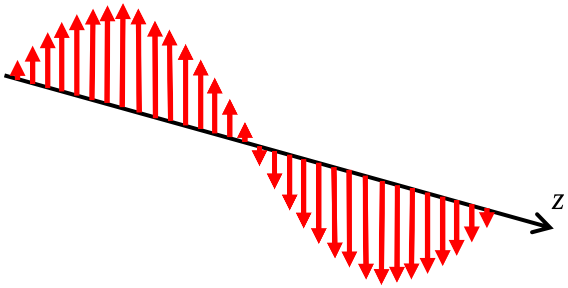
Chiral interaction of light and matter in confined geometries

Non-equilibrium dynamics of strongly interacting photons,
Kavli Institute for Theoretical Physics,
University of California, Santa Barbara, CA, USA
Oct. 5–9, 2015

Arno Rauschenbeutel
Vienna Center for Quantum Science and Technology,
Atominstitut, TU Wien, Austria

Introduction – Non-transversal Polarization

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



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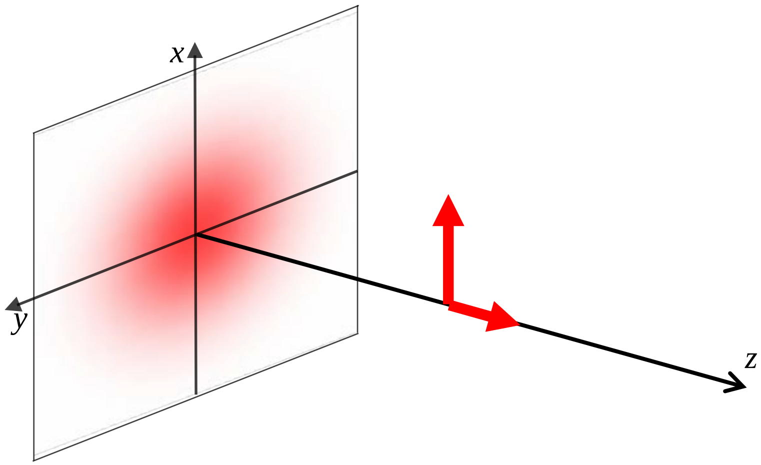

$$\vec{\nabla} \cdot \vec{E} = 0$$

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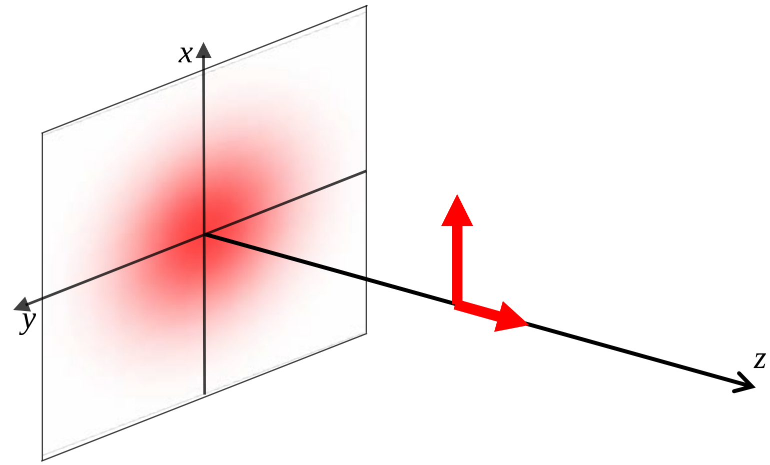

- Origin of longitudinal field
  - Non-zero transversal divergence
  - E. g., if transversal E-field points along the field gradient
  - ➔ Longitudinal field component

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

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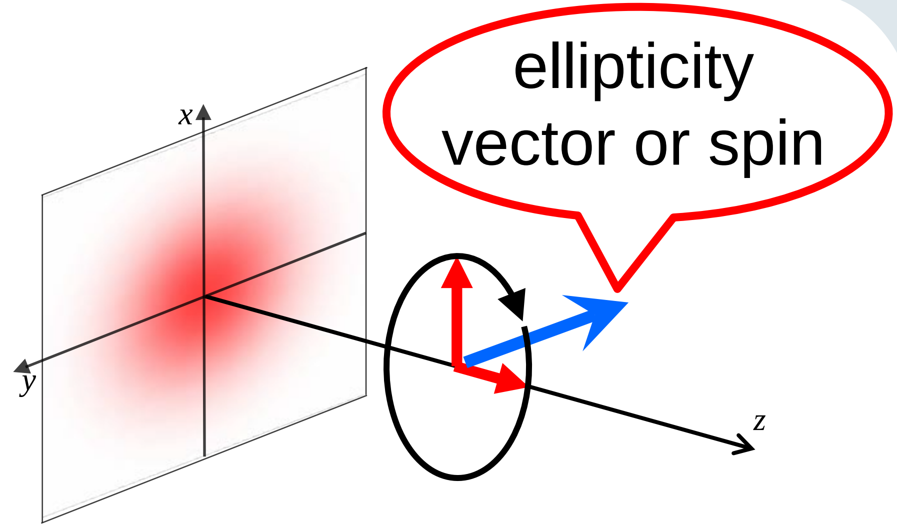

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  - Non-zero transversal divergence
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  - ➔ Longitudinal field component

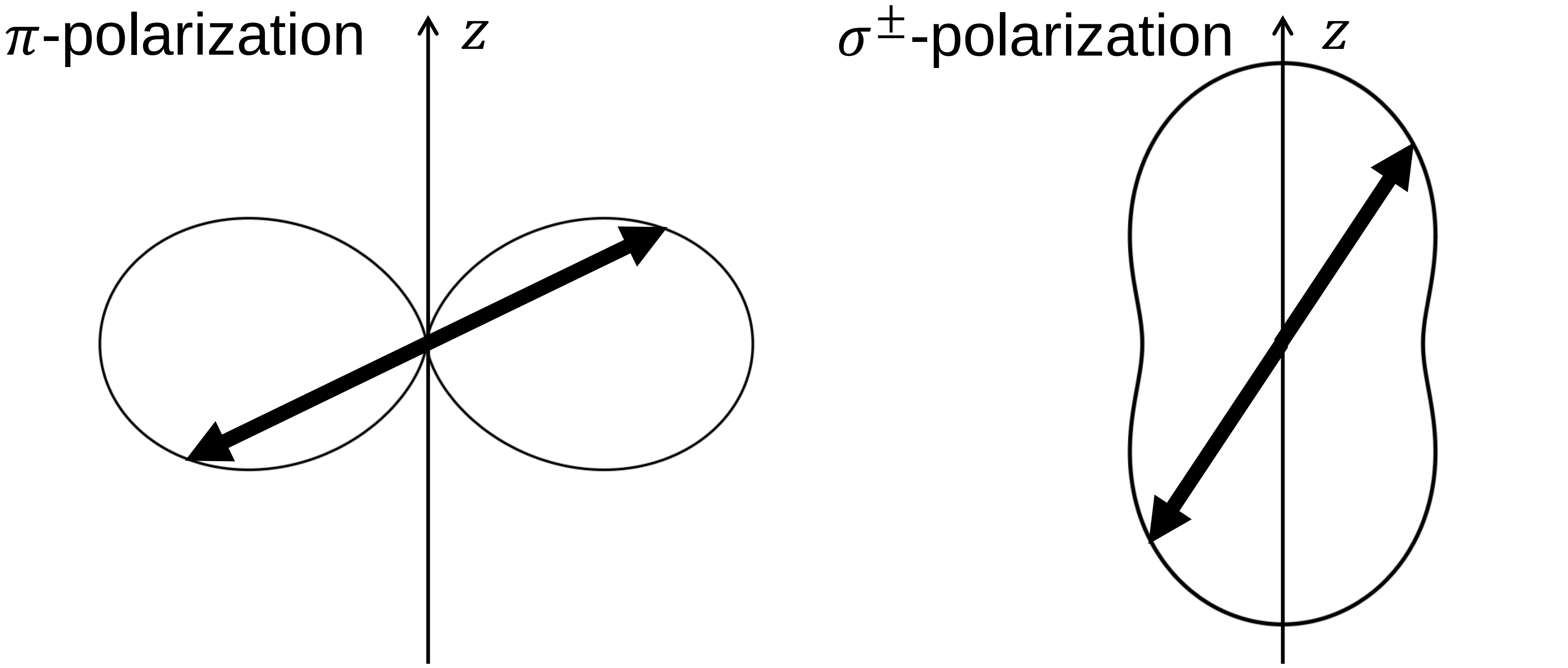
$$E_z = i\frac{\lambda}{2\pi}\left(\vec{\nabla}_{trans}\cdot\vec{E}_{trans}\right)$$

oscillates 90° out of phase!!

➡ Significant longitudinal field if gradient is significant on wavelength scale

Introduction – Spontaneous Emission

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:

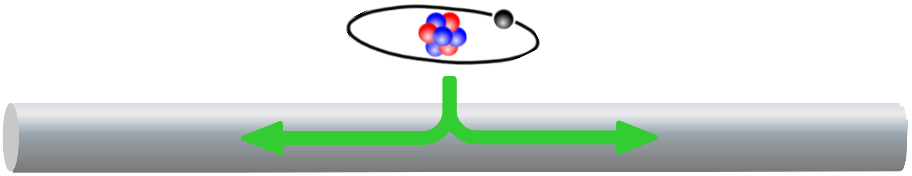


⇒ Emission in any given direction is the same as for opposite direction

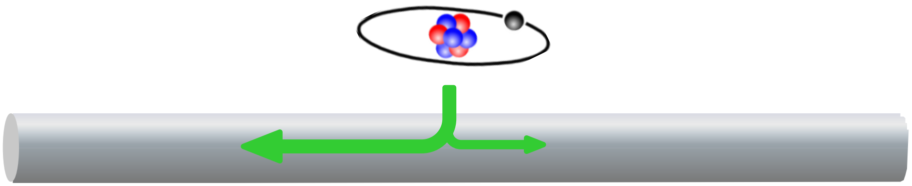
Intro: Directional Spontaneous Emission

Emitters coupled to a nanophotonic waveguide

- Symmetric:



- Asymmetric:



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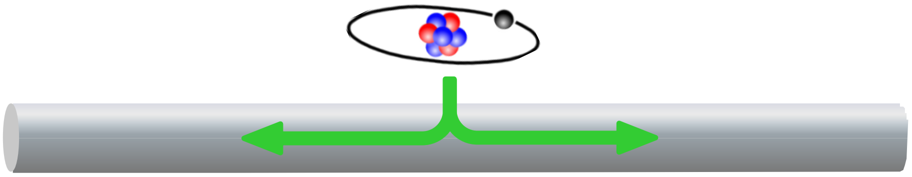

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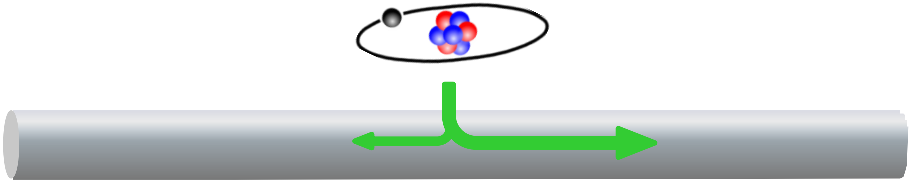
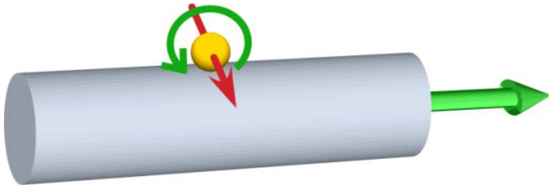


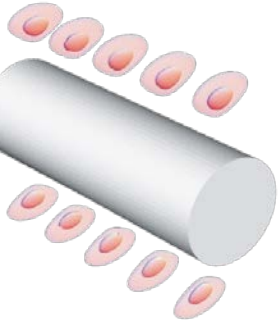
Overview

- Guided modes in optical nanofibers

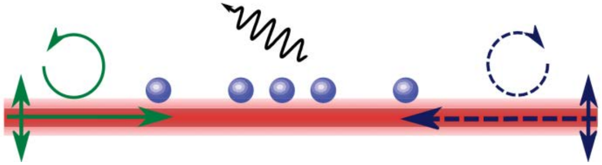
- Directional emission of a gold nanoparticle



- Directional atom-waveguide interface

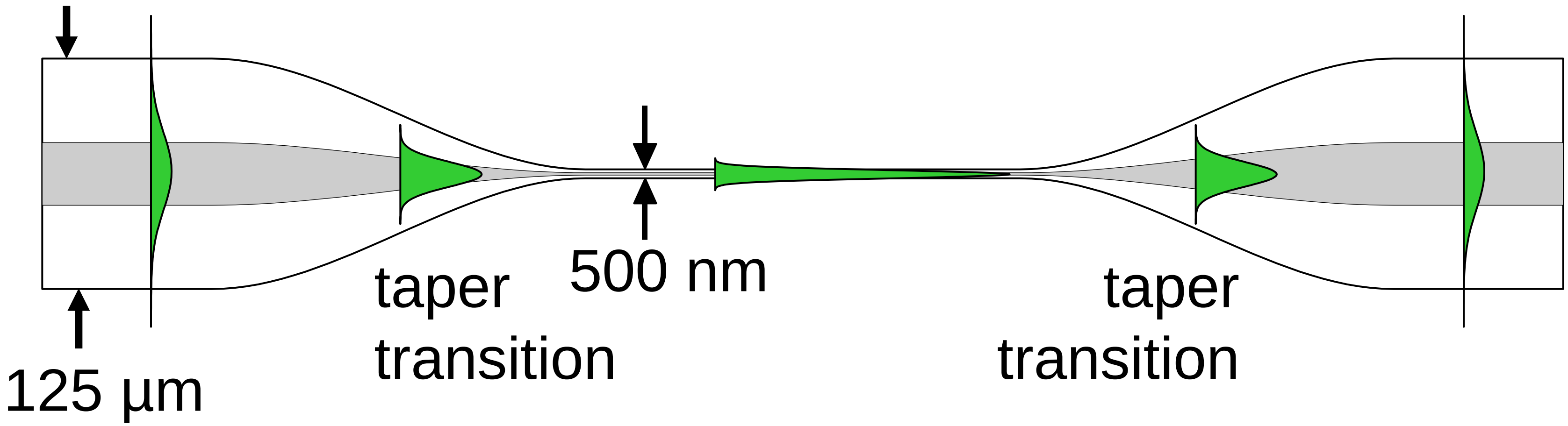


- Nonreciprocal nanophotonic waveguide



Nanofibers as the Waist of a Tapered Fiber

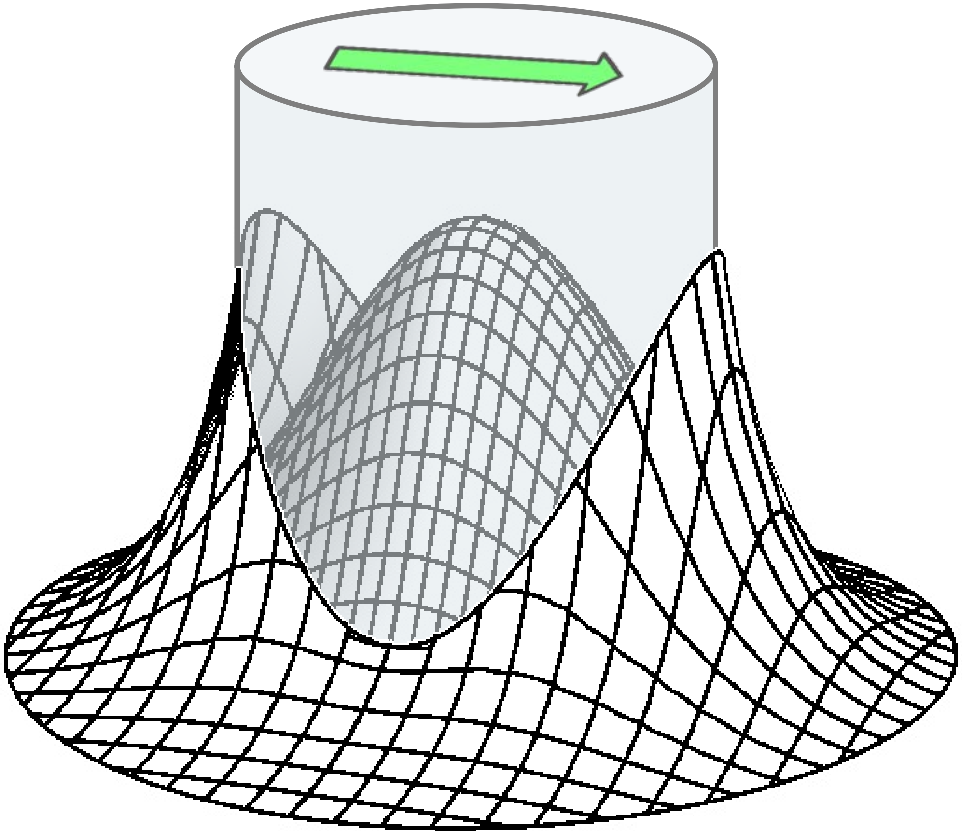
Efficient coupling of light into and out of the nanofiber



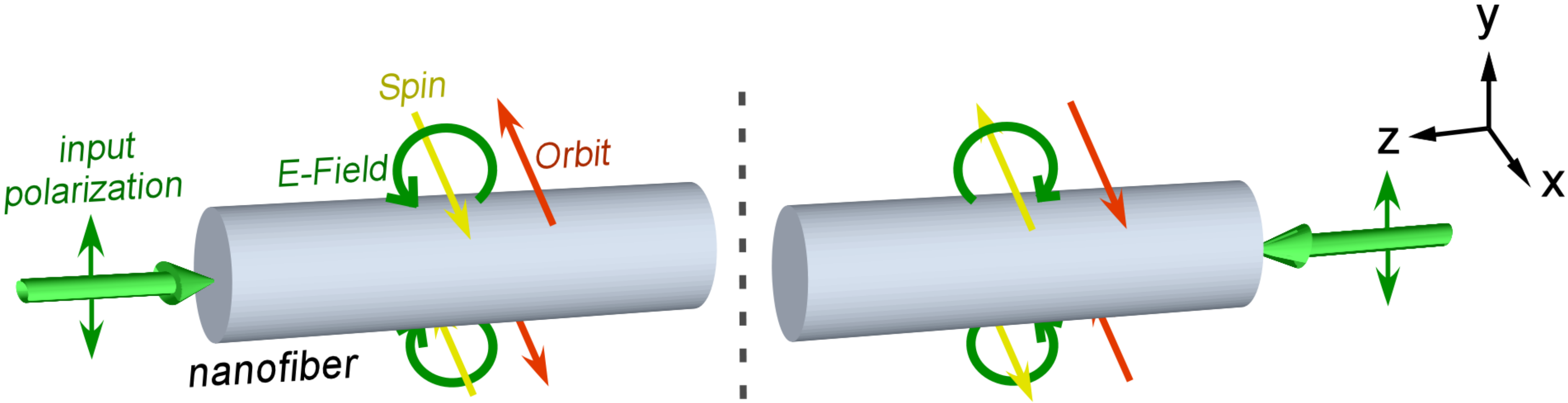
- Adiabatic mode transformation ⇒ up to 99% transmission
- Withstands >100 mW of transmitted optical power in vacuum

HE_{11} Mode: Intensity Distribution

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



HE_{11} Mode: Polarization Properties



Define effective chirality: $\chi = \vec{\epsilon} \cdot (\vec{k}/|\vec{k}| \times \vec{e}_r) \geq 0$

⇒ Photons in evanescent fields are effectively chiral.

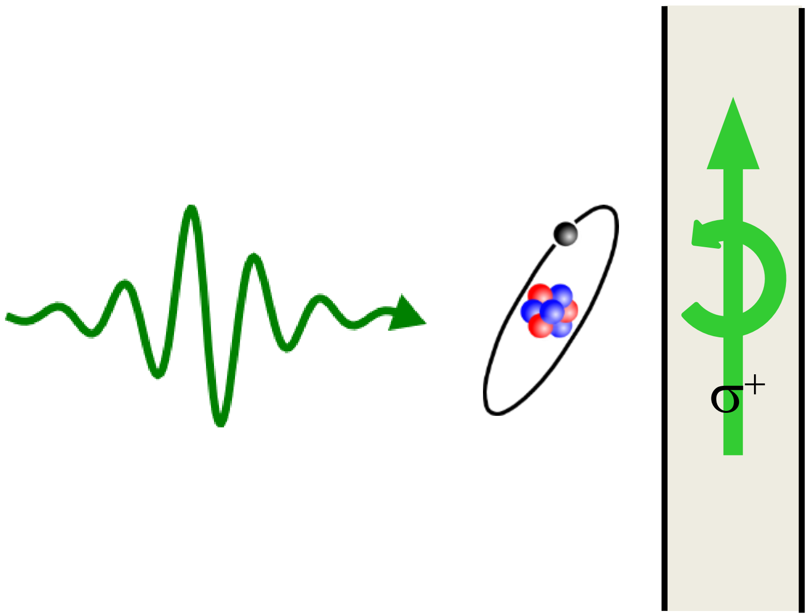
⇒ Local ellipticity (or spin) changes sign with direction of propagation.

Directional Spontaneous Emission

Recipe

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

  ... emission of a σ^+-photon



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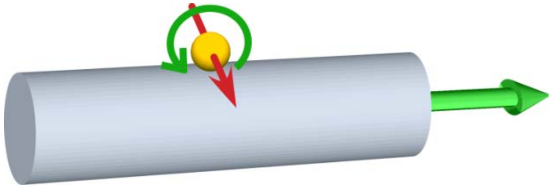
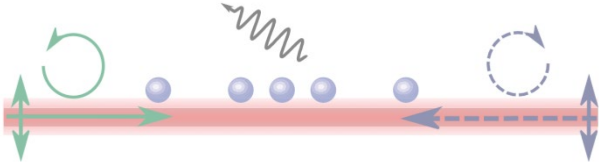


- Directional atom-waveguide interface

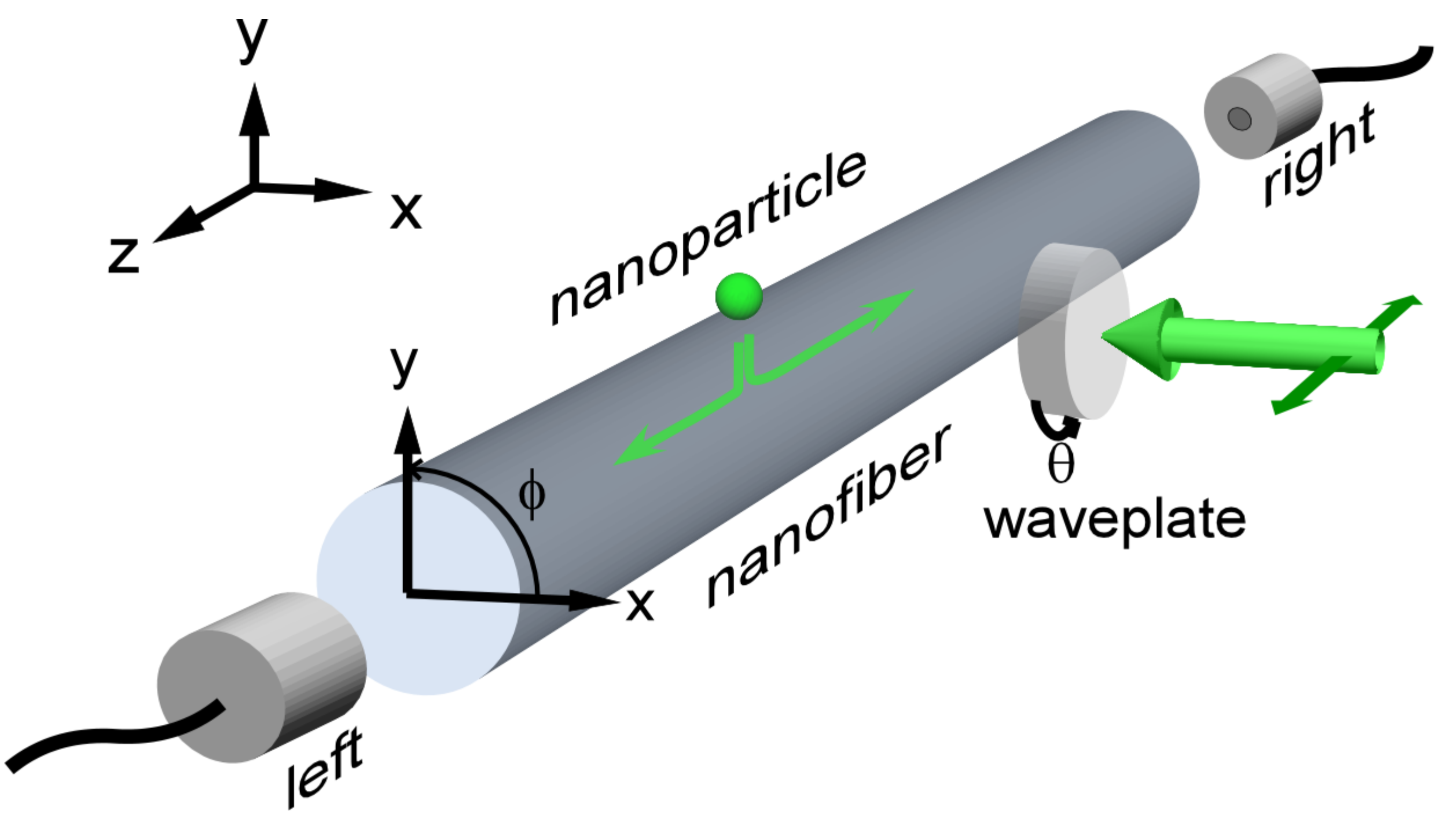
- Nonreciprocal nanophotonic waveguide



Experimental Set-Up

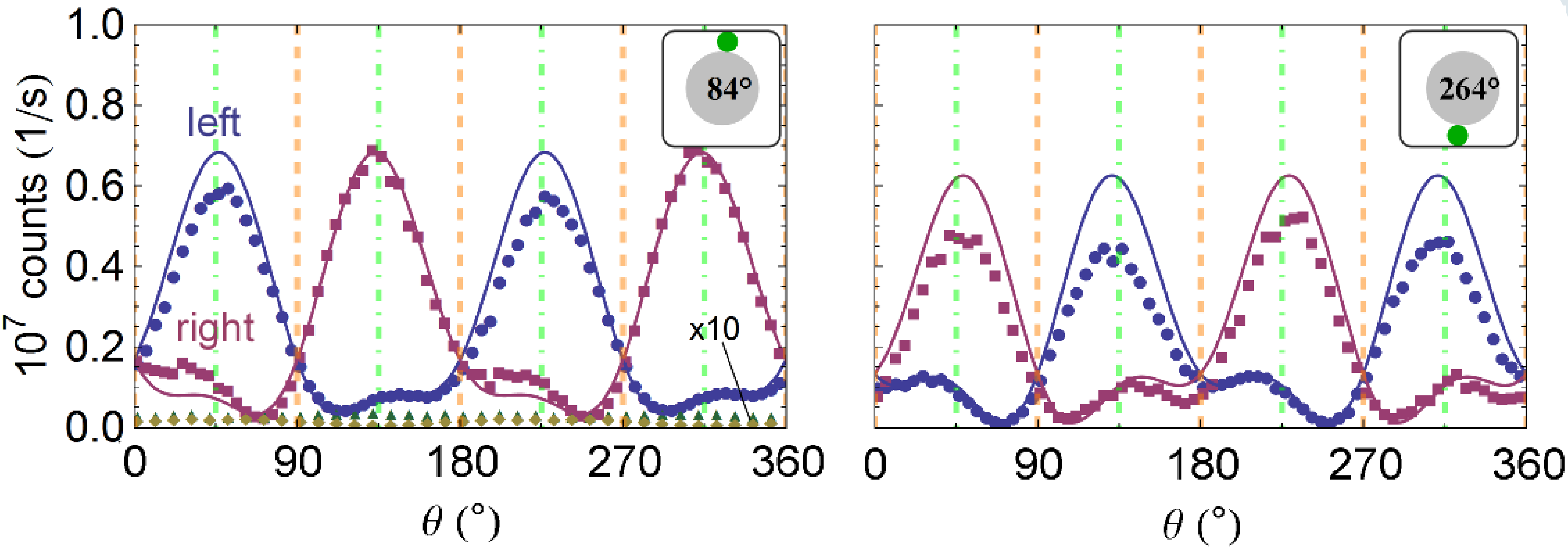
System: Gold nanoparticle (Ø=90 nm) on silica nanofiber (Ø=315 nm)

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



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

Chiral Waveguide Coupling



Calculate directionality from above data:

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

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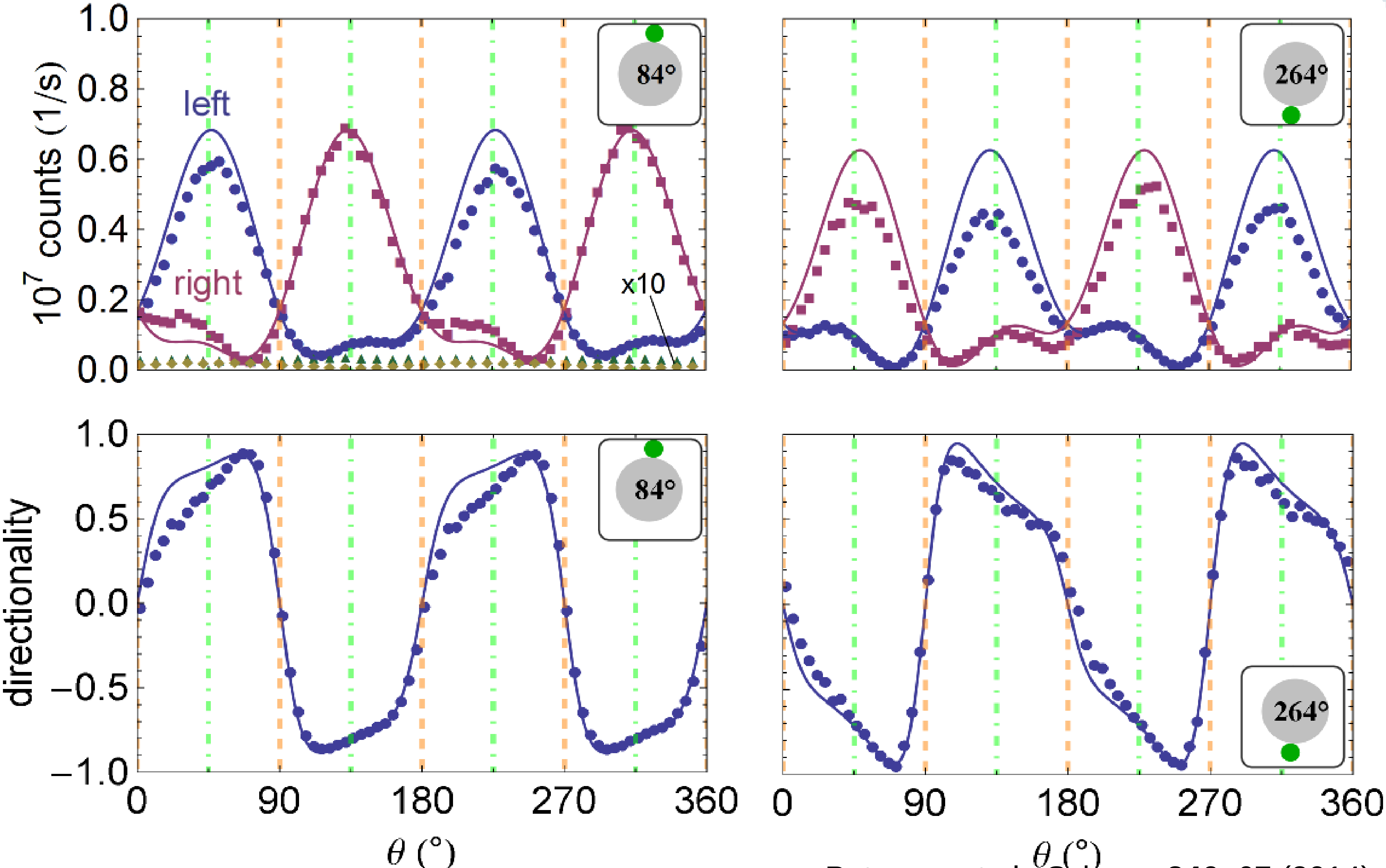

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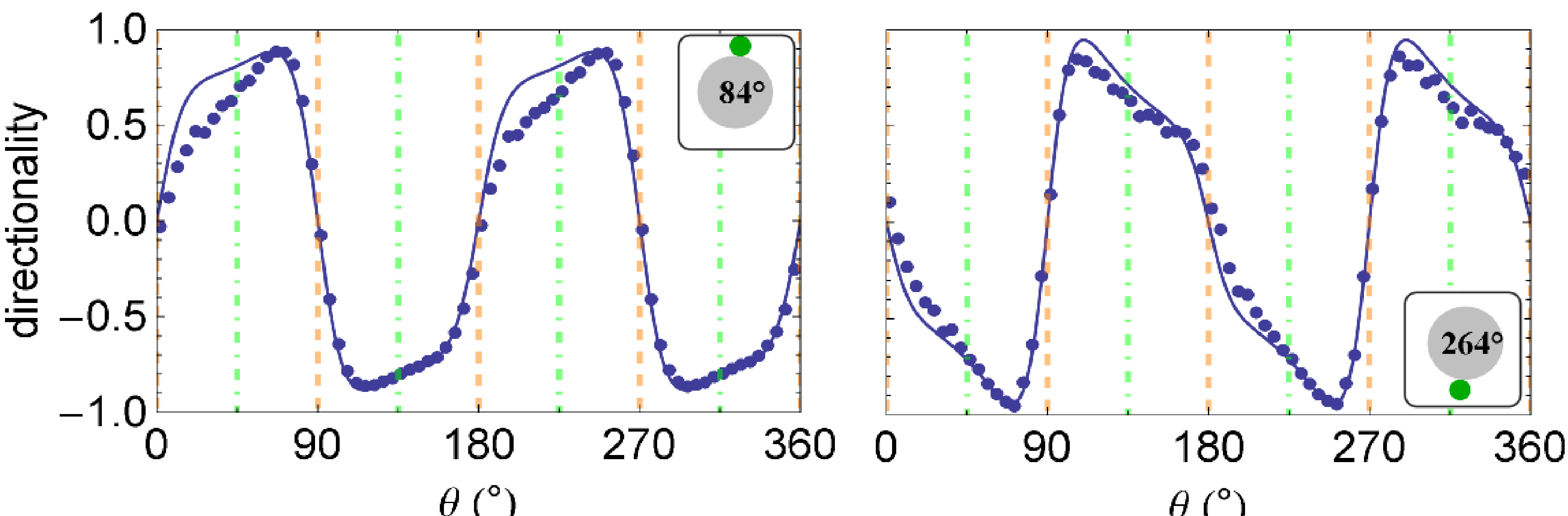
Chiral Waveguide Coupling

- Maximum directionality:

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

- Corresponding ratio of left/right photon fluxes:

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



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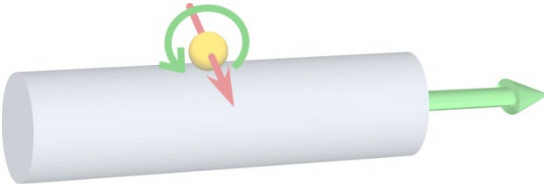

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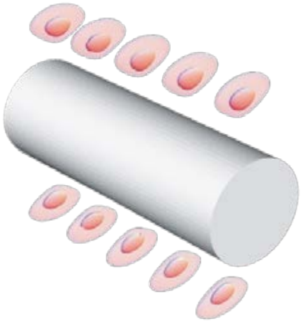

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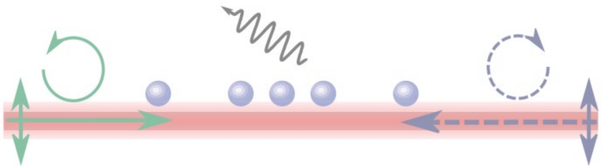
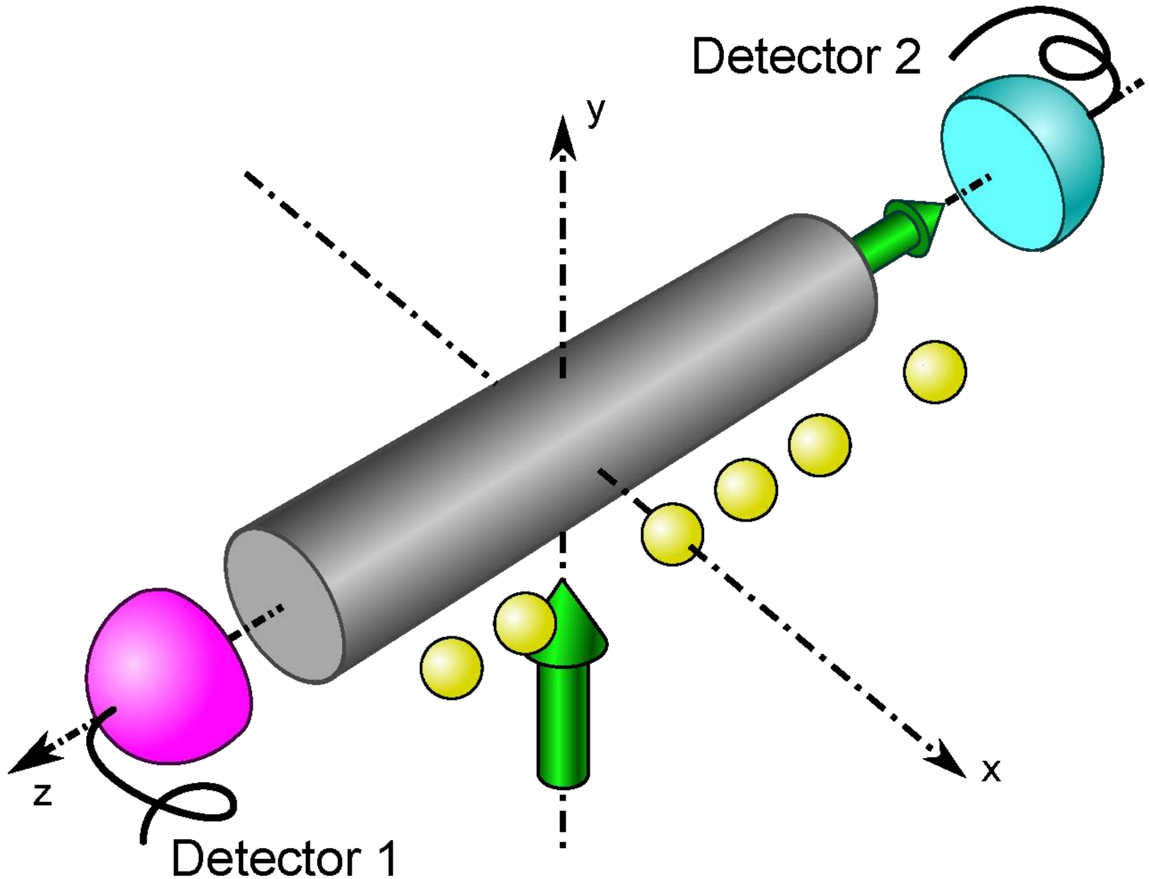


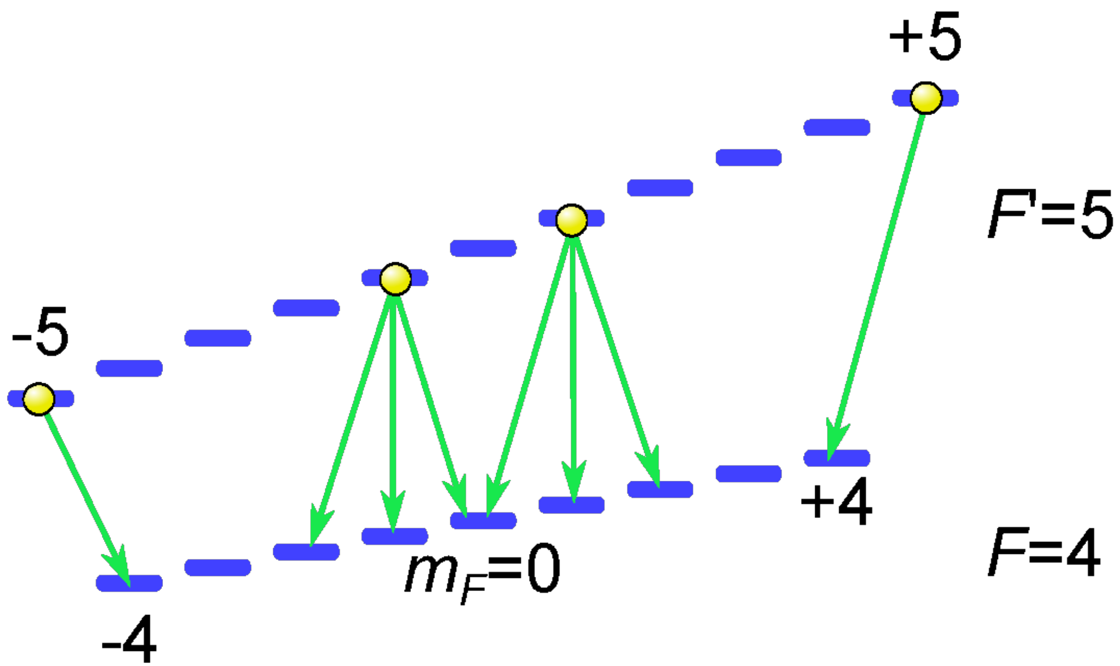
Experimental Set-Up

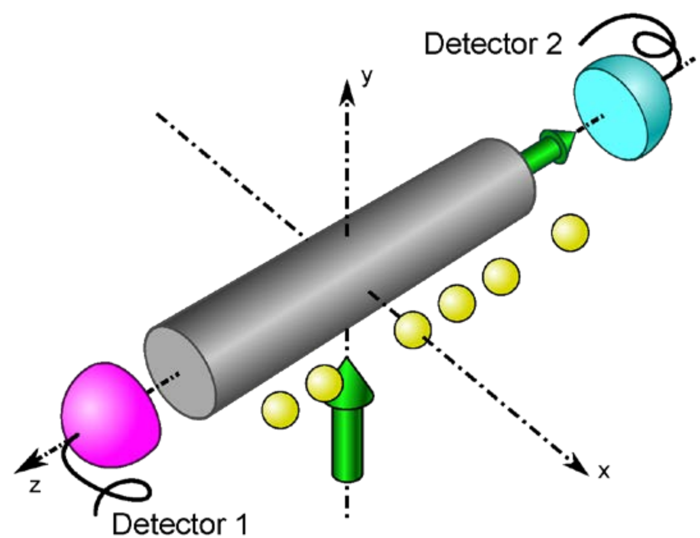
Nanofiber with cesium atoms on one side



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

Cesium D2-Line Level Scheme





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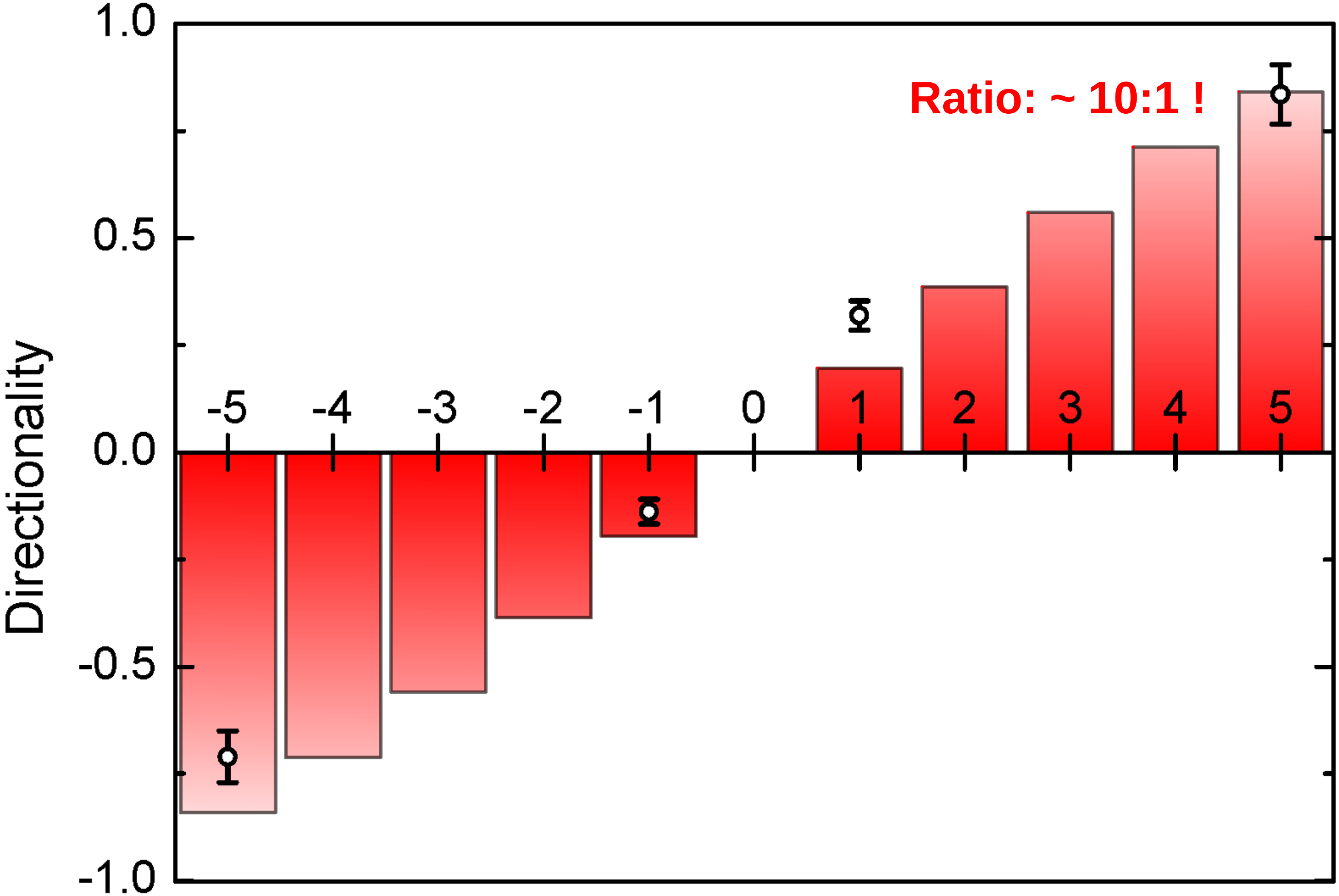
Directional Atom-Waveguide Interface

Quantum state-controlled directional spontaneous emission



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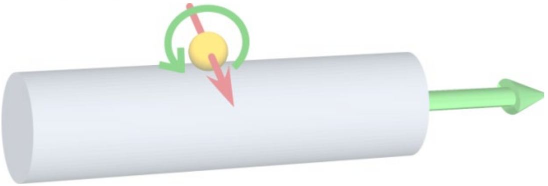

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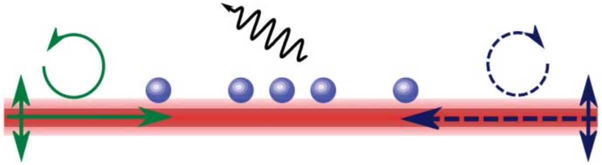
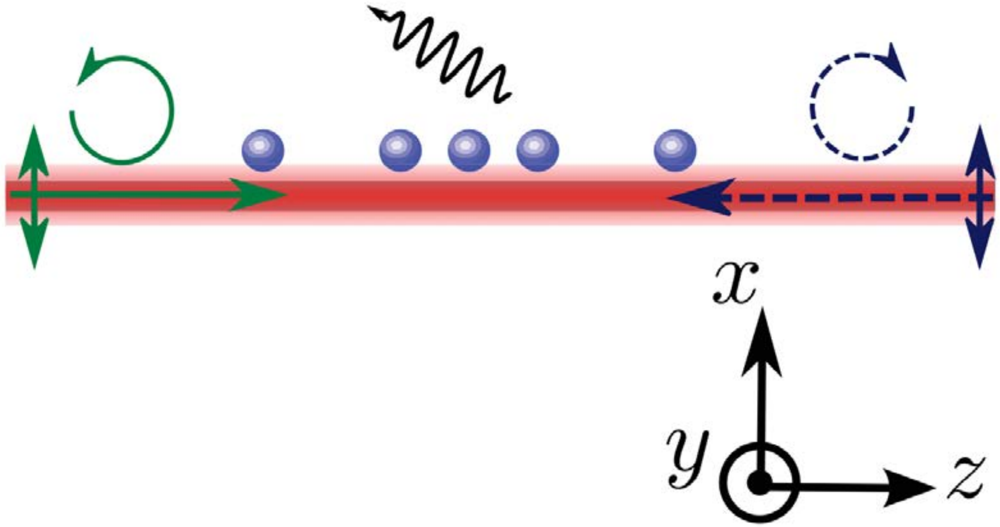


Experimental Set-Up

Nanofiber with spin-polarized atoms on one side



C. Sayrin et al., arXiv:1502.01549 (2015)

Nonreciprocal nanophotonic waveguide

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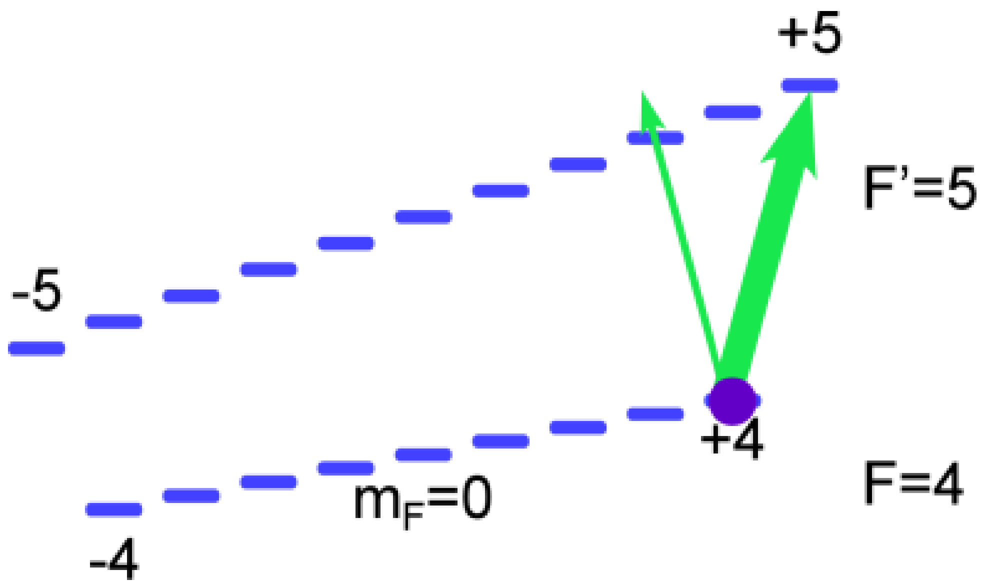

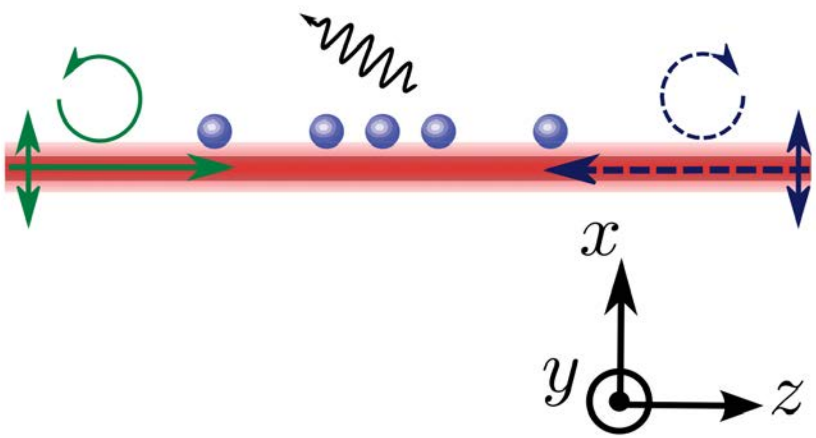

- Forward (backward) transmission of 78 % (13 %).
- Isolation of 8 dB.
- Data agrees with prediction for $\langle N \rangle = 27$ atoms.

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Nonreciprocal nanophotonic waveguide

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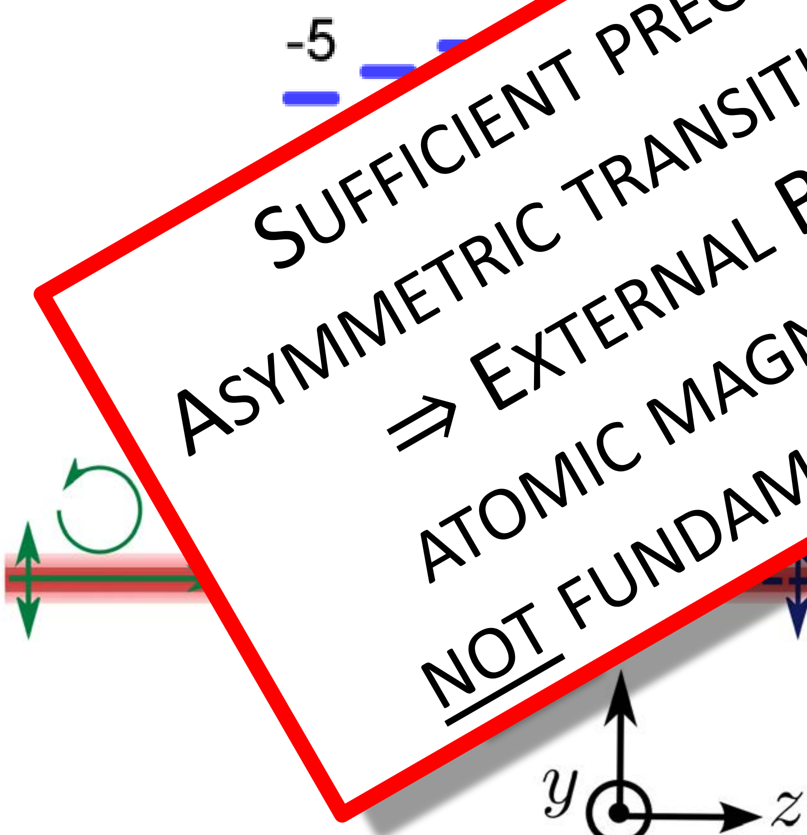

Sufficient precondition:
Asymmetric transition strengths
⇒ External B-field and
atomic magnetic moment
<u>Not</u> fundamentally required

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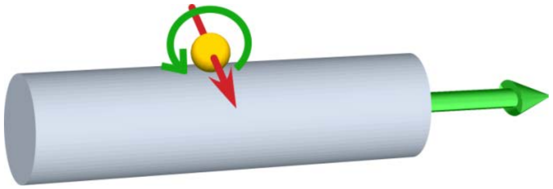
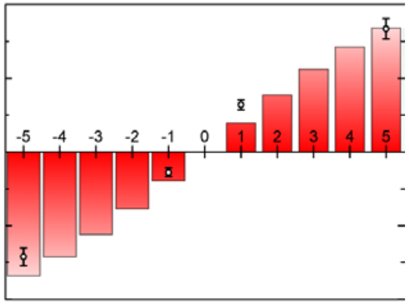
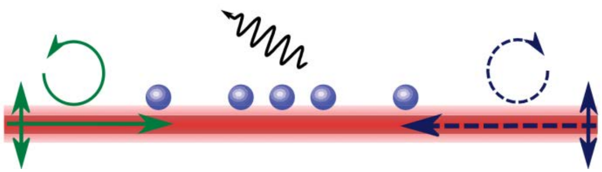
Summary

- 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 analogue of microwave ferrite resonance isolators
  - High isolation and forward transmission







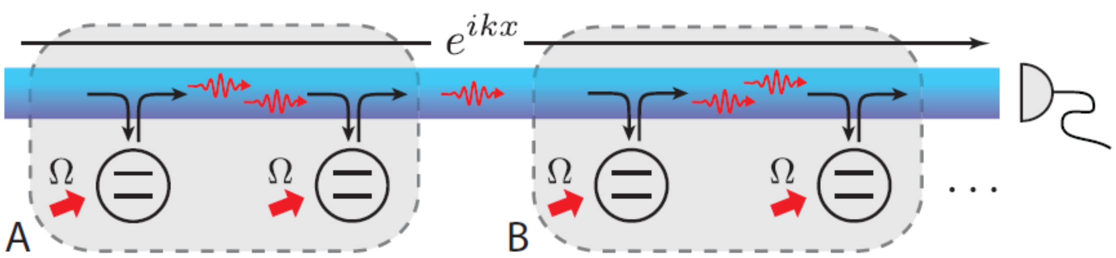
Perspectives

Optical signal processing and routing of light

Nanophotonic sensors for detecting and identifying scatterers with intrinsic polarization asymmetry

Revisit "one-dimensional atom" ⇒ qualitatively new effects

Collective emission creates pure entangled state



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

Thanks…

Students: Bernhard Albrecht, Martin Blaha, Benjamin Fränkel, Jakob Hinney, Yijian Meng, Adarsh Prasad, Daniel Reitz, Samuel Rind, Hardy Schauffert, Michael Scheucher, Stefan Walser, Elisa Will

Group Technician: Thomas Hoinkes

Postdocs & Senior Scientist: Christoph Clausen, Adèle Hilico, Pham Le Kien, Sarah Skoff, Philipp Schneeweiß, Jürgen Volz

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Funding

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Thank you for your attention!