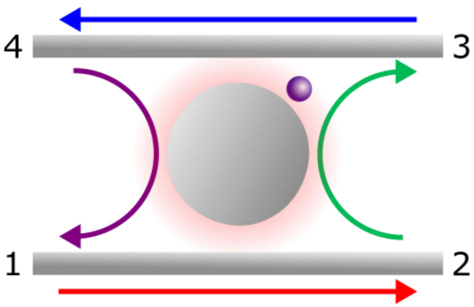

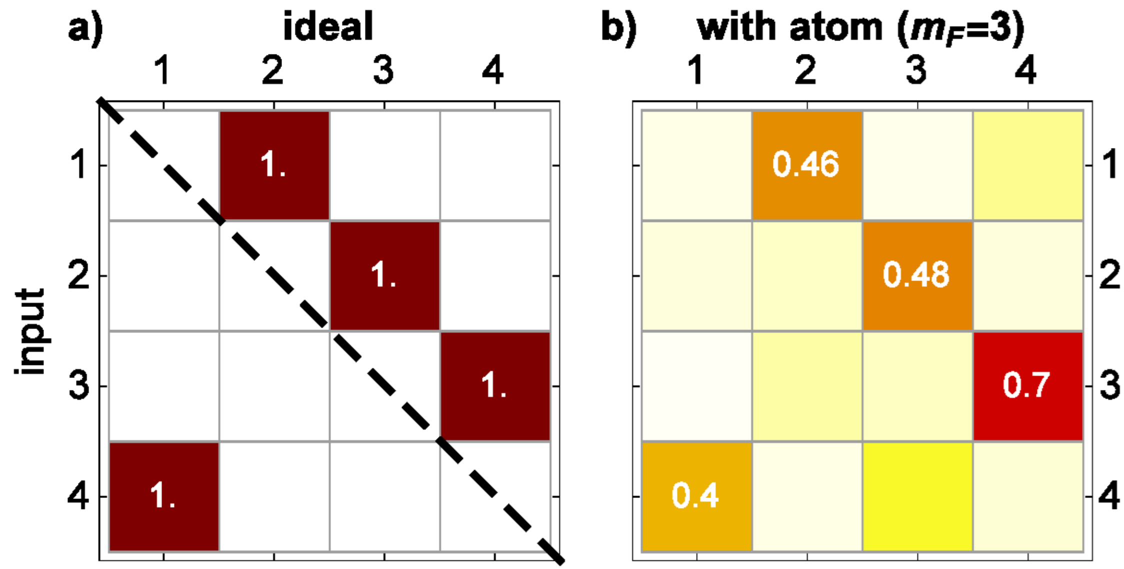

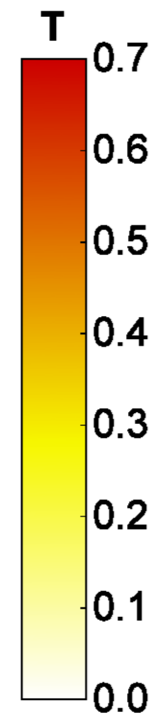

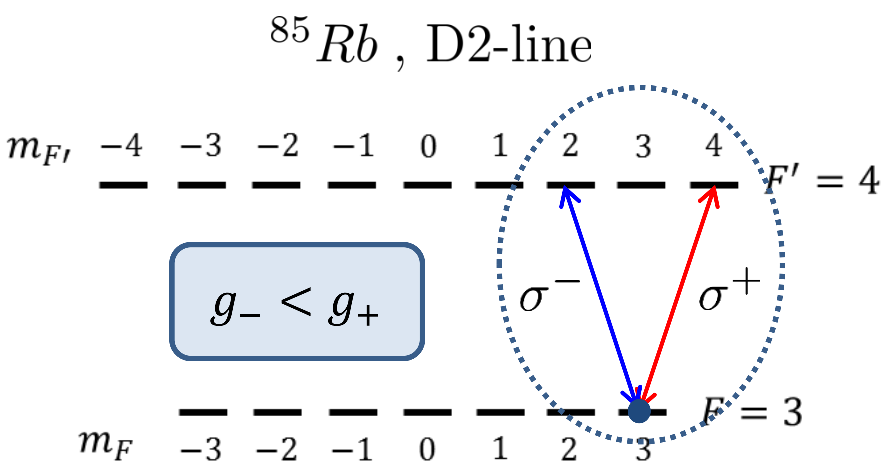

M. Scheucher et al., Science **354**, 1577 (2016)

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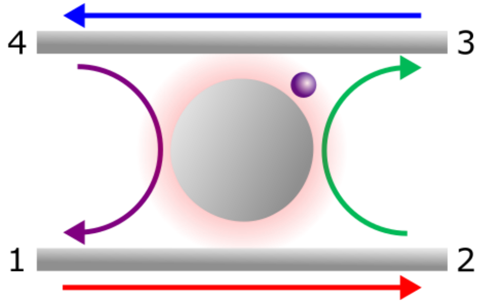
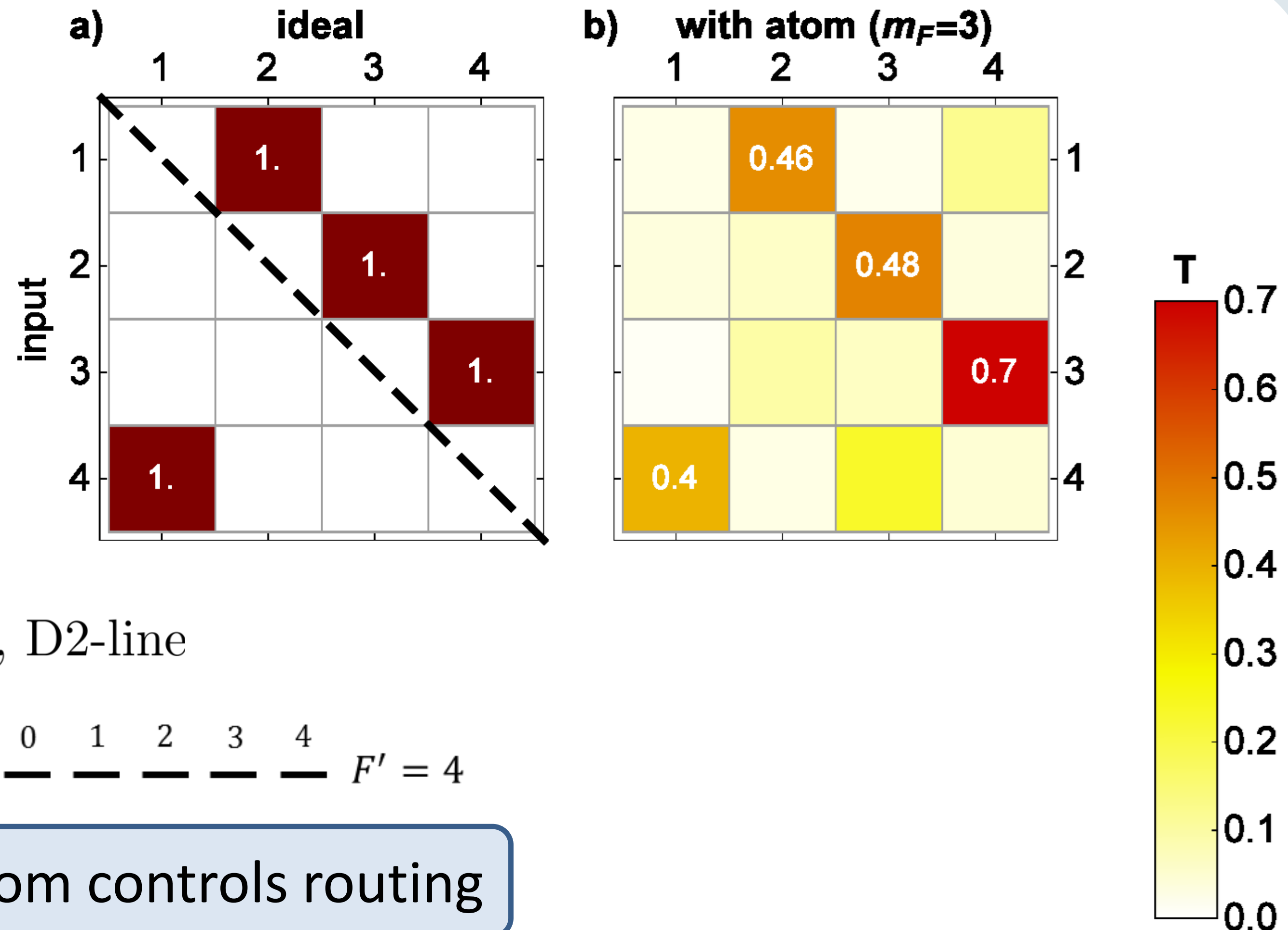
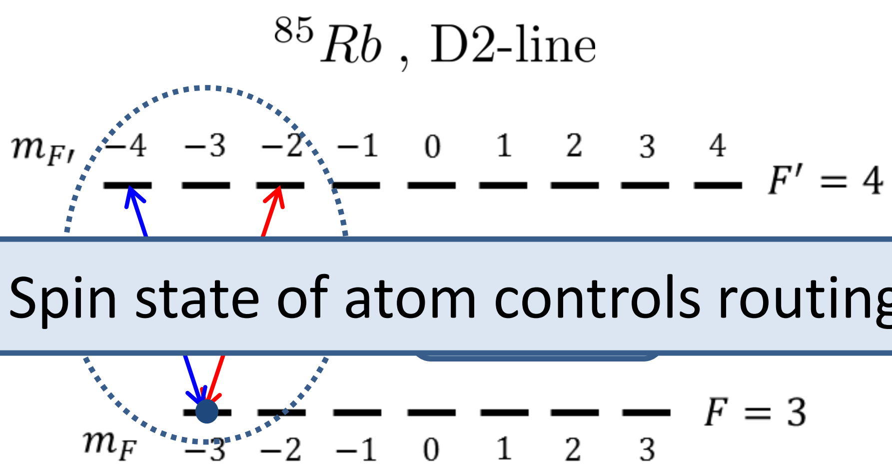


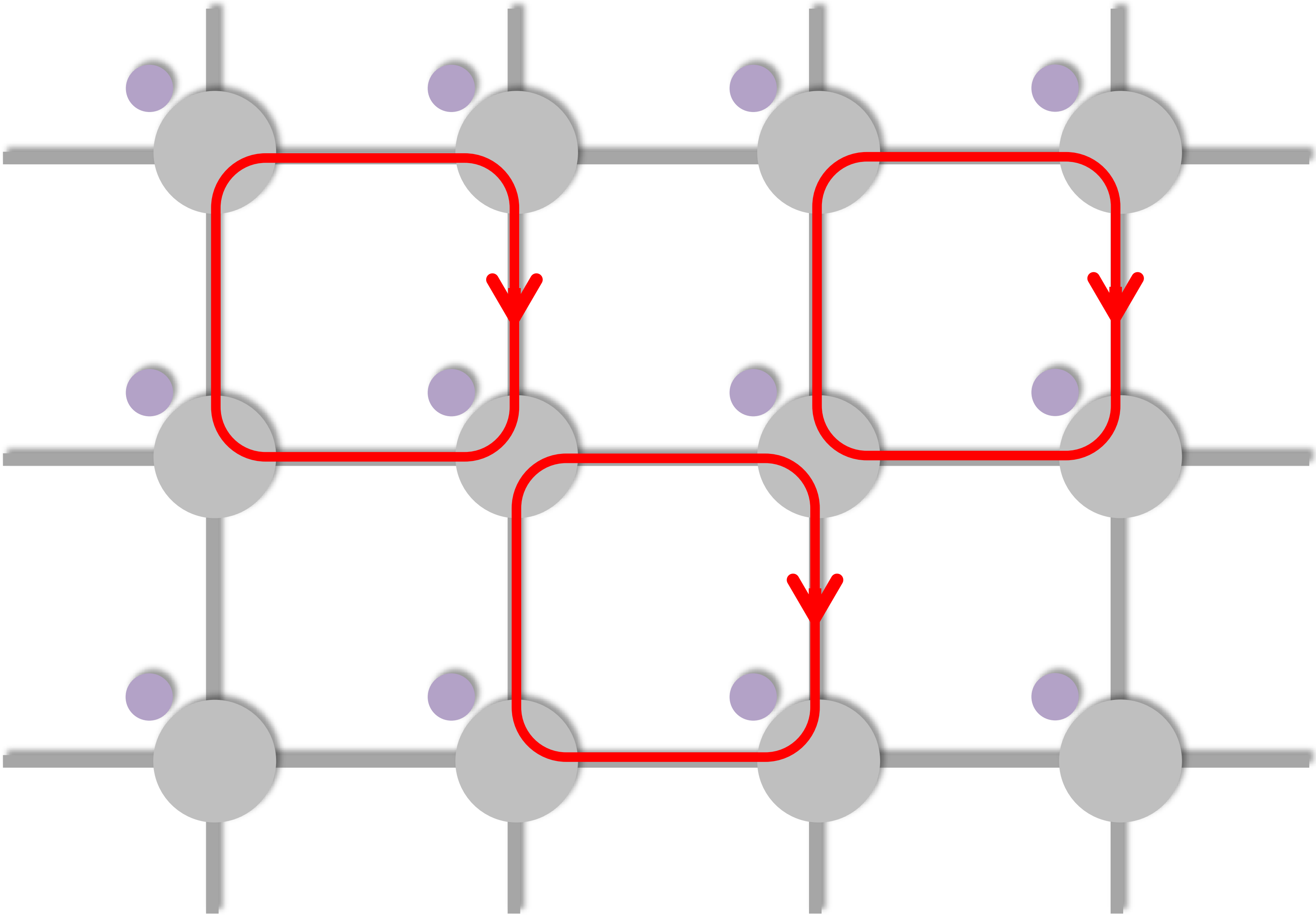




Spin state of atom controls routing

M. Scheucher et al., Science **354**, 1577 (2016)

Network of Quantum Circulators



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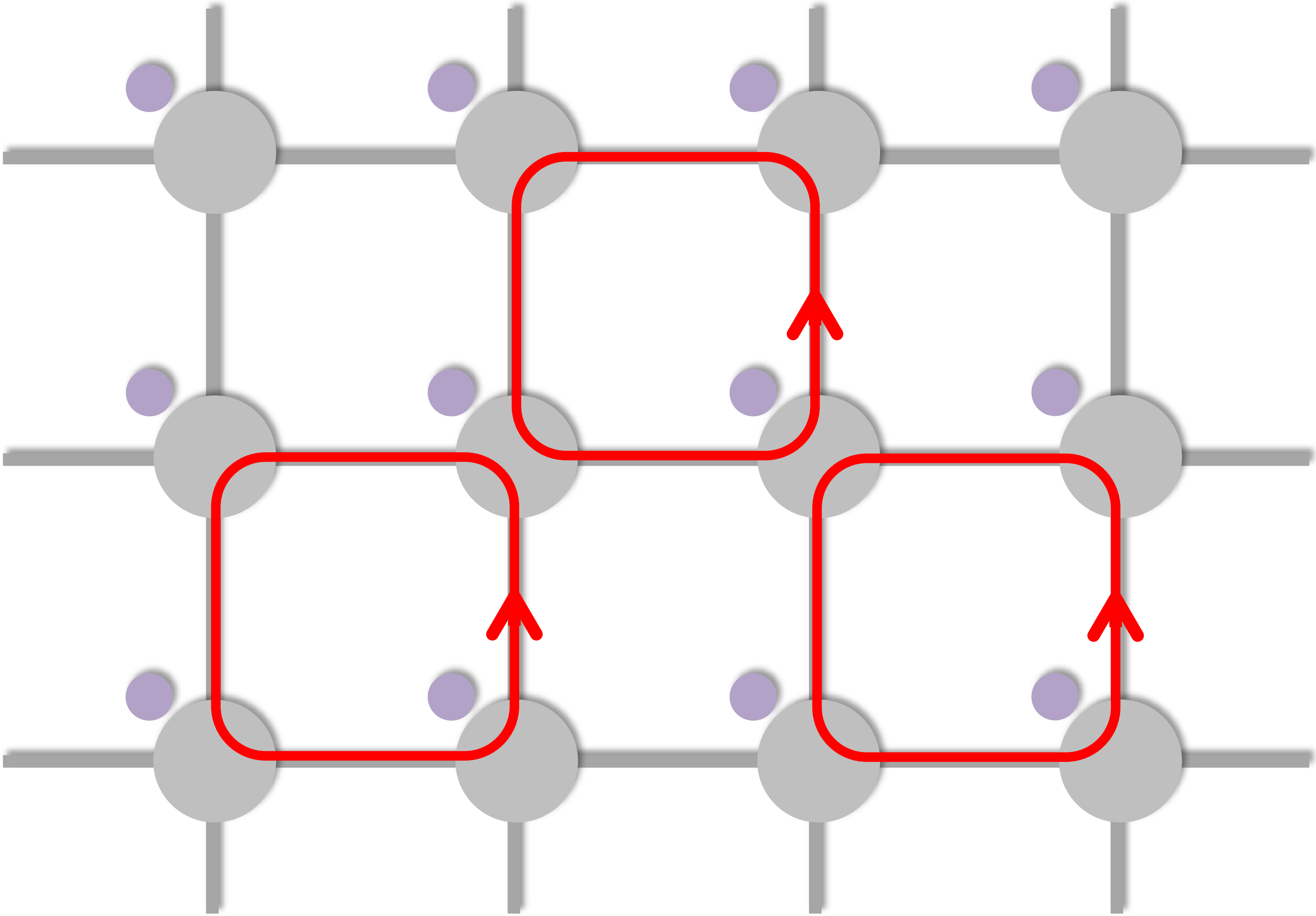

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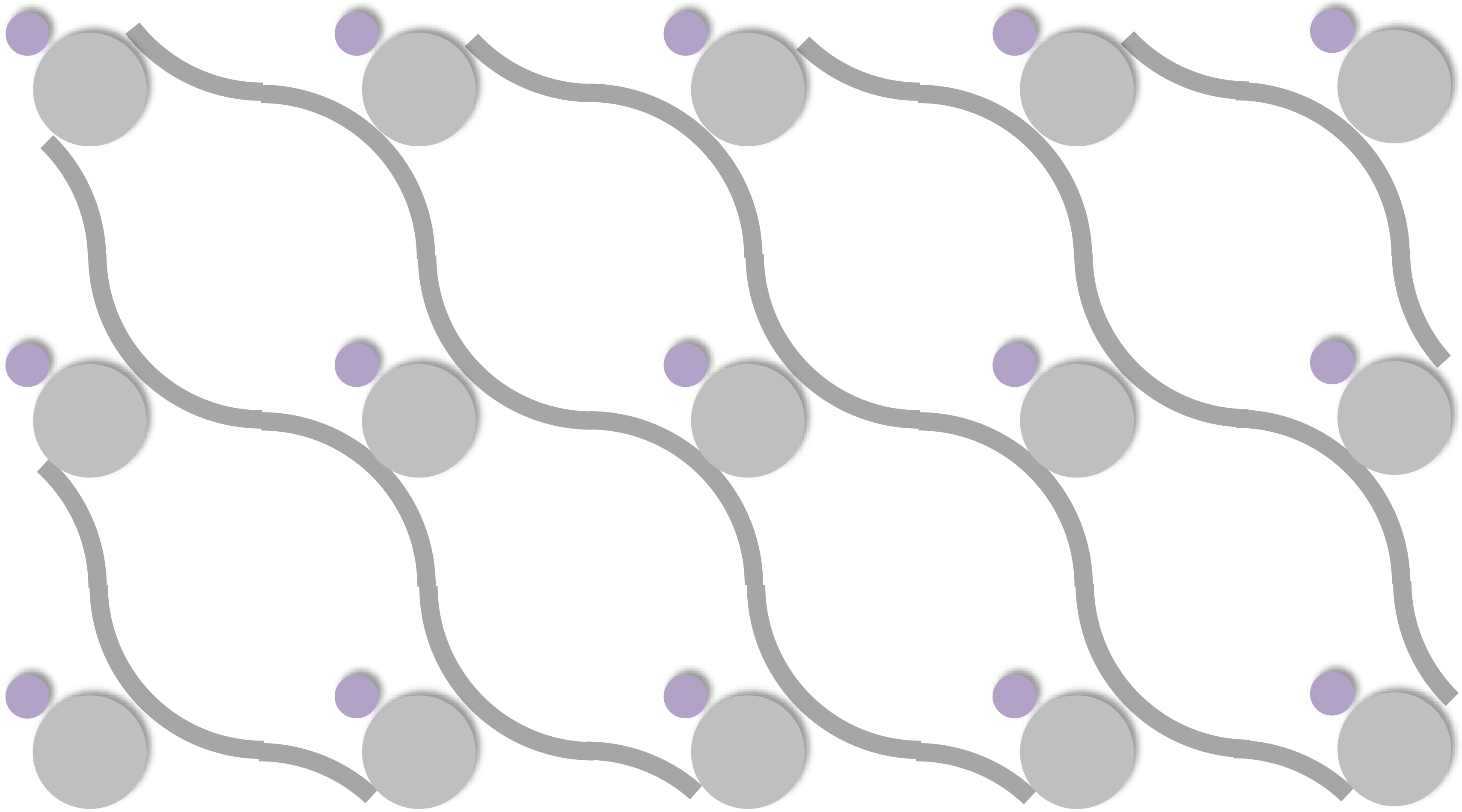
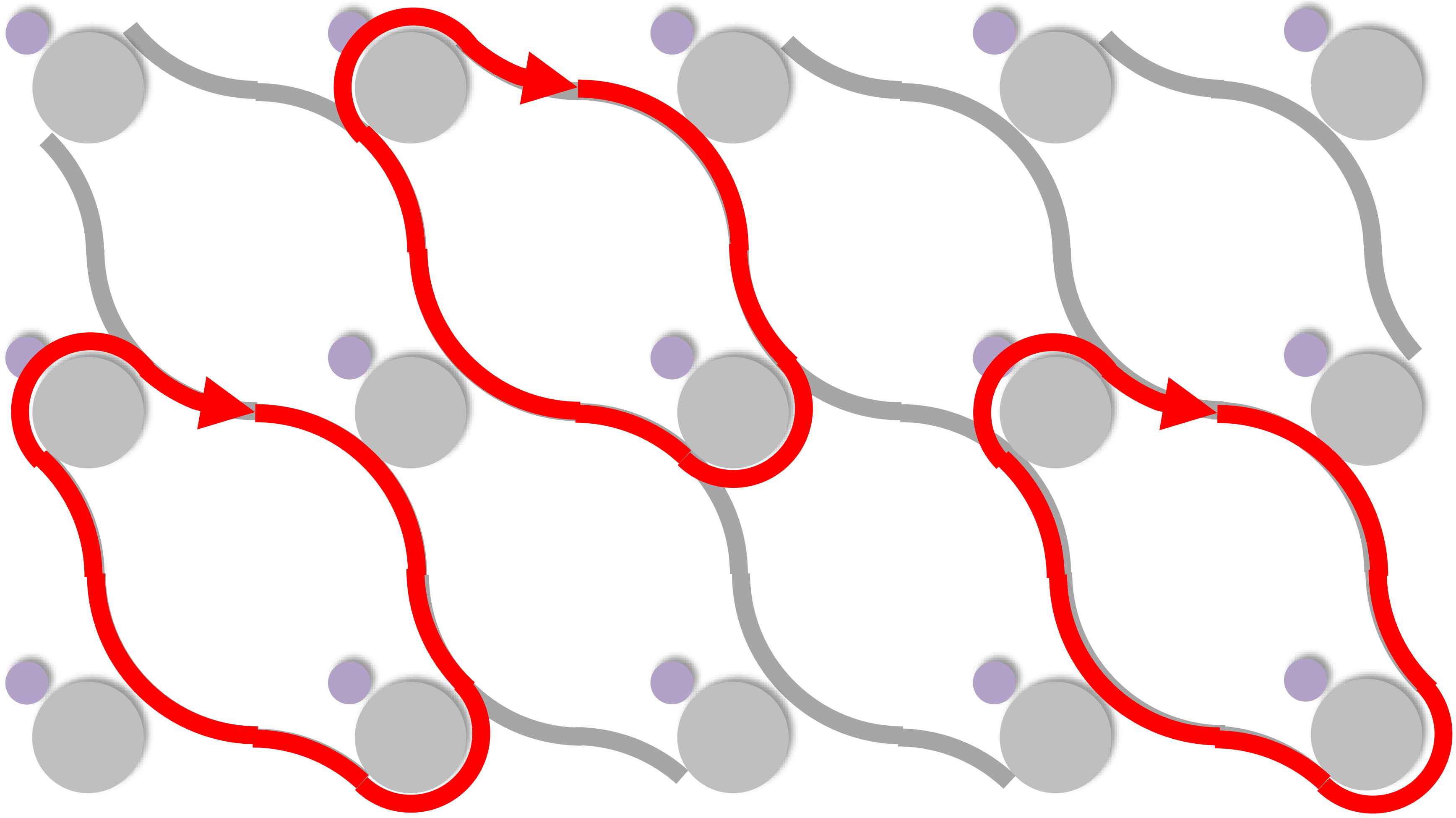


Bulk Isolator



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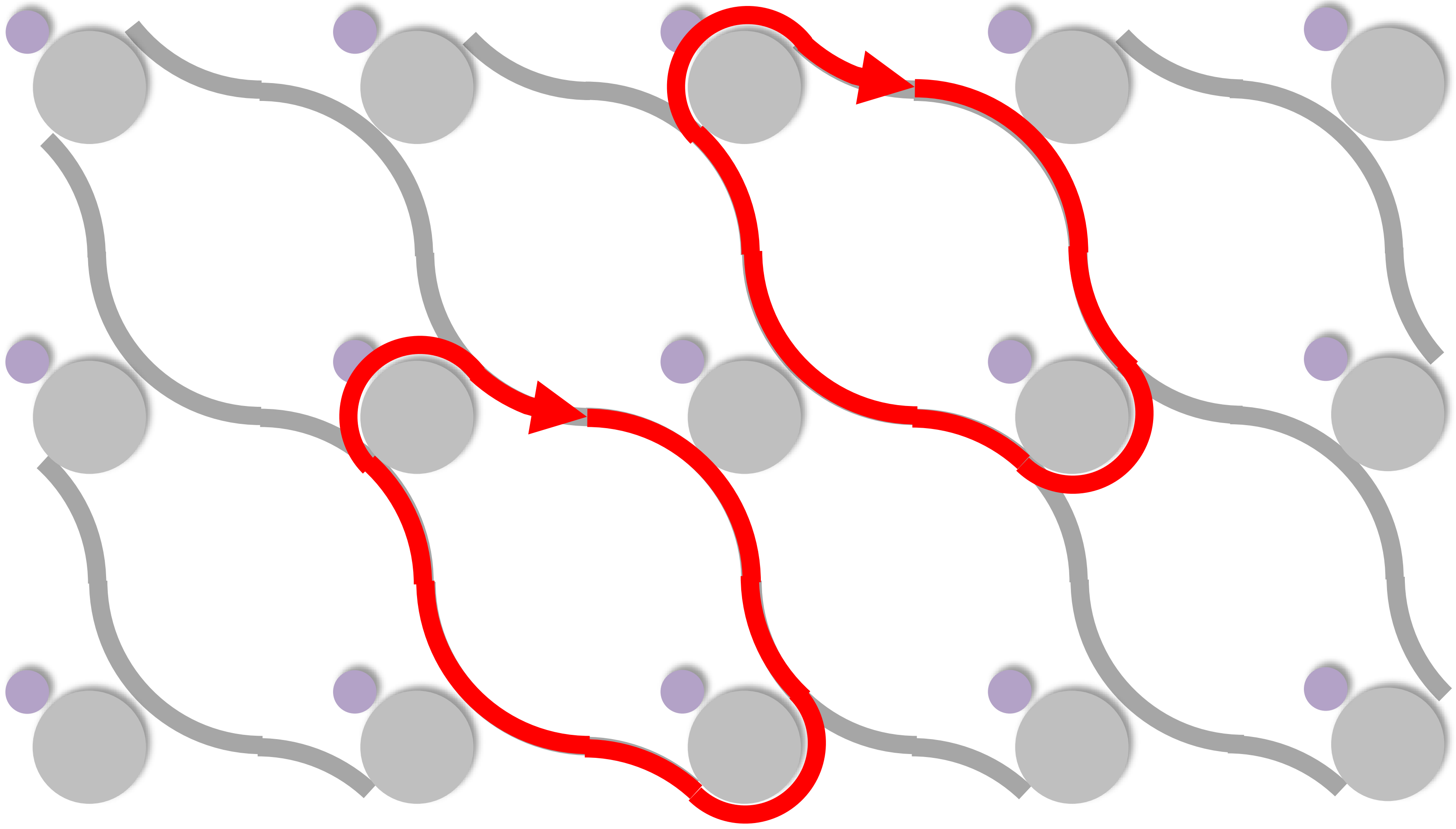

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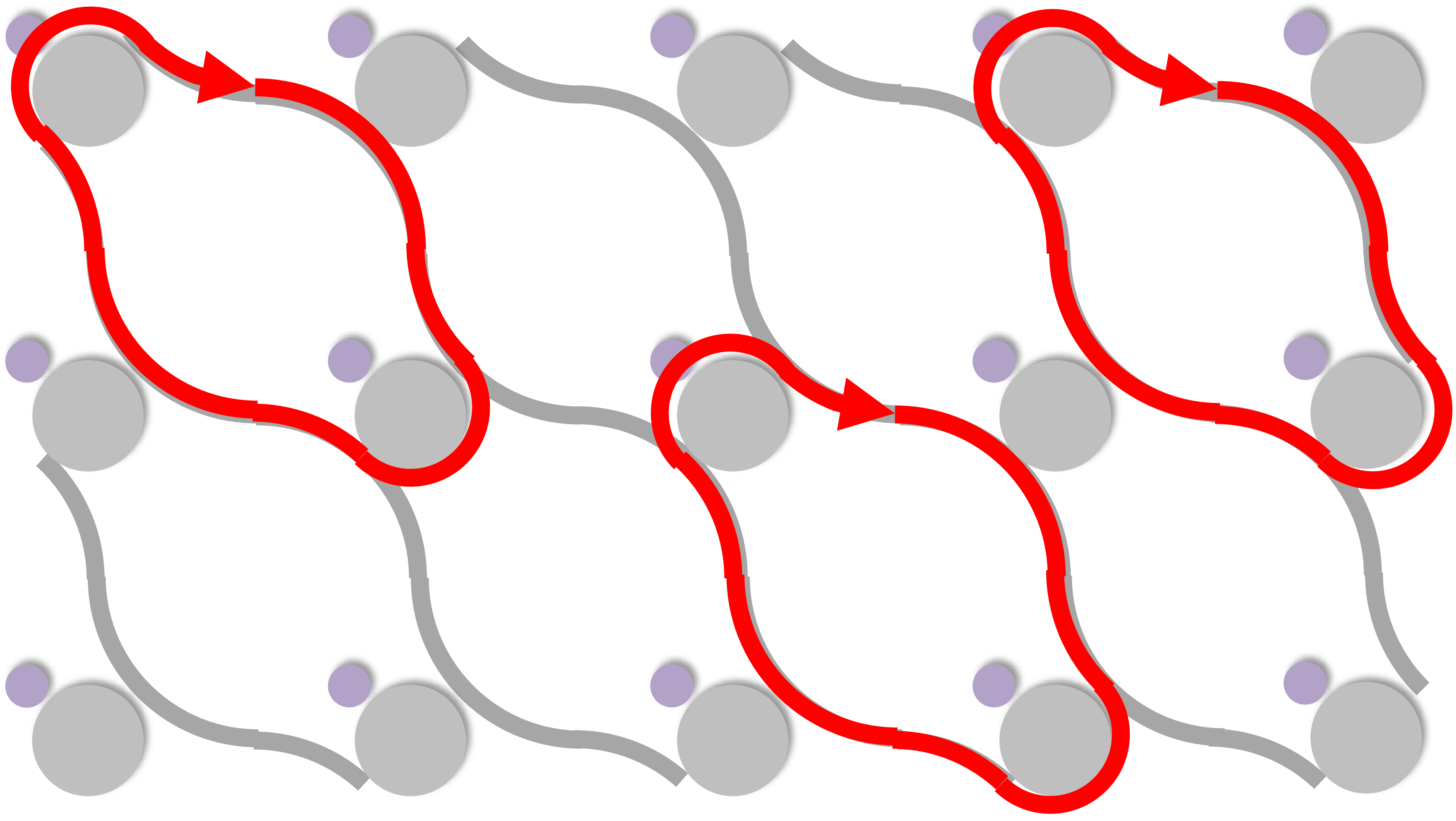

Chiral Edge Channel