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Revisiting Light-Matter Interaction in Quantum Nanophotonics

Quantum Science Seminar
July 2, 2020

Arno Rauschenbeutel
Department of Physics, Humboldt-Universität zu Berlin, Germany

Introduction – Nanophotonic Devices

Optical technologies

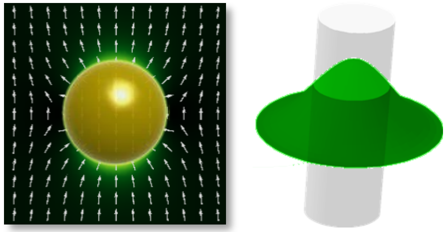
size $\gg \lambda$

Geometrical optics

size $\sim \lambda$

Diffraction
Interference

size $< \lambda$

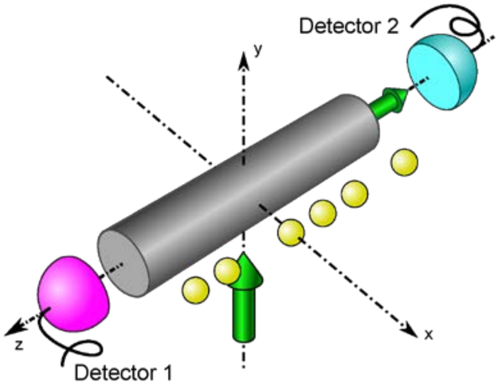


Nanophotonics

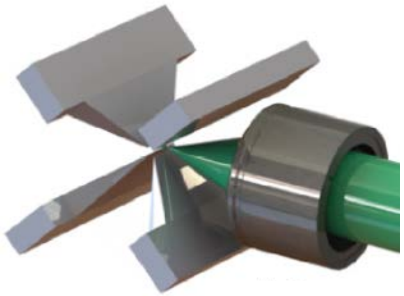
λ: operating wavelength

Overview

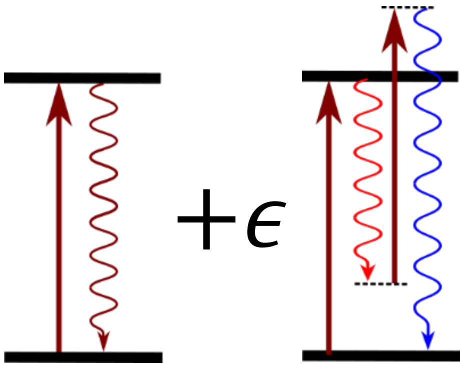
- Chiral Nanophotonic Waveguide Interface



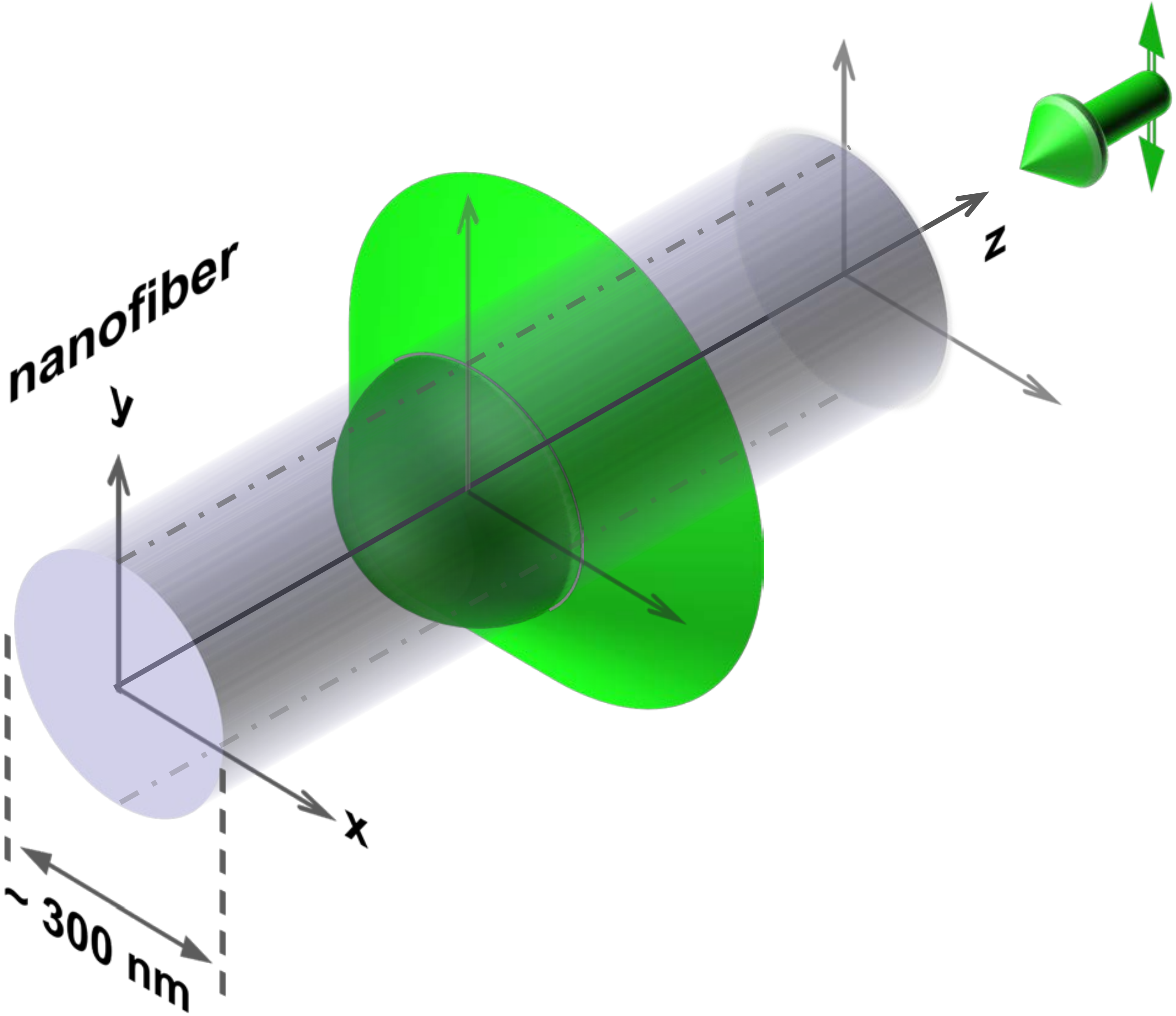
- Seeing a Single Atom Where it Is Not



- Correlating Photons Using the Collective Nonlineary of Weakly Coupled Atoms



Introduction – Guided Light in Nanofibers



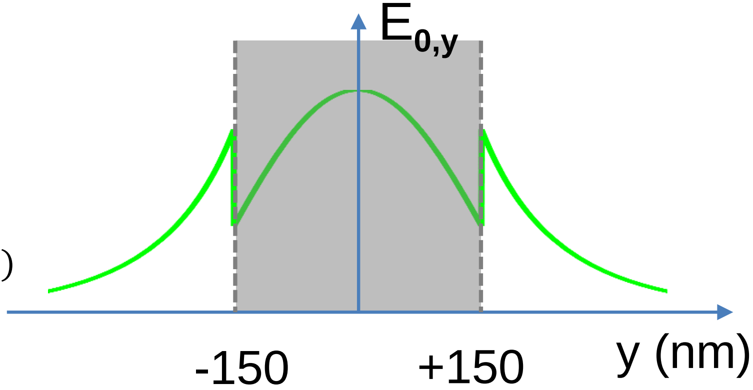
Introduction – Guided Light in Nanofibers

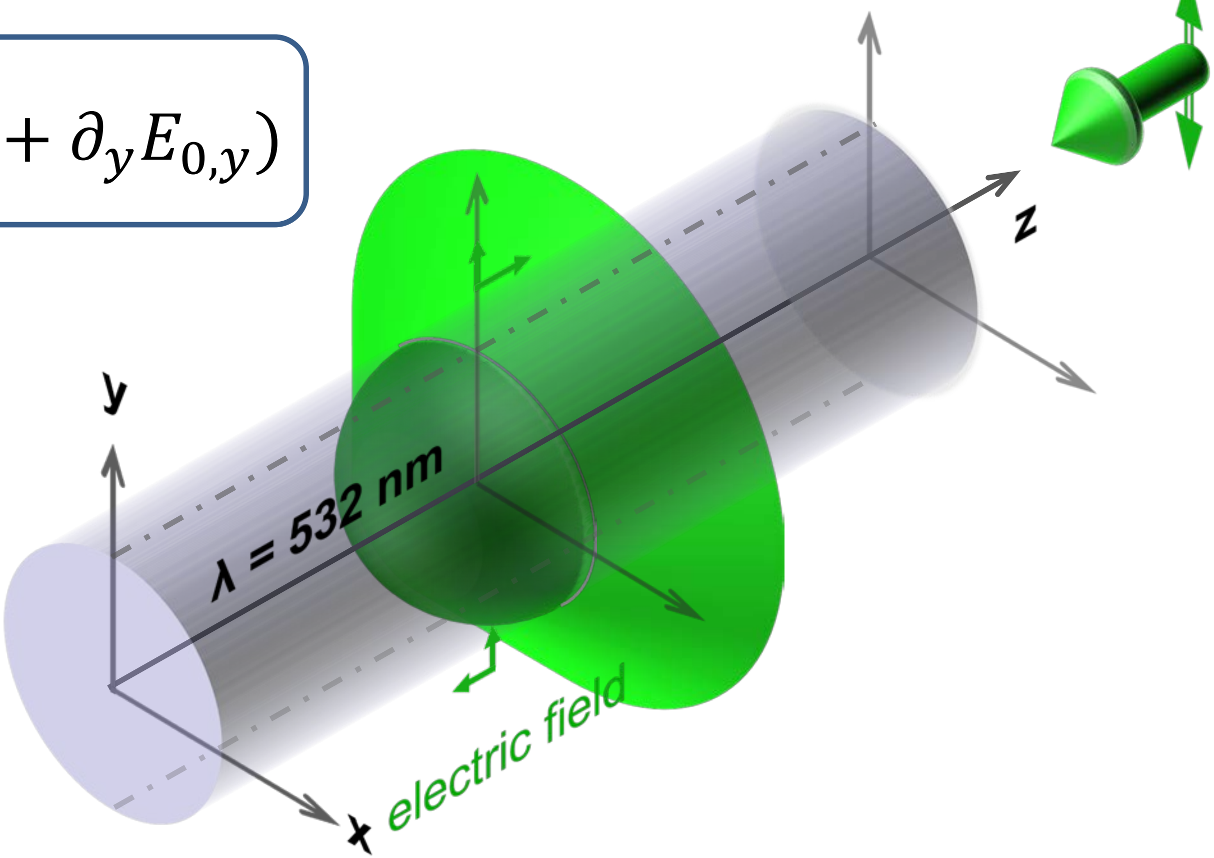
- Gauss‘s law

$$\partial_x E_x + \partial_y E_y + \partial_z E_z = 0$$

with $\vec{E} = \vec{E}_0(x,y)\, e^{i(kz-\omega t)}$

$$E_{0,z} = i\,\frac{\lambda}{2\pi}\left(\cancel{\partial_x E_{0,x}} + \partial_y E_{0,y}\right)$$





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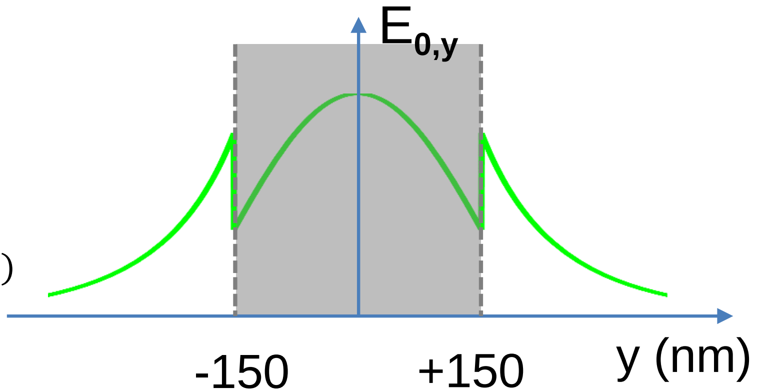
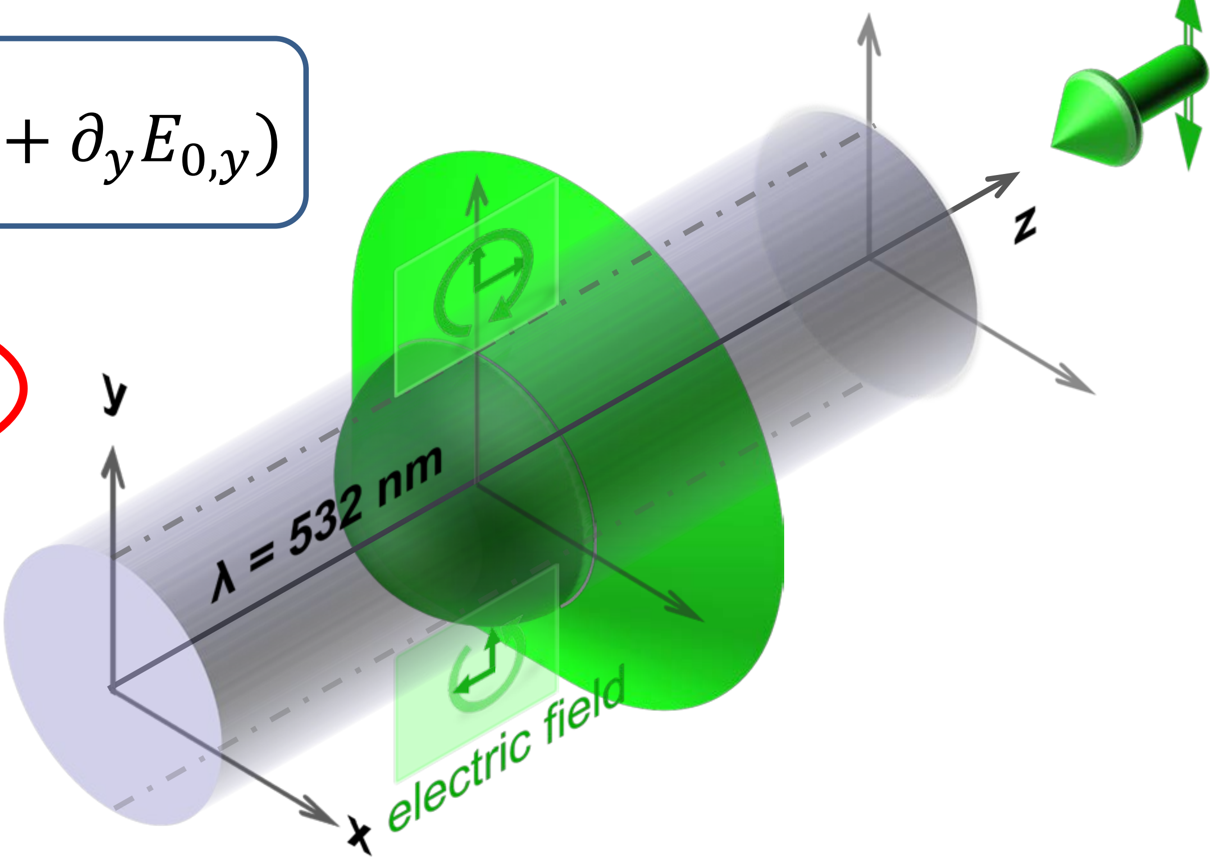
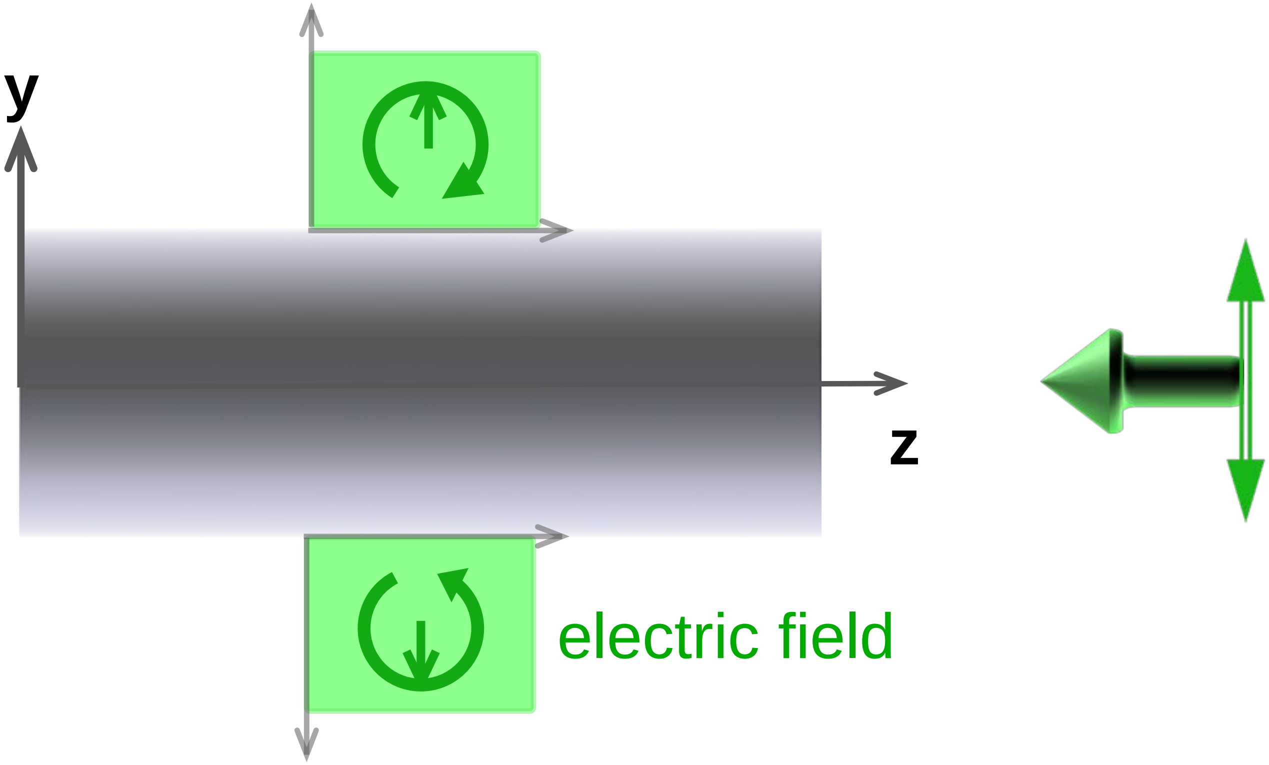
oscillates 90° out of phase!!





Intro – Spin-Orbit Coupling of Light



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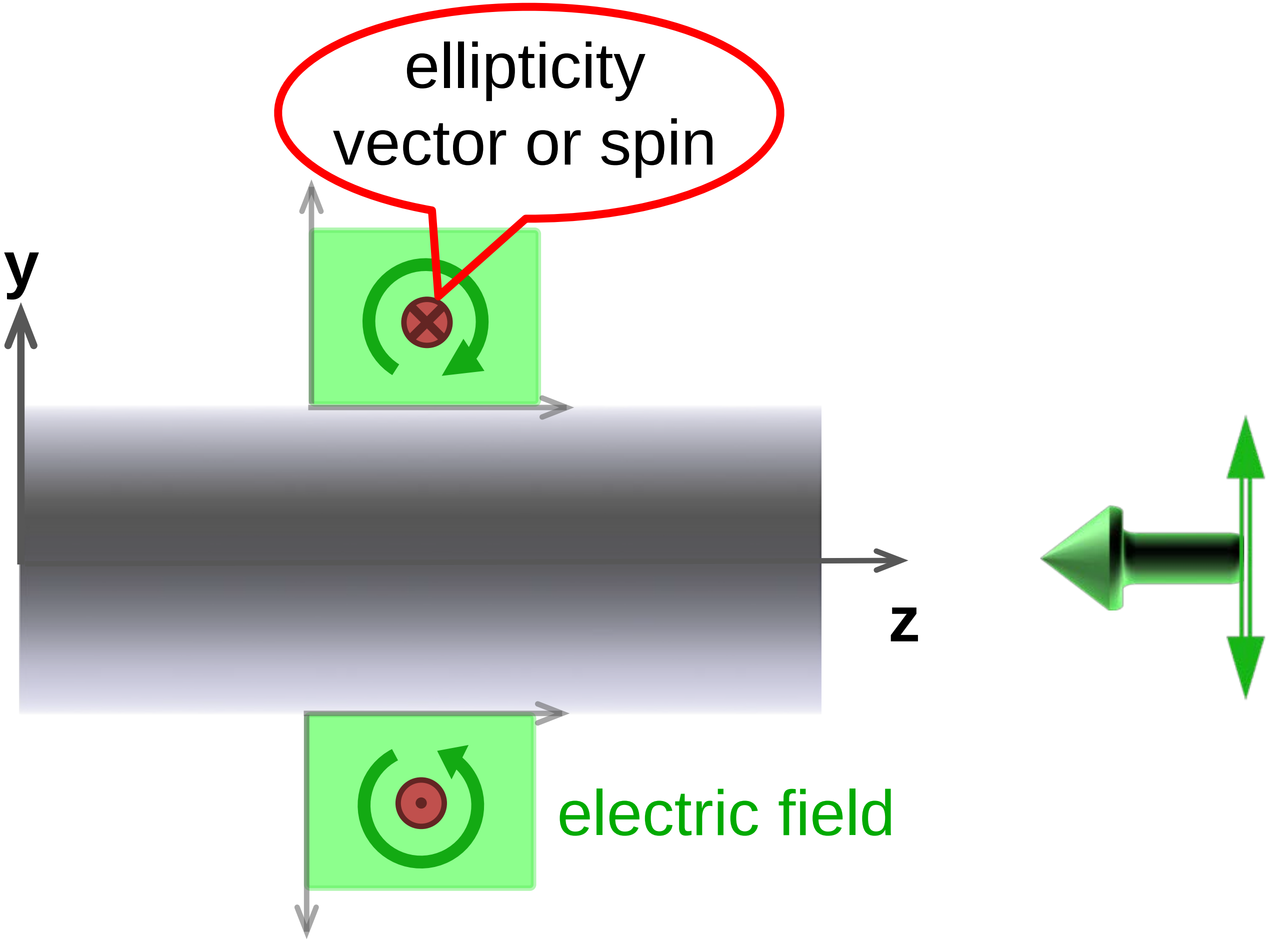
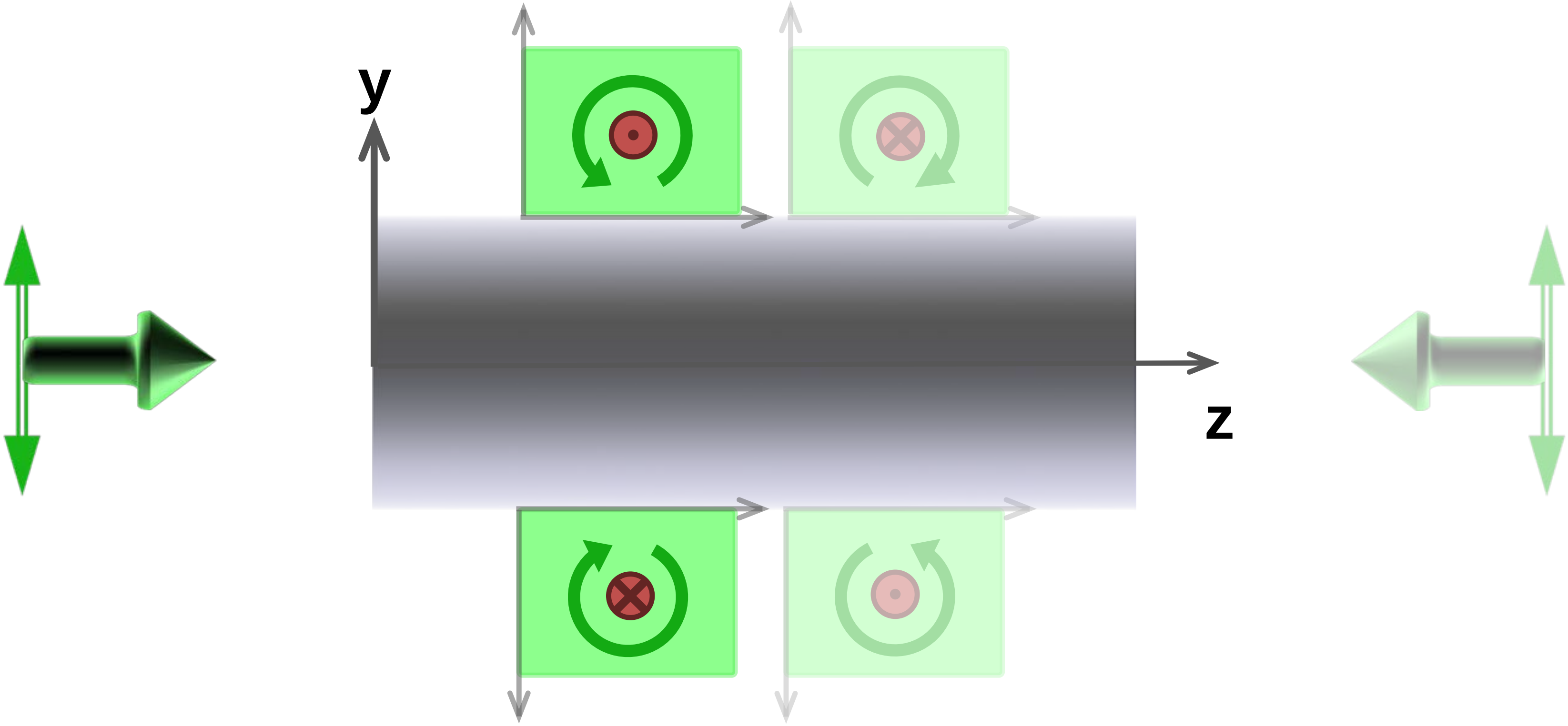


➡ Local spin depends on transverse position

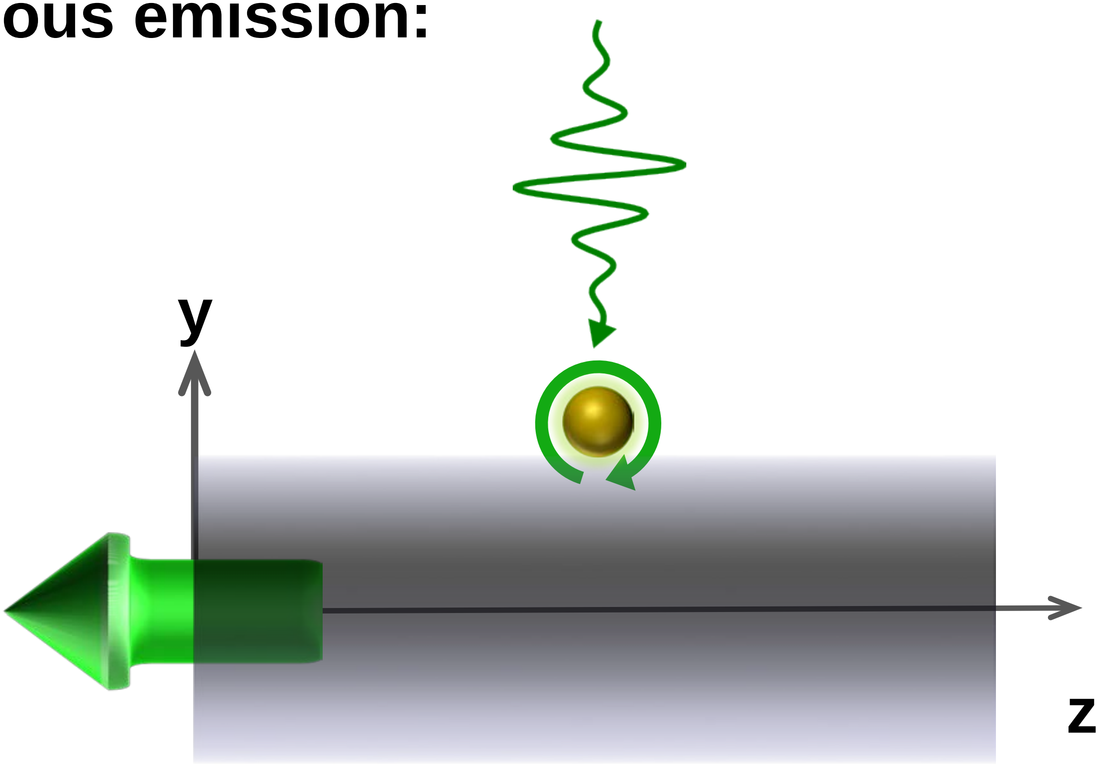
Intro – Spin-Momentum Locking of Light



- Local spin depends on transverse position
- Local spin changes sign with **propagation direction**

Directional Spontaneous Emission

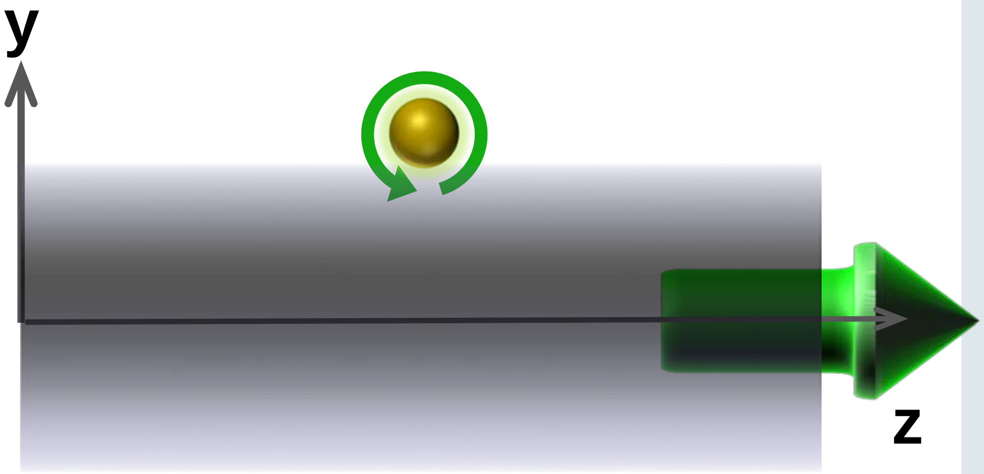
- **Effects on spontaneous emission:**
  - Place emitter on nanofiber surface
  - Optically excite it



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

Directional Spontaneous Emission

- **Effects on spontaneous emission:**
  - Place emitter on nanofiber surface
  - Optically excite it
  - Polarization defines direction of emission (chiral coupling)



  - Also see work by Capasso, Dayan, Fox, Kuipers, Lee, Leuchs, Lodahl, Martinez, Oulton, Rarity, Skolnick, and Zayats.

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

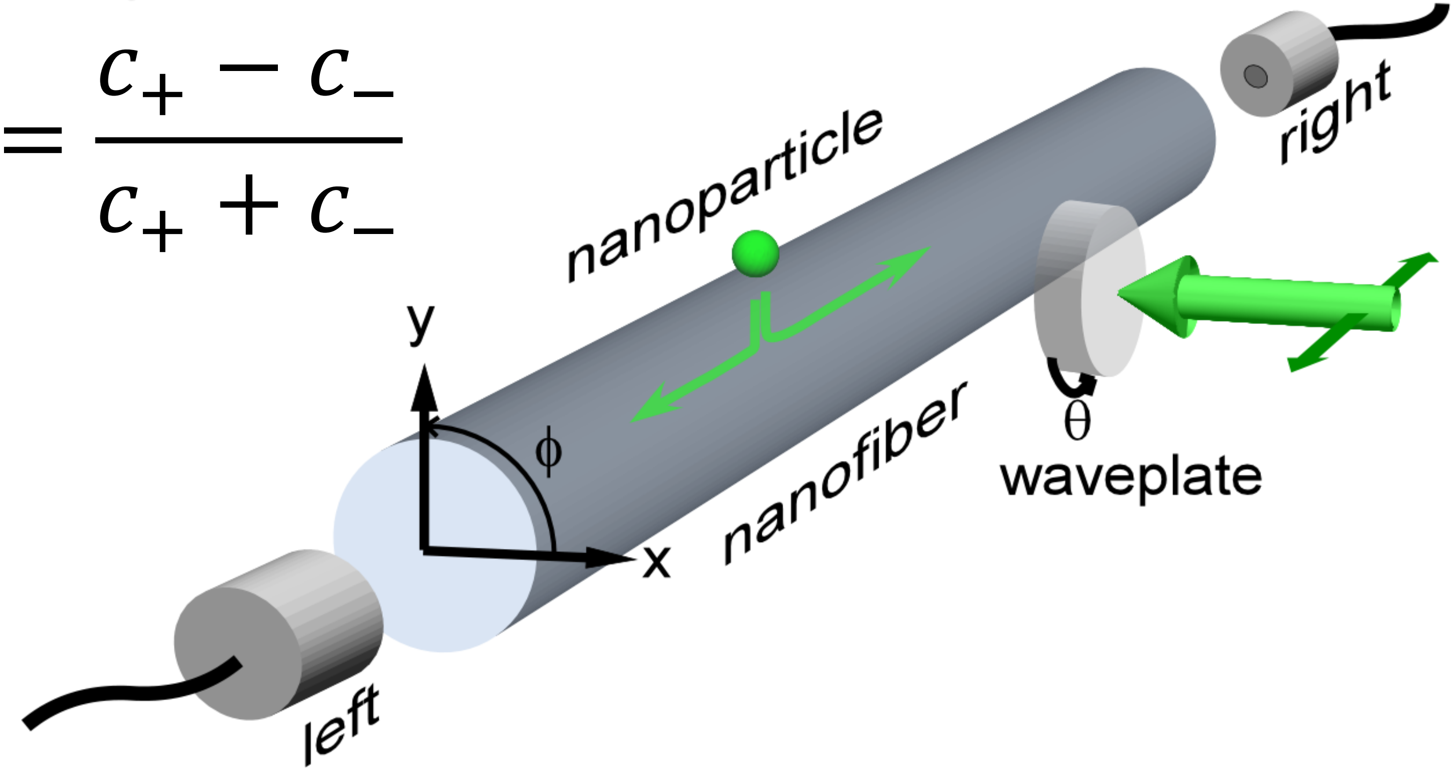
Experimental Set-Up

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:

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



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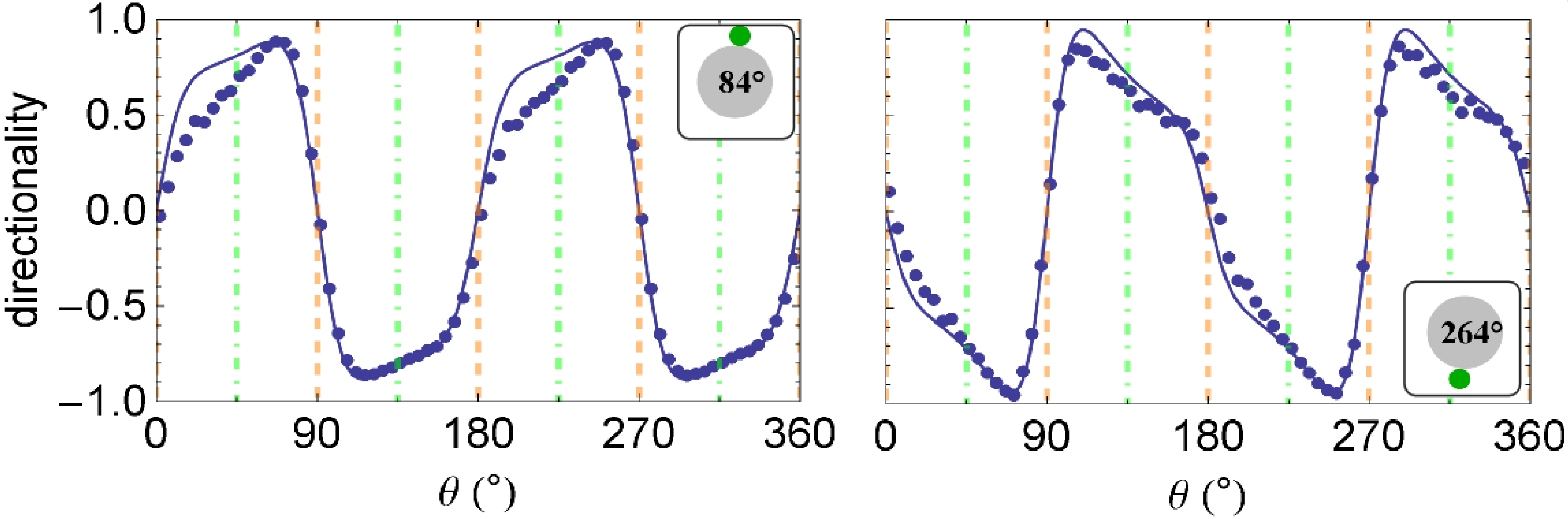
Chiral Waveguide Coupling



- Maximum directionality:

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

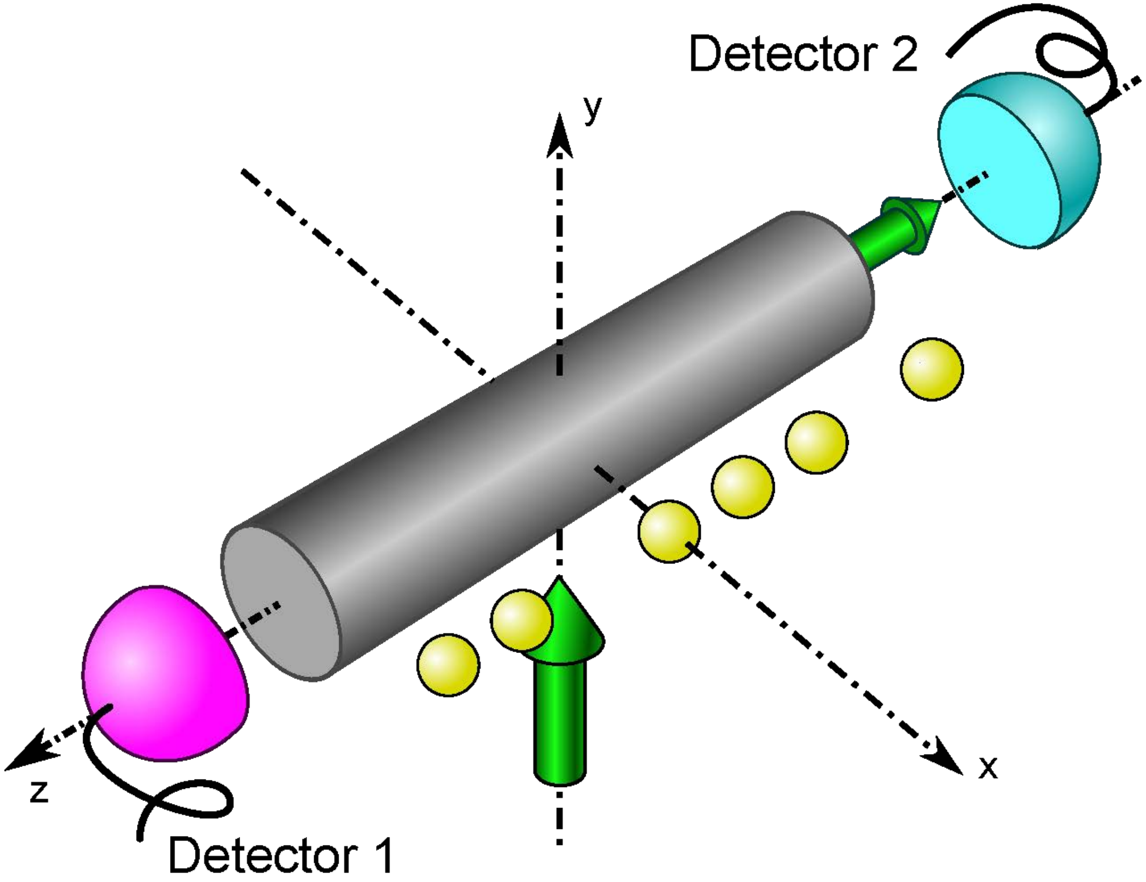
- Corresponding ratio of left/right photon fluxes:

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

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

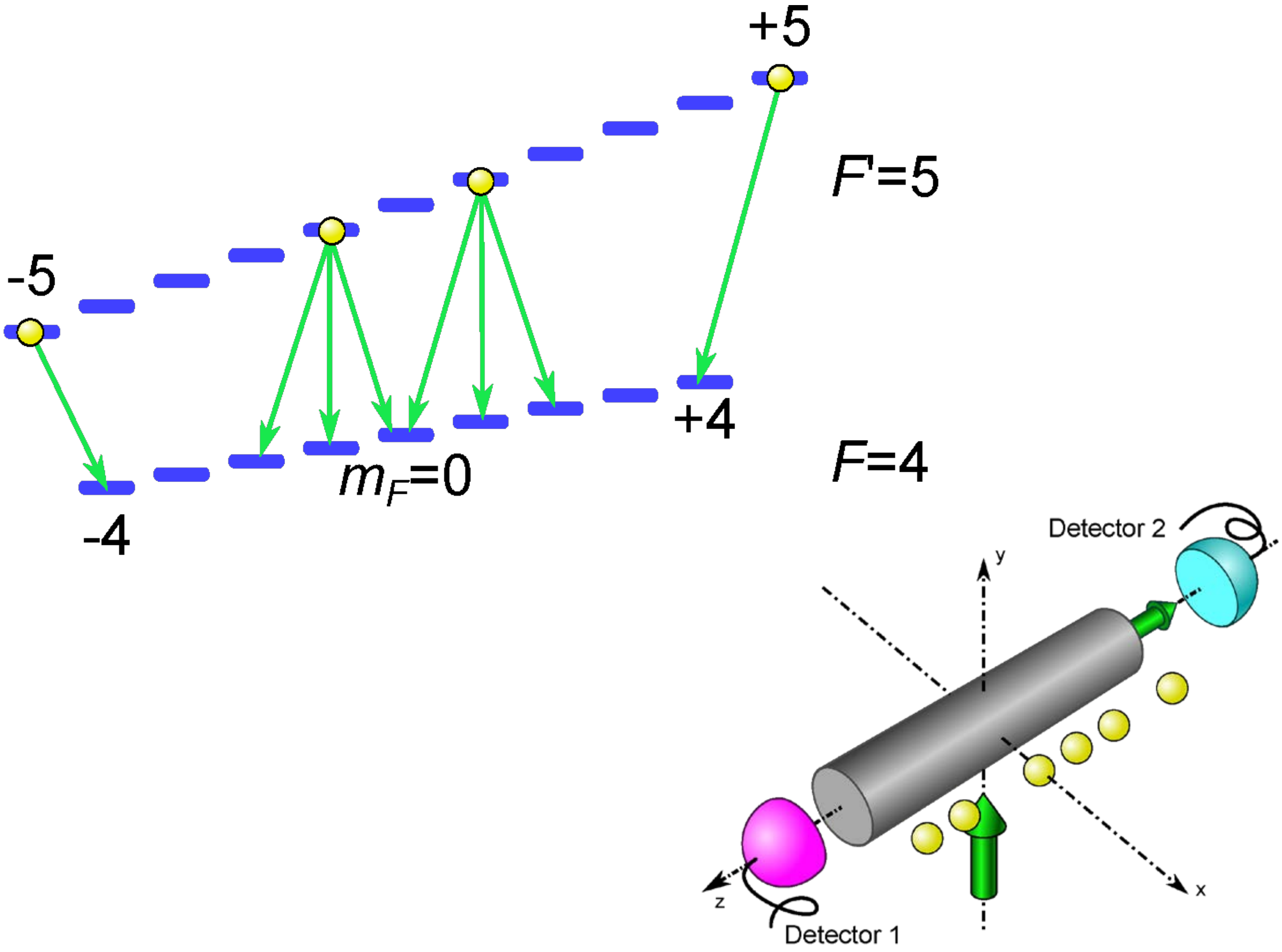
Experimental Set-Up

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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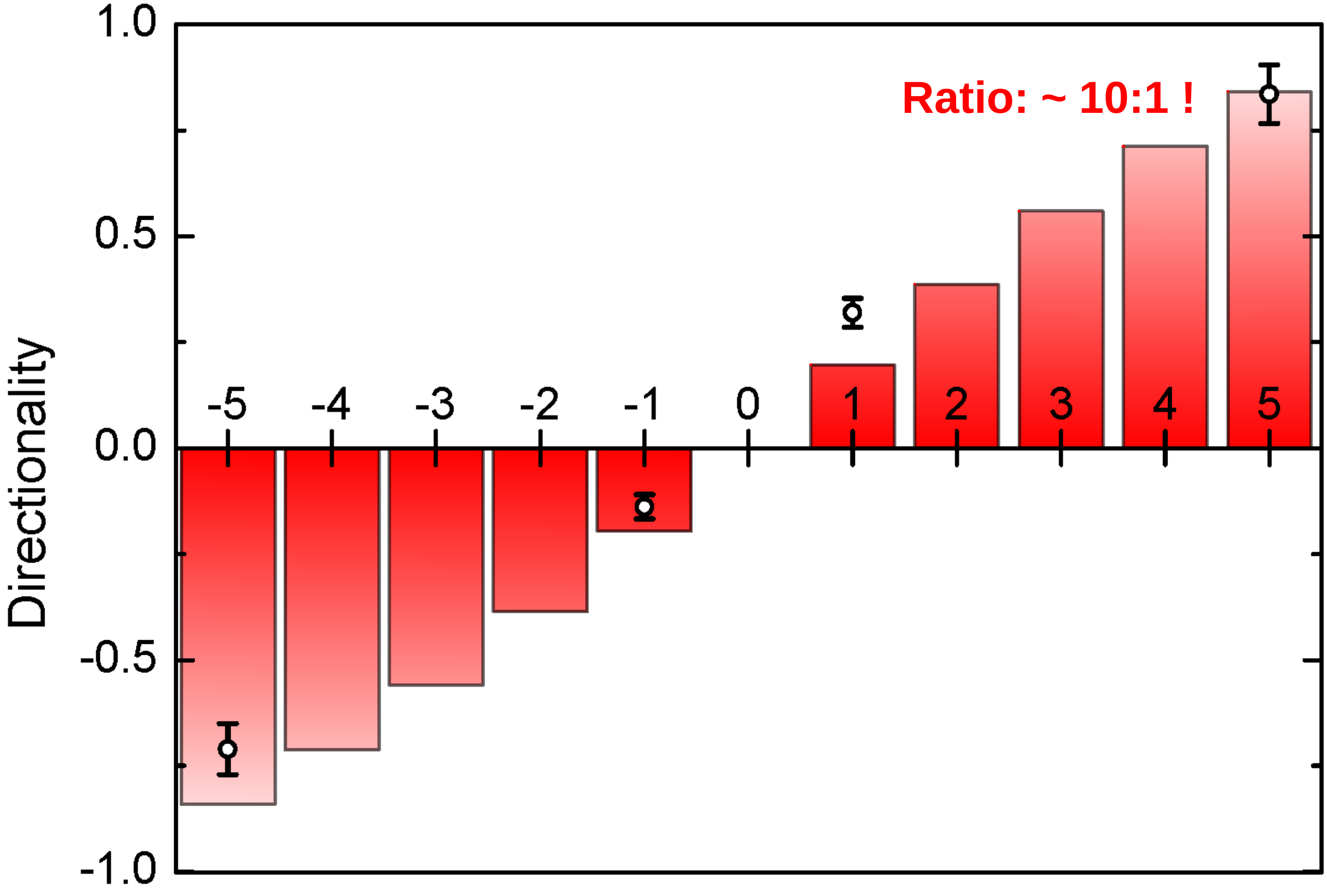
Directional Atom-Waveguide Interface

Quantum state-controlled directional spontaneous emission



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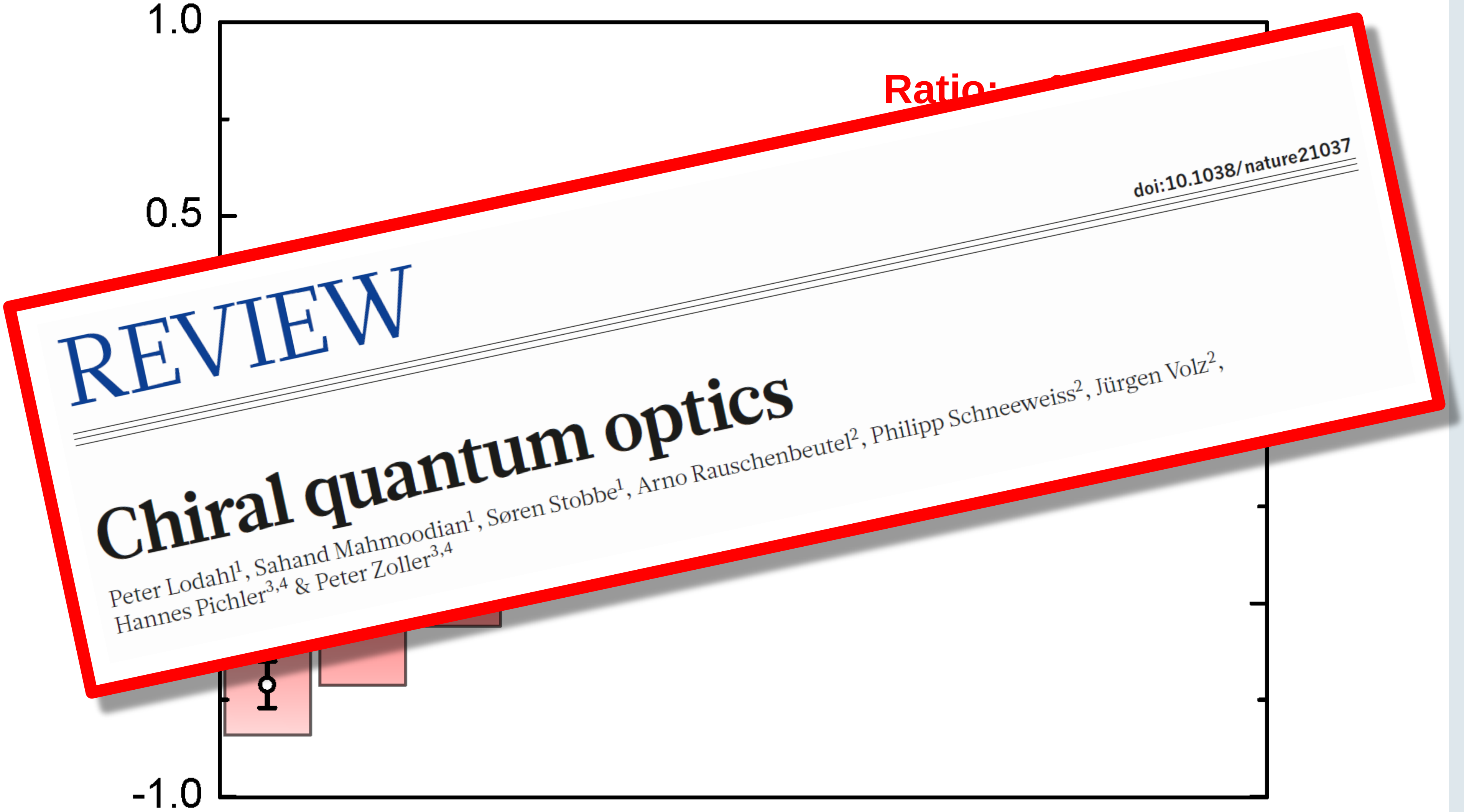

doi:10.1038/nature21037

REVIEW

Chiral quantum optics

Peter Lodahl[1], Sahand Mahmoodian[1], Søren Stobbe[1], Arno Rauschenbeutel[2], Philipp Schneeweiss[2], Jürgen Volz[2], Hannes Pichler[3,4] & Peter Zoller[3,4]

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

Thanks…

<u>Nanoplasmonic Emitter:</u> Jan Petersen and Jürgen Volz

<u>Cold Atom Experiment:</u> Clément Sayrin, Bernhard Albrecht, Rudolph Mitsch, and Philipp Schneeweiß

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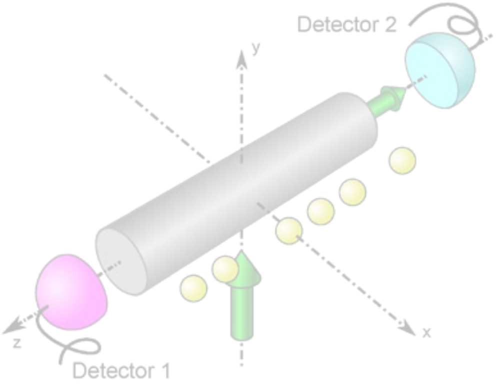

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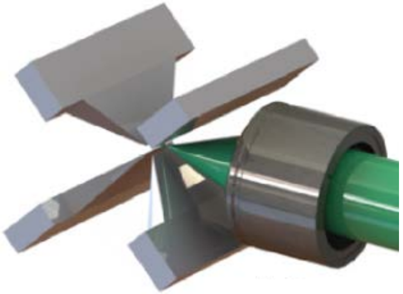

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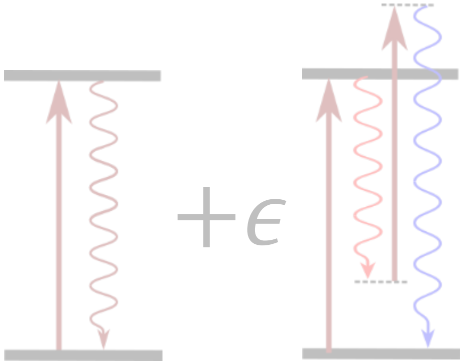
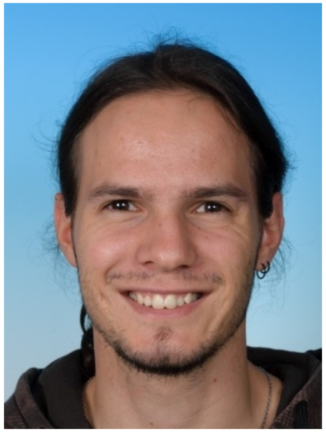


Thanks…

TU Wien:

University of Innsbruck:


Stefan Walser


Gabriel Araneda


Yves Colombe

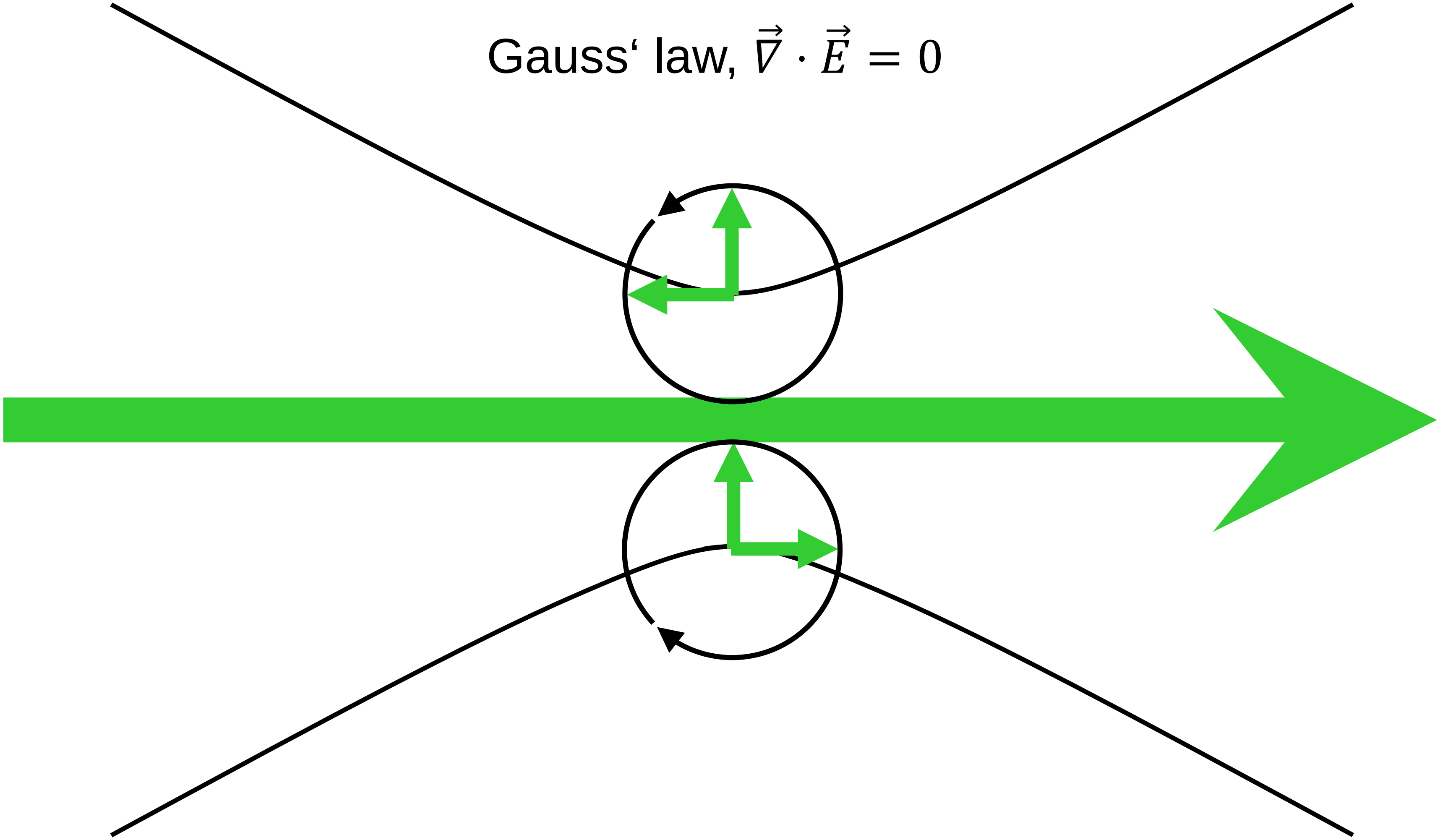

Jürgen Volz


Daniel Higginbottom
(ANU Canberra)


Rainer Blatt

Intro – Spin–Orbit Coupling in Free Space

- Linearly polarized propagating focused Gaussian mode



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

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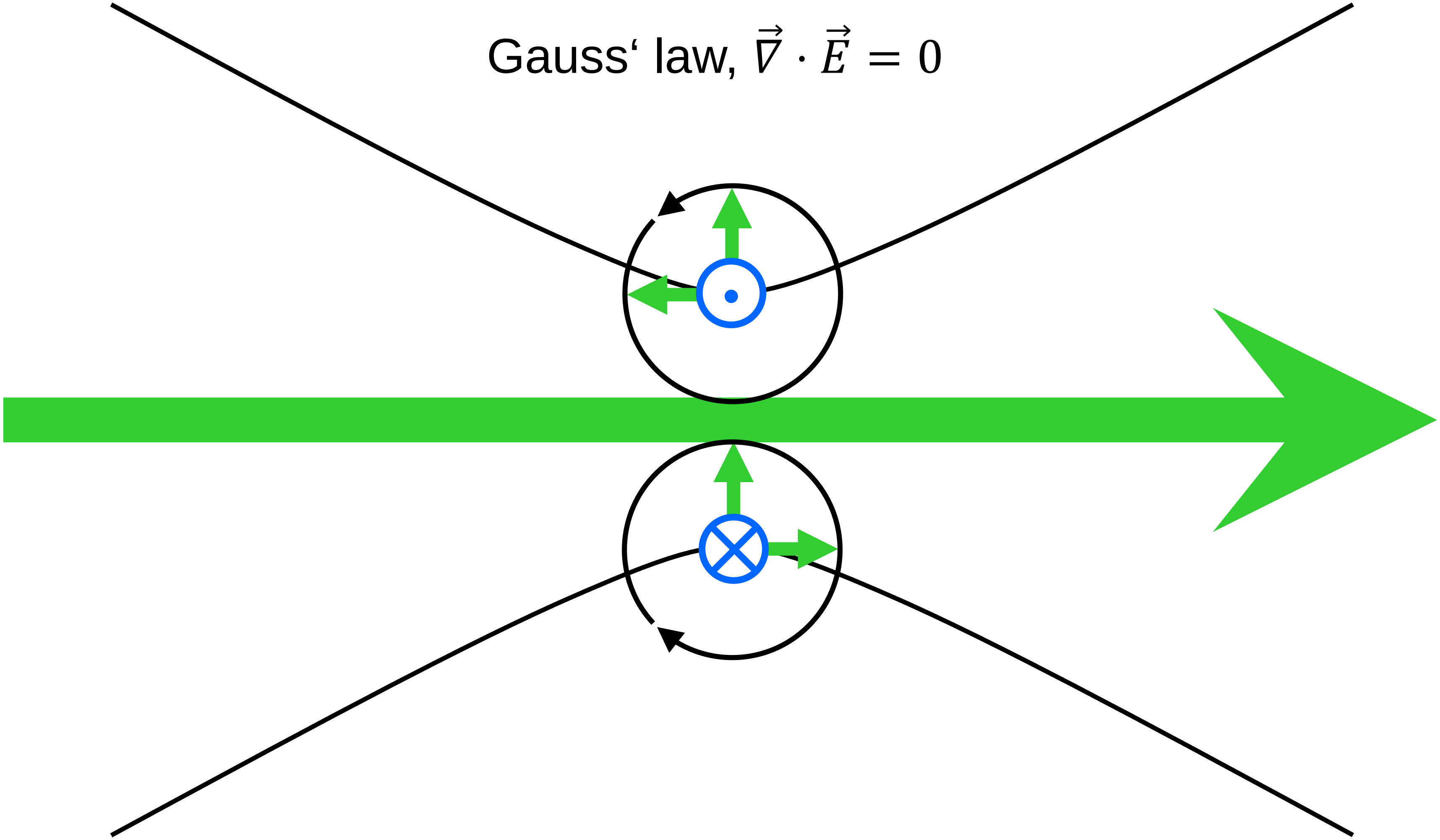

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⇒ Local ellipticity (or spin) depends on transverse position

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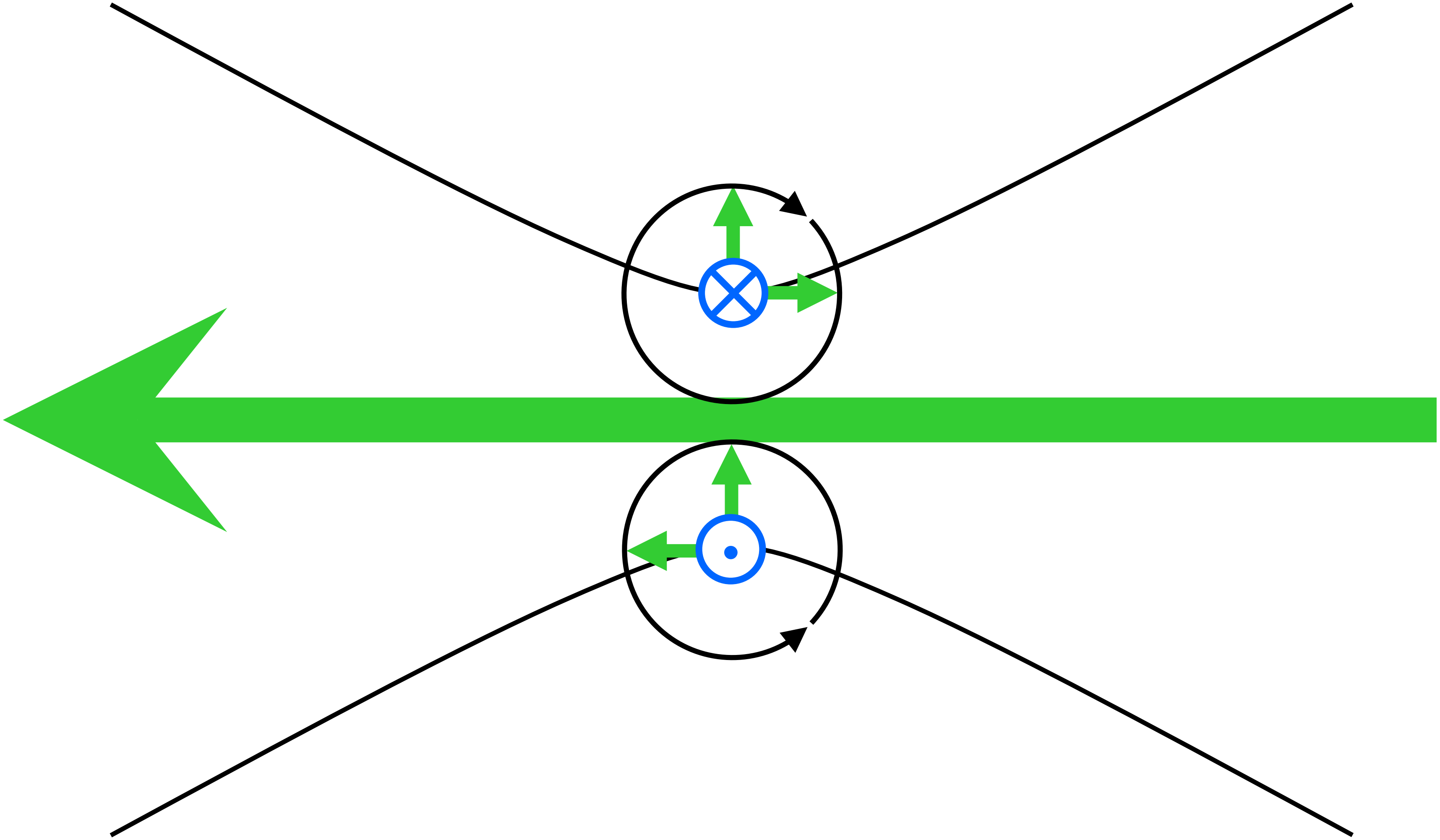
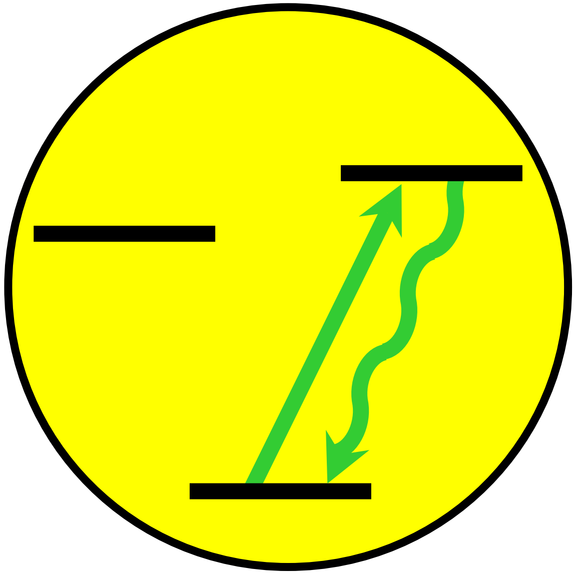


⇒ Local ellipticity (or spin) changes sign with direction of propagation

Chiral Coupling & Free Space Optics

- Driving a σ^+–transition w. r. t. transverse quantization axis:



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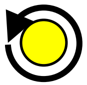

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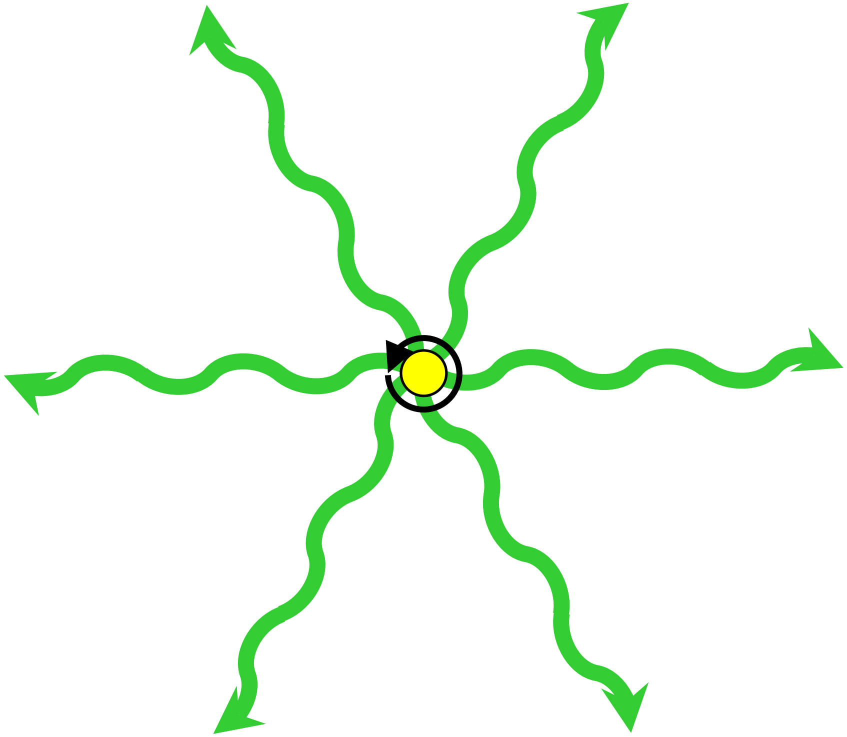
- Collecting fluorescence of a σ^+-polarized emitter:



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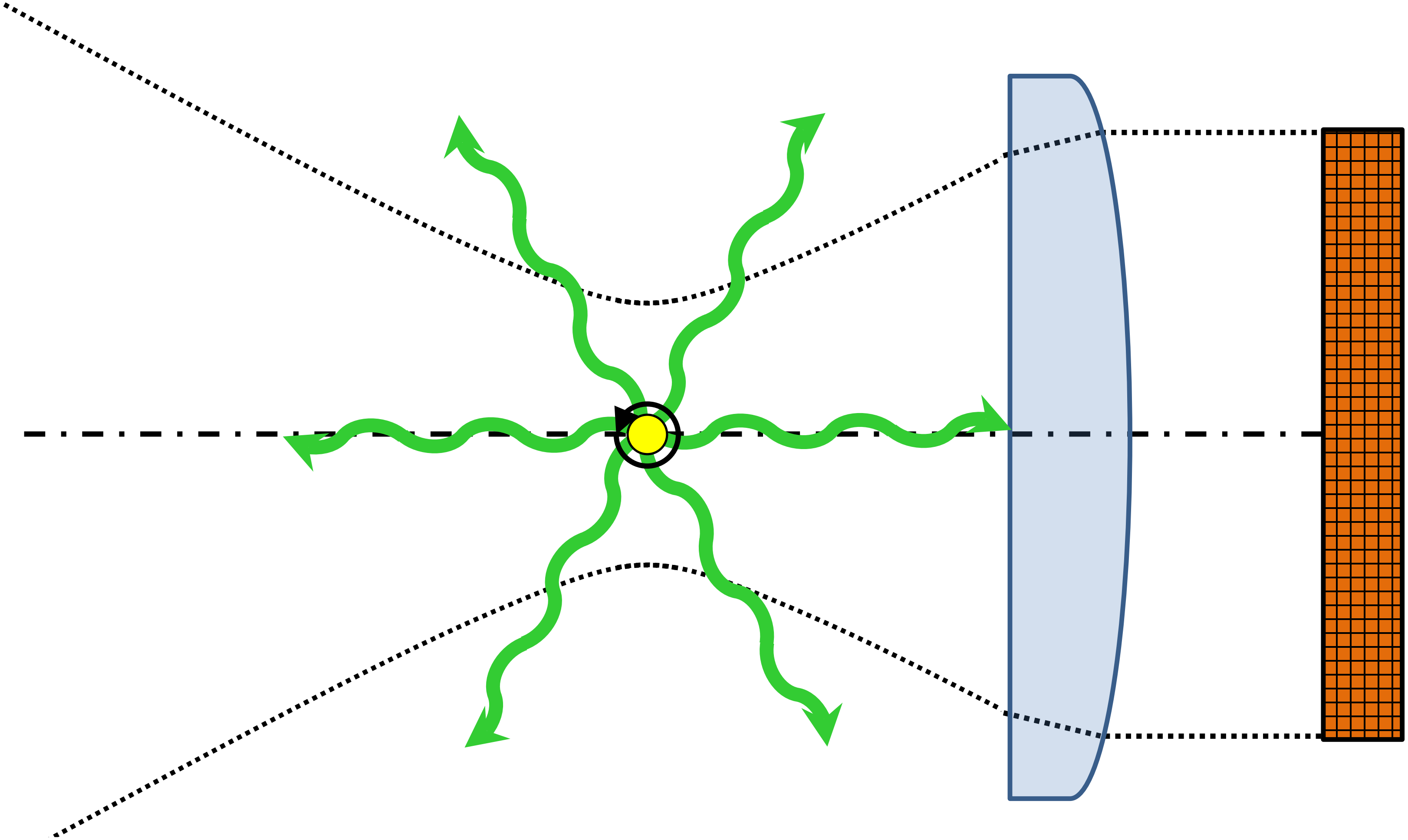

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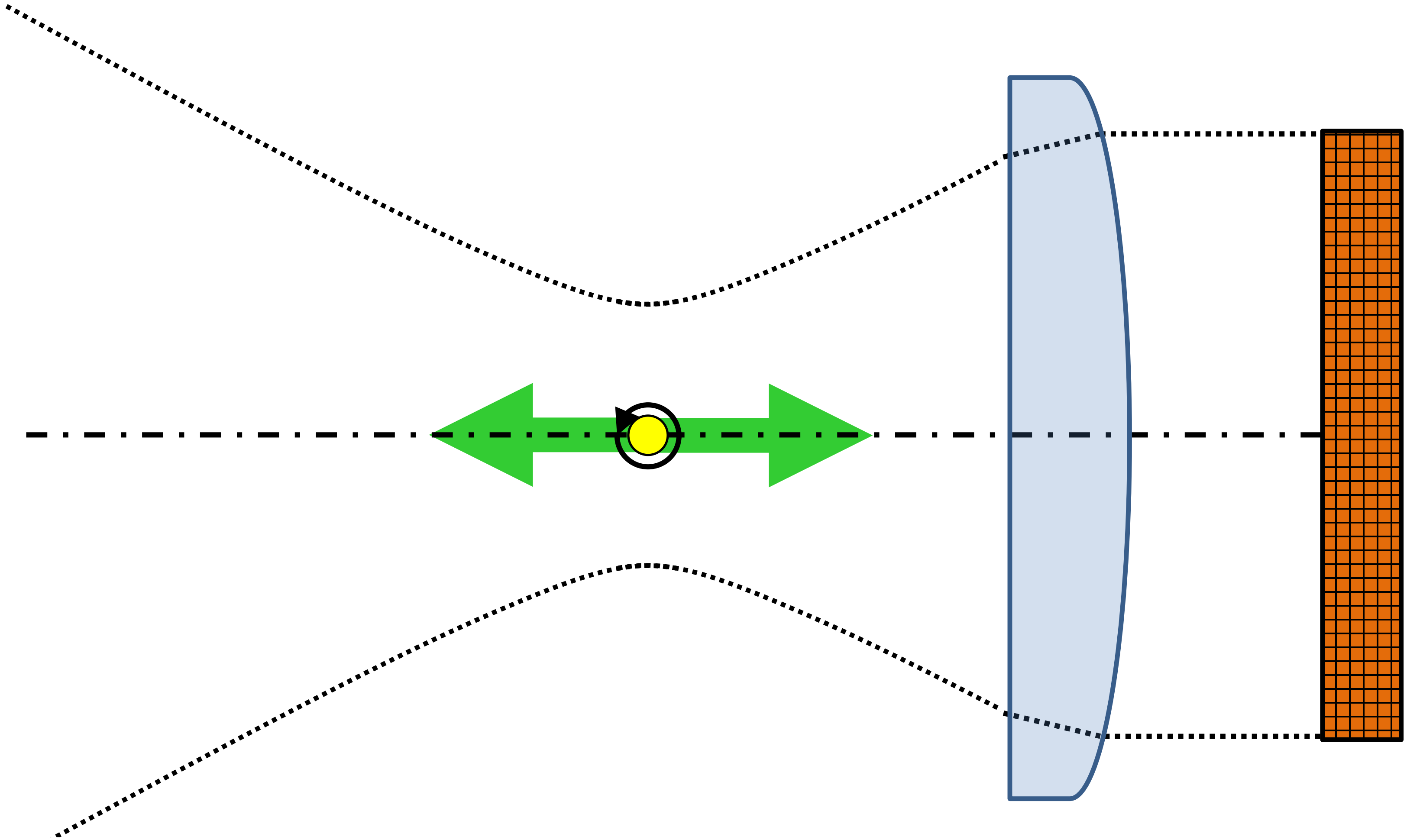

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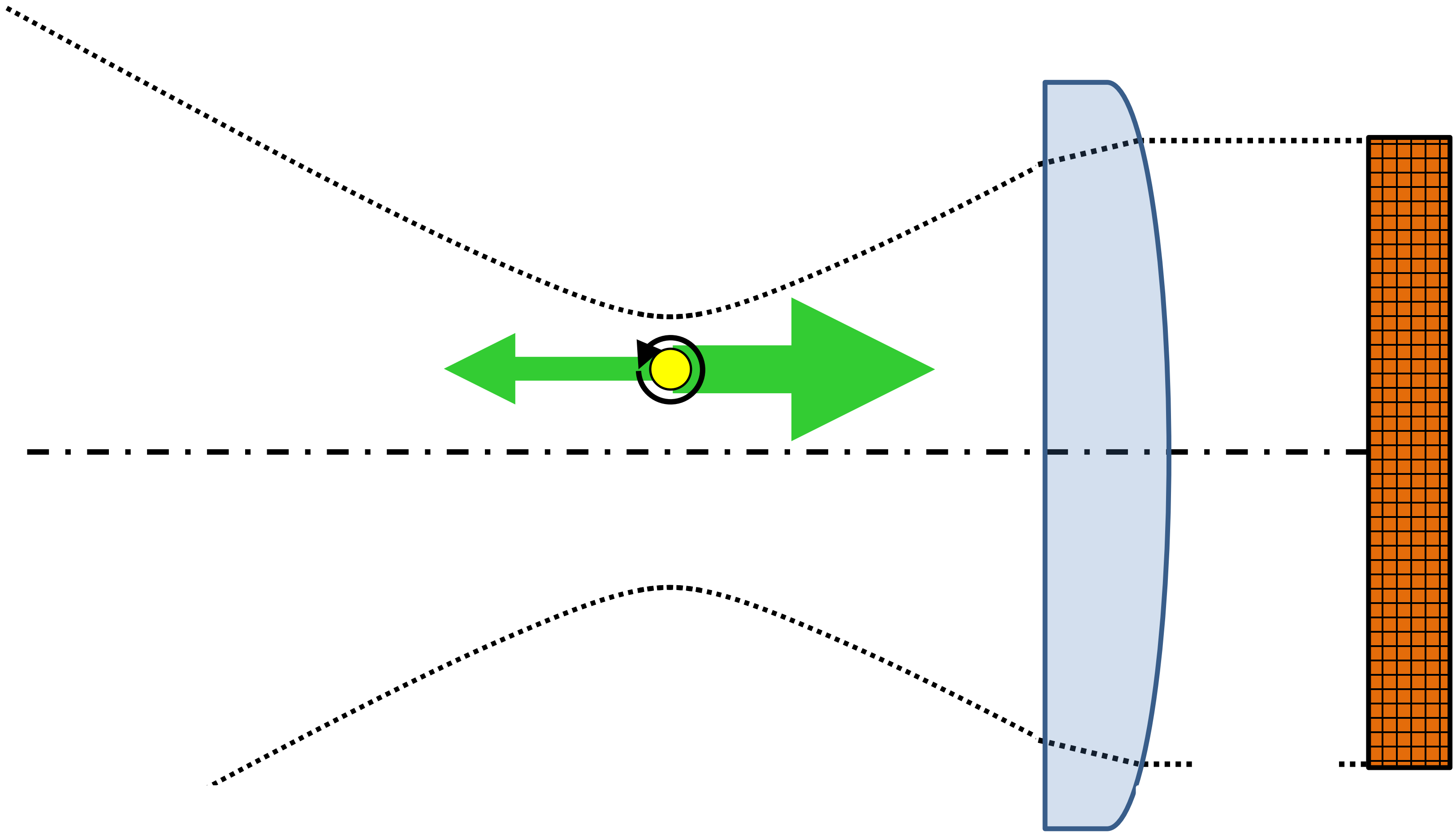

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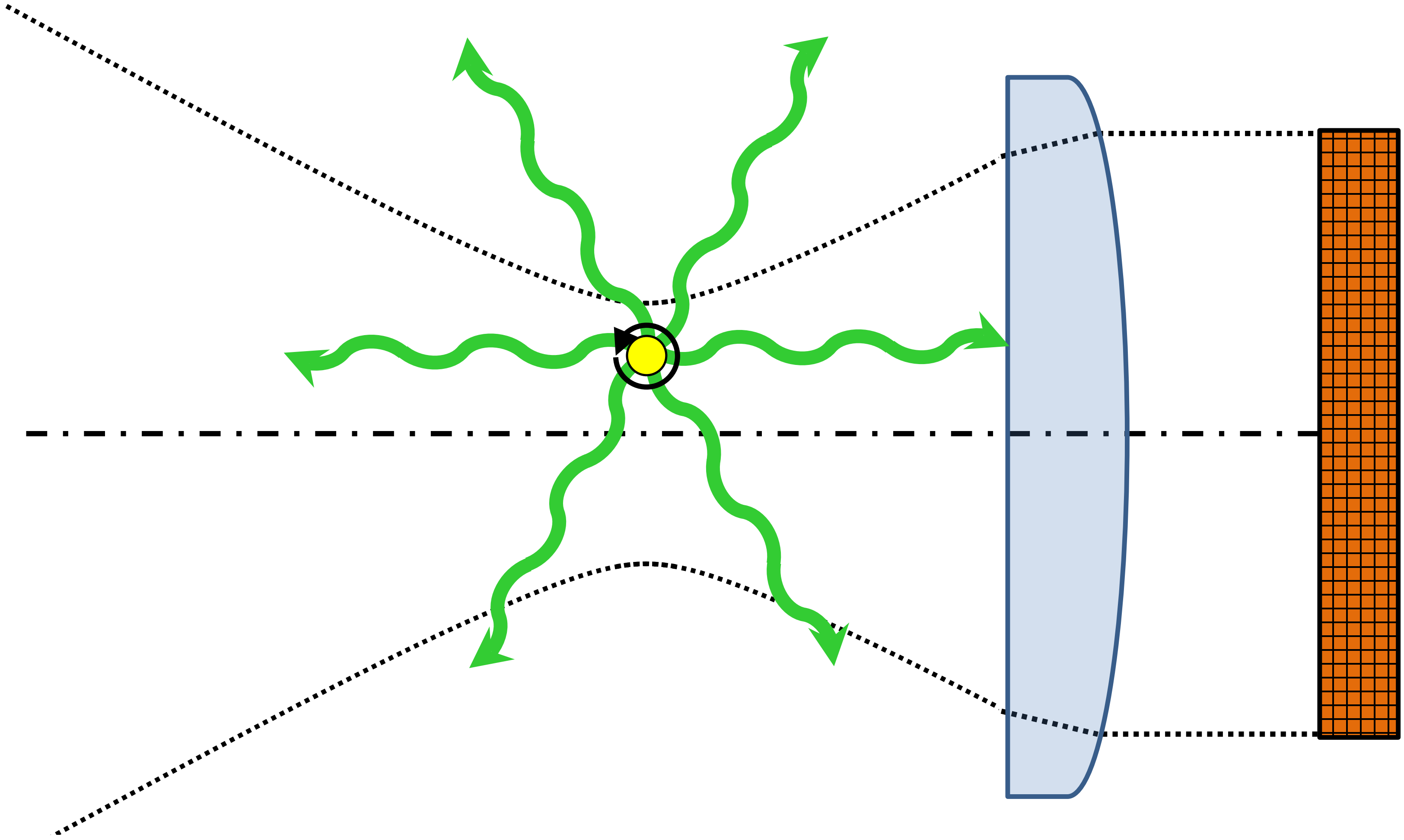

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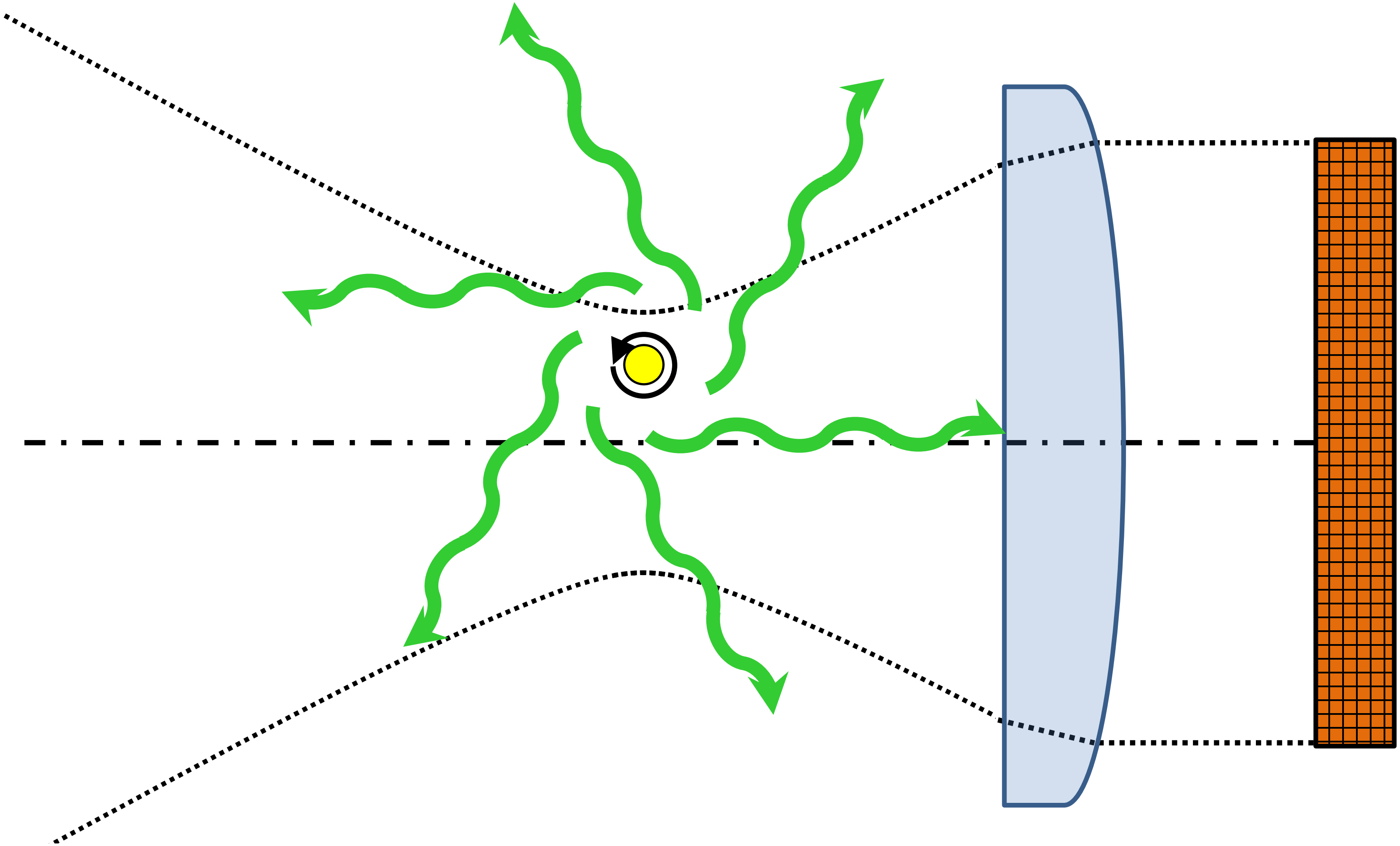


Chiral Effects in Imaging

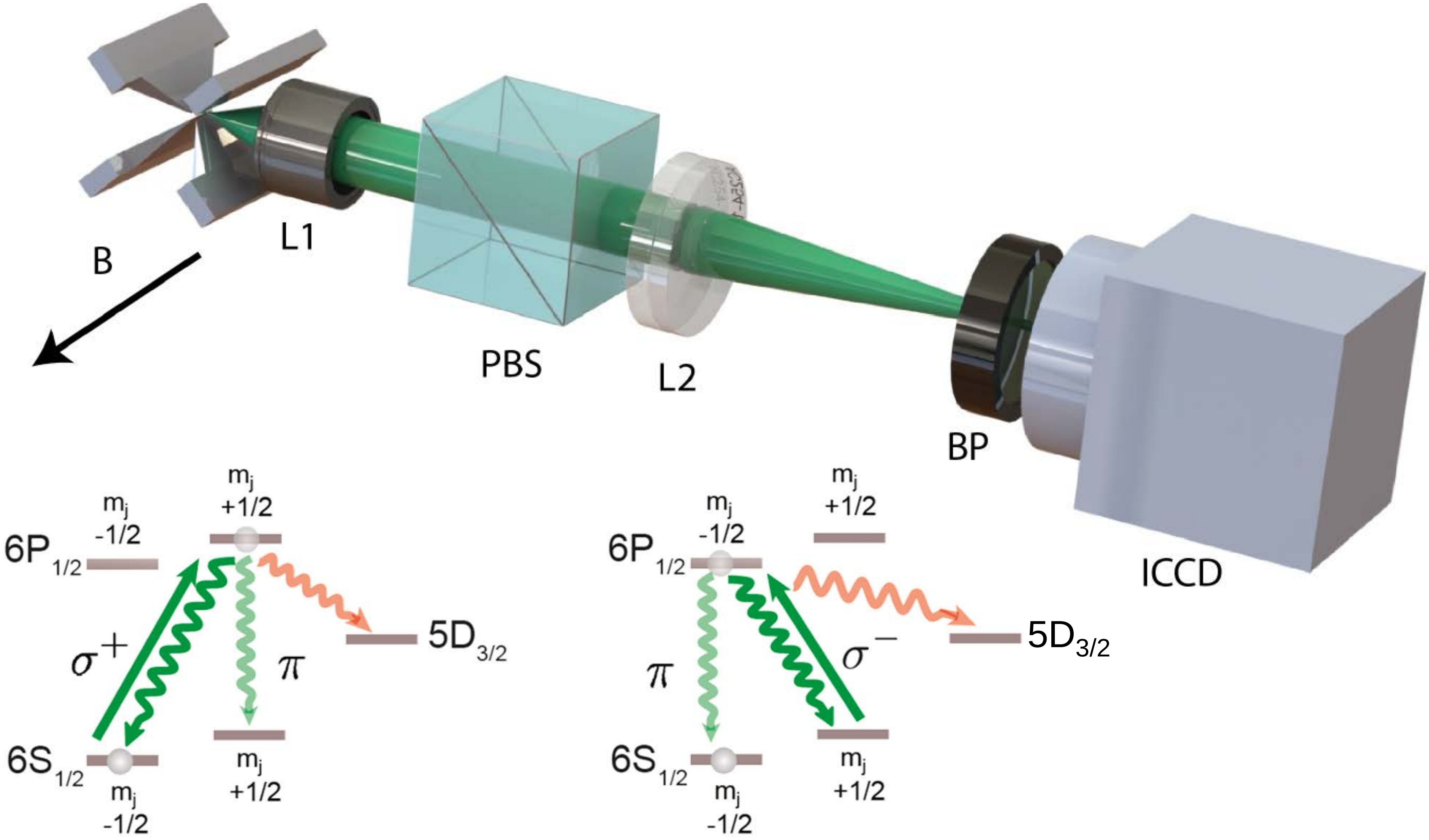
If we take the classical problem of an electron describing a small circle, we find that in addition to the terms in $1/r$ the electric force at a distance has others in λ/r^2, and this means that the wave front of the emitted radiation faces not exactly away from the origin, but from a point about a wave-length away from it. […] It implies that the photon which is to carry away the energy and angular momentum from an atom of radius 10^{-8} cm starts its life outside the atom at a distance 10^{-5} cm away.

Charles G. Darwin, *Notes on the Theory of Radiation*, Proc. Roy. Soc. A, **136**, 36 (1932).

Seeing a Single Atom Where it Is Not

^{138}Ba^{+}-ion confined in a linear Paul trap

Araneda et al., Nat. Phys. **15**, 17 (2019)



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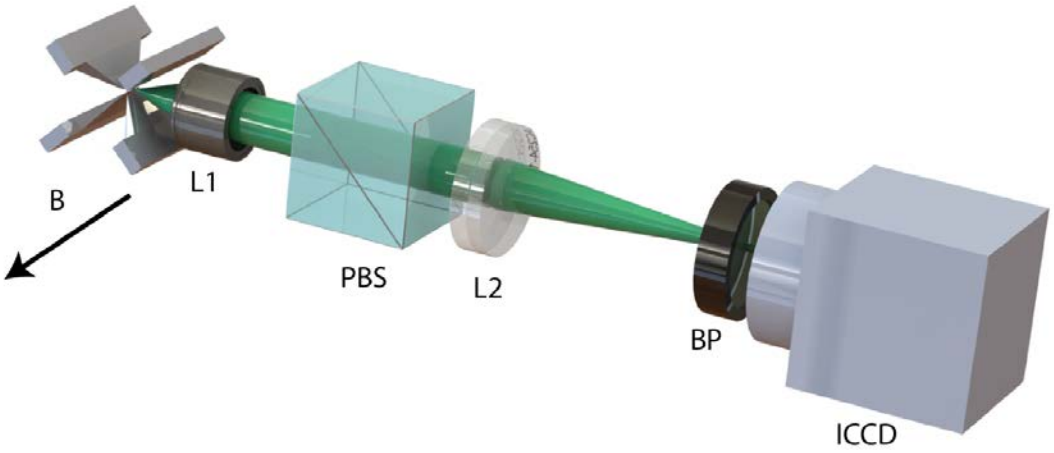
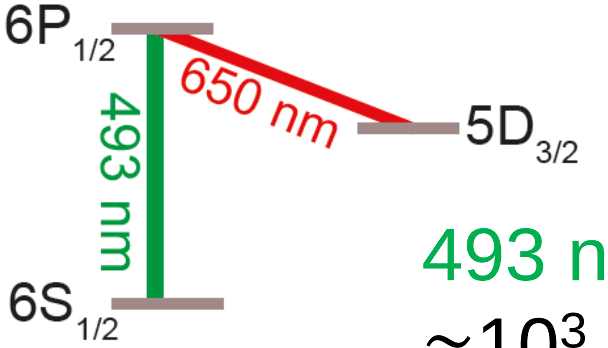
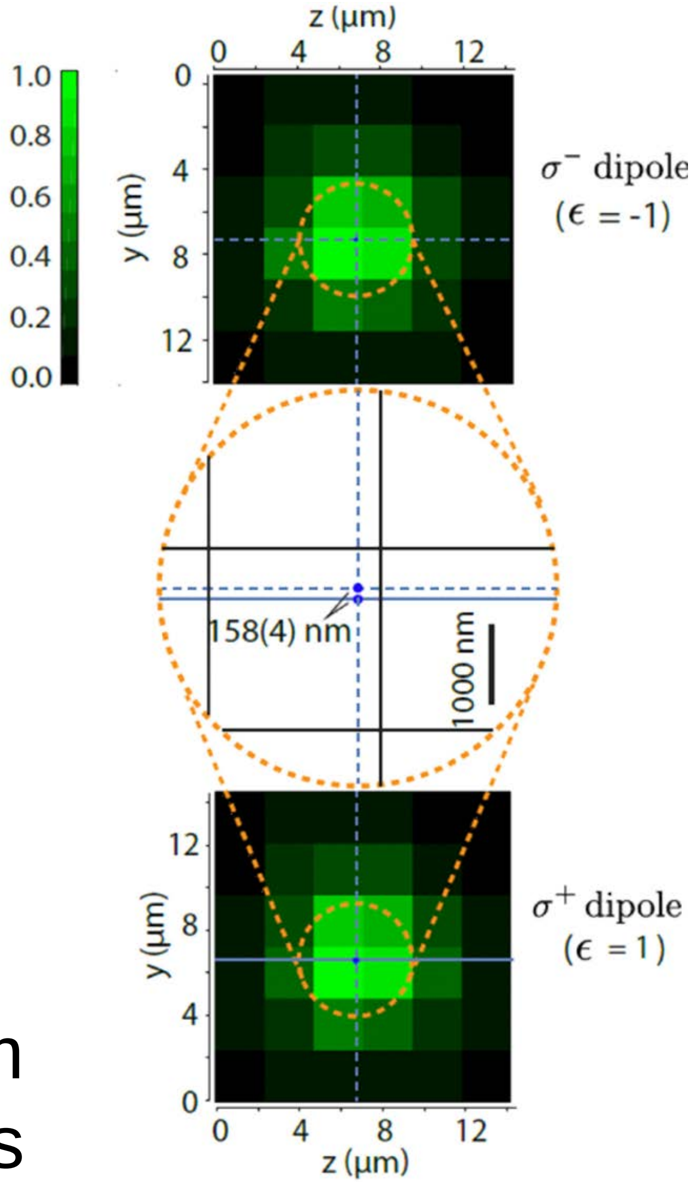




493 nm / π = 157 nm

$\approx 10^3 \times {}^{138}$Ba^{+}-radius



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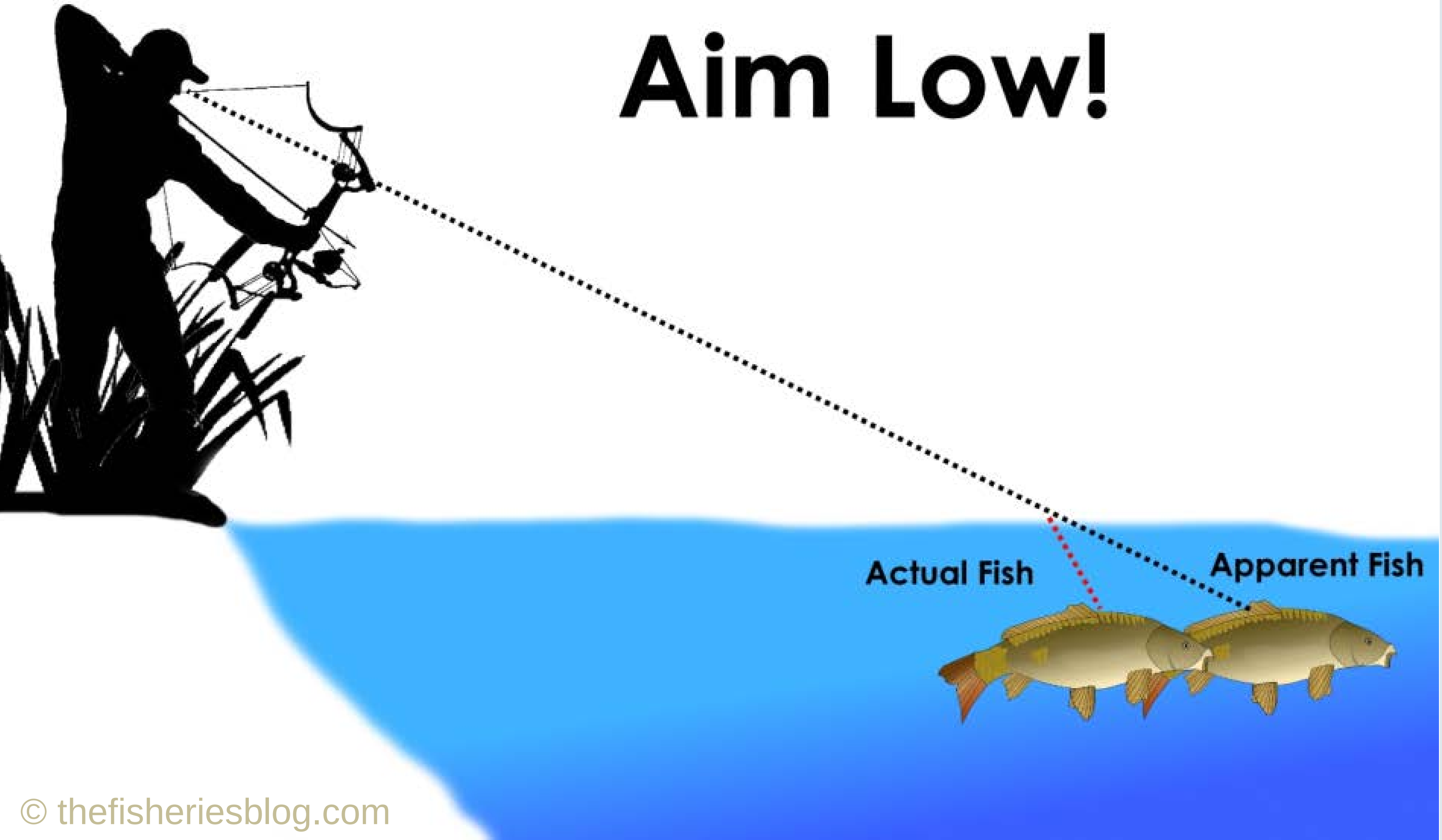

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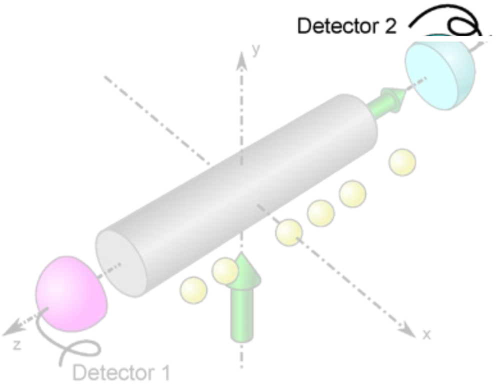

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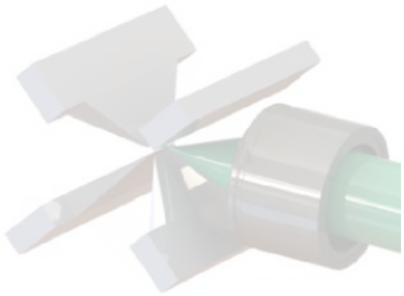

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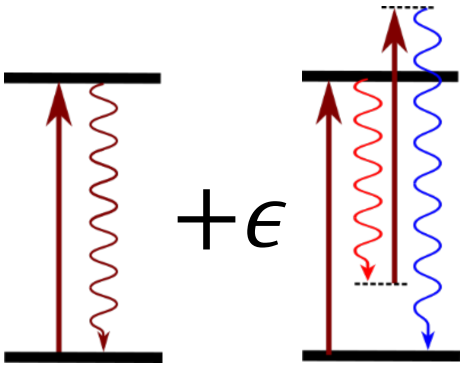

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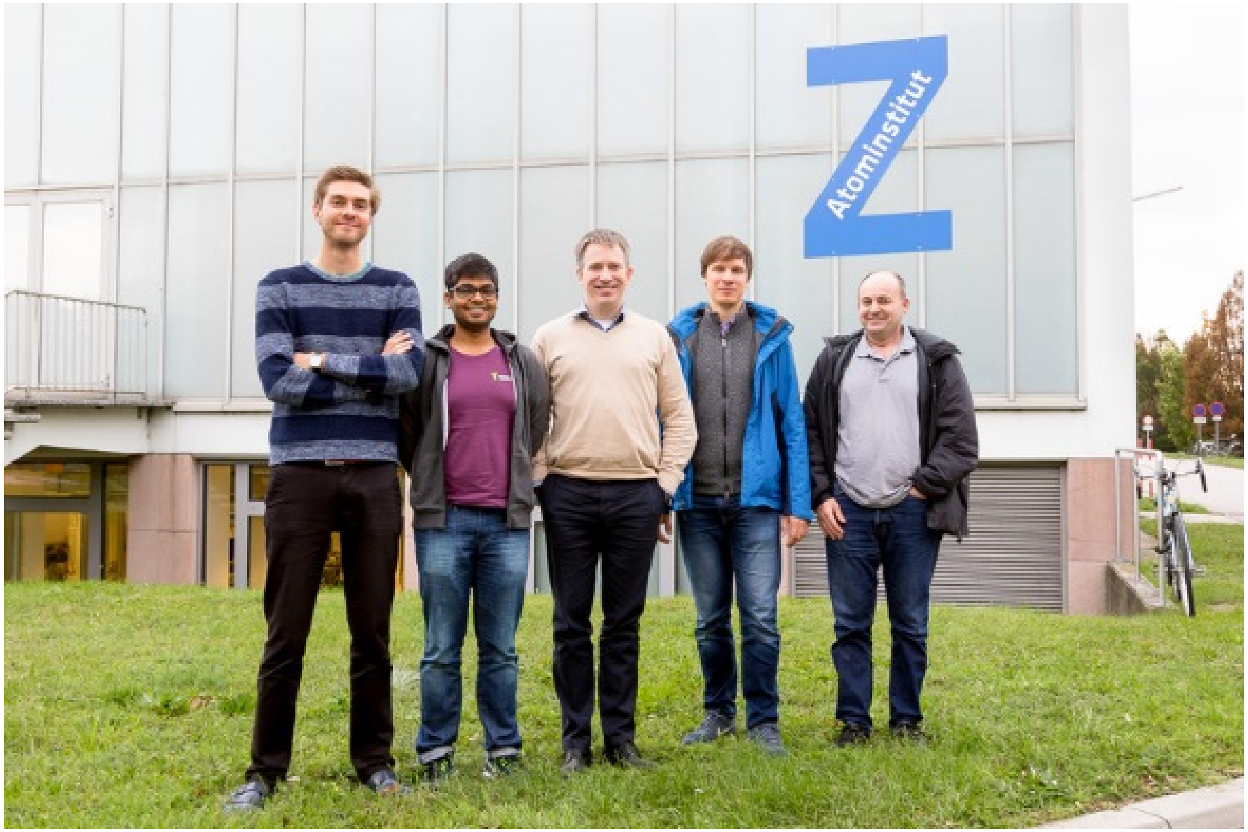
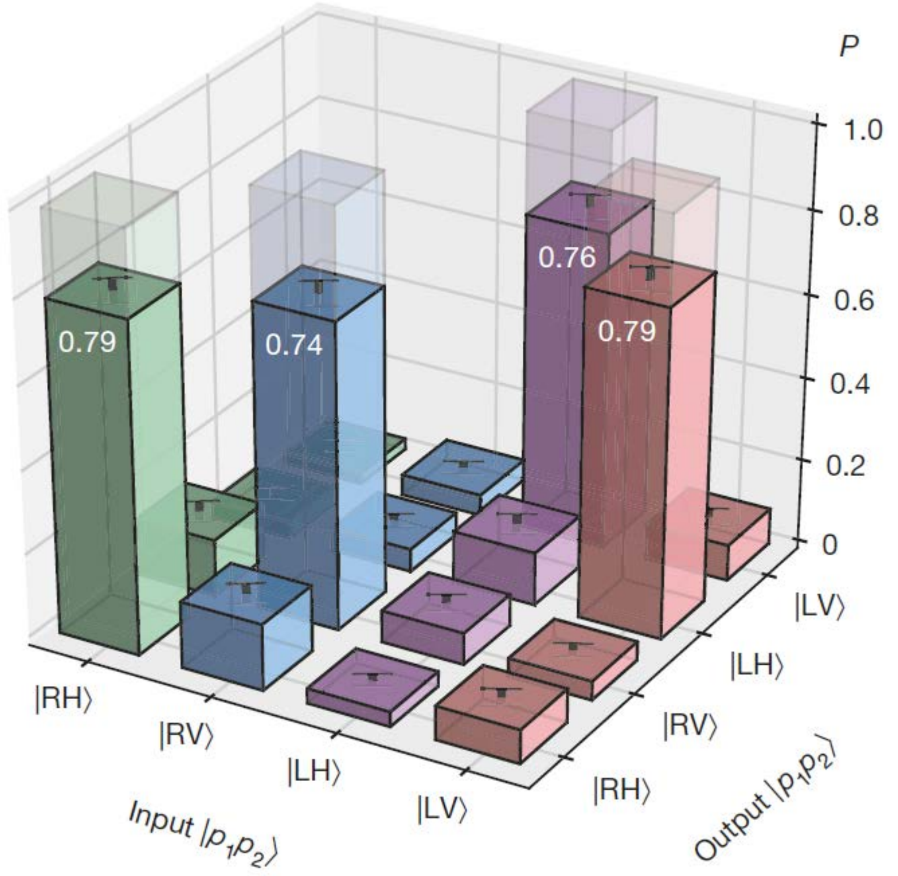


***Experiment Crew @ TU Wien / HU Berlin*:**
Jakob Hinney, Adarsh Prasad, Philipp Schneeweiß, Jürgen Volz

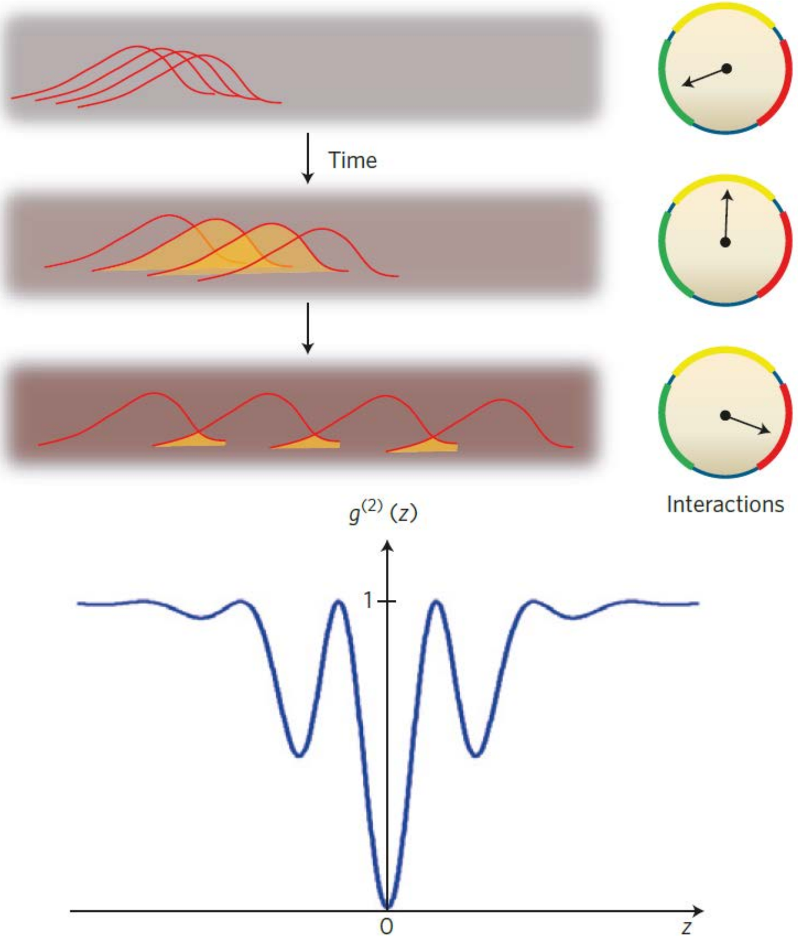
***Theory Collaboration @ U Hannover & U Copenhagen*:**
Klemens Hammerer, Sahand Mahmoodian, Anders S. Sørensen

Intro – Strong Photon–Photon Interactions

Quantum nonlinear optics for quantum information processing and quantum simulation



B. Hacker et al., Nature **536**, 193 (2016)



D. E. Chang et al., Nat. Phot. **8**, 685 (2014)

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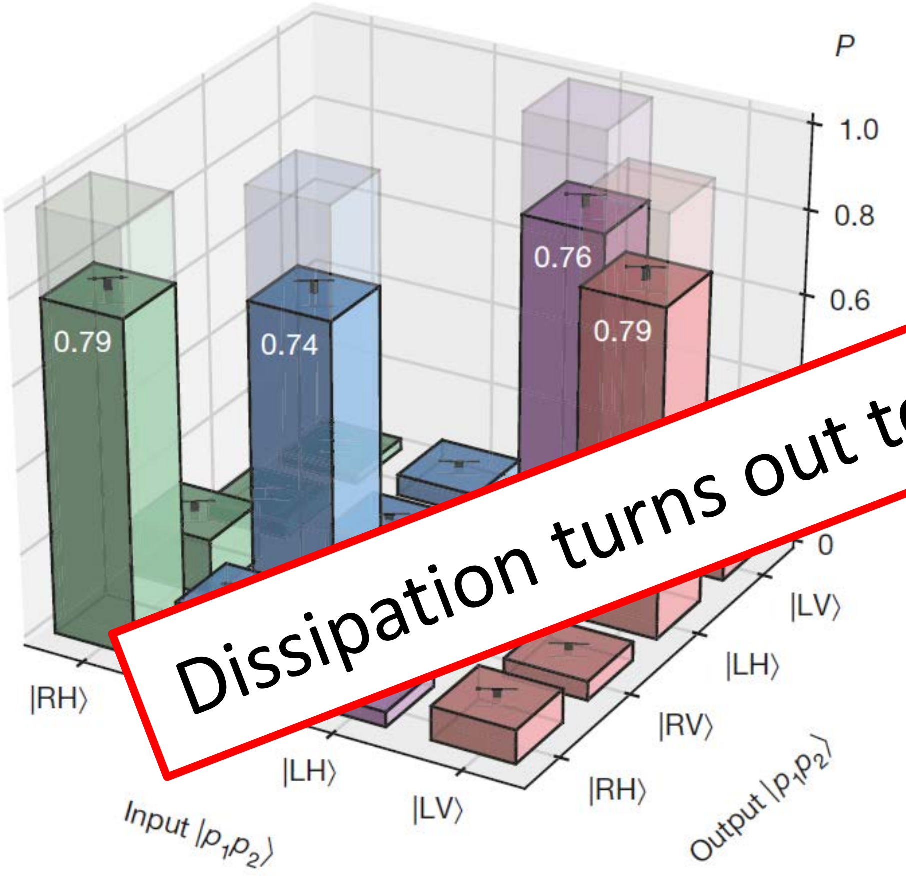

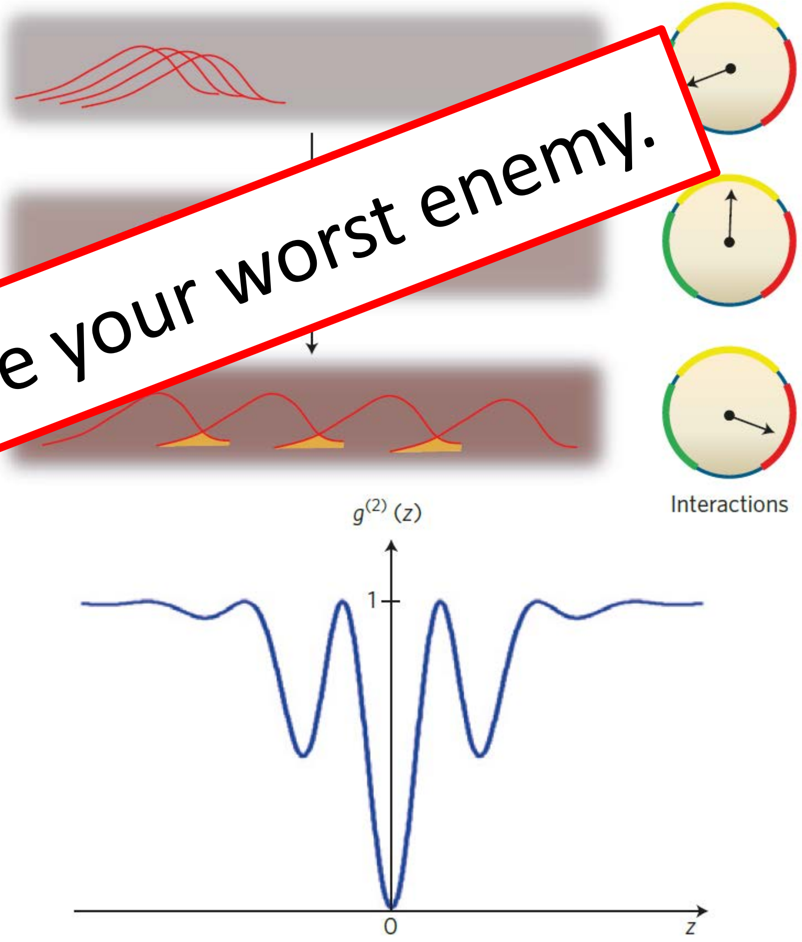

Dissipation turns out to be your worst enemy.

B. Hacker et al., Nature **536**, 193 (2016)

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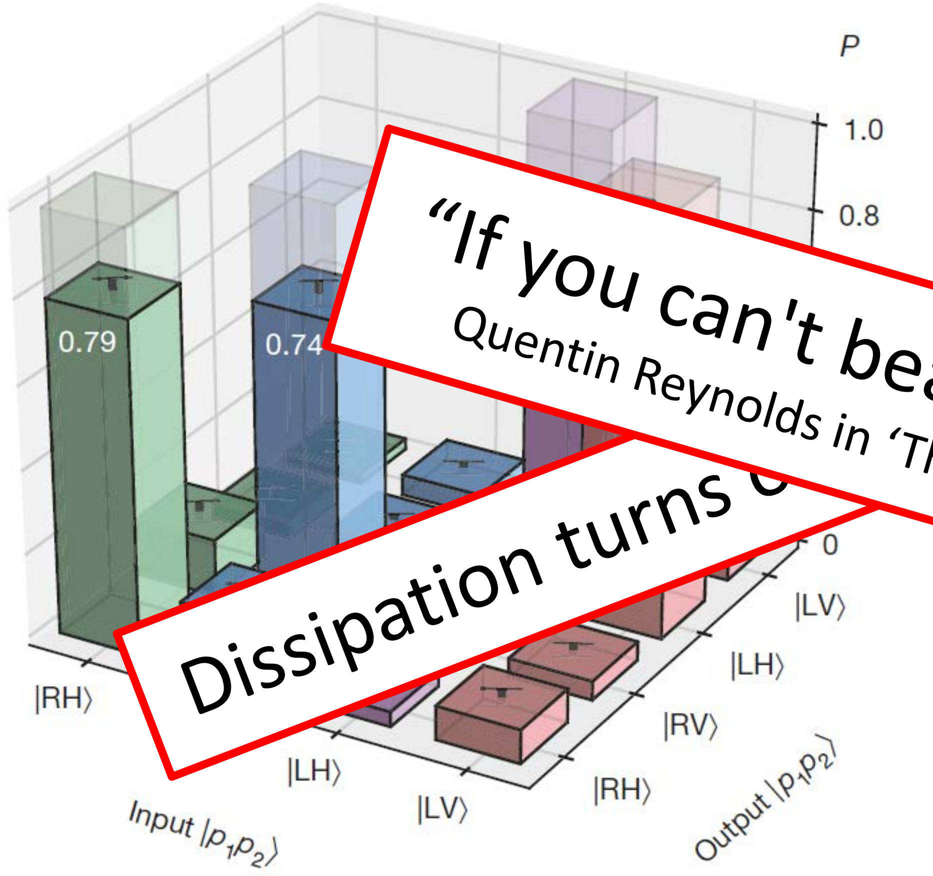

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Dissipation turns o

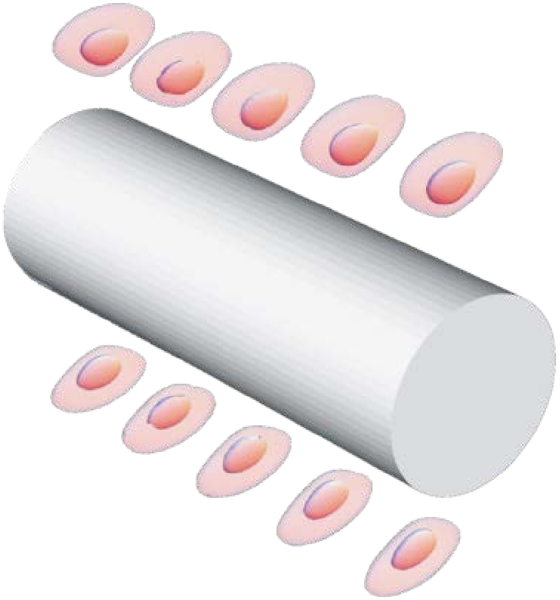
our worst enemy.

“If you can't beat 'em, join 'em.”

Quentin Reynolds in ‘The Wounded Don't Cry’

Two-Color Nanofiber-Based Atom Trap

Two arrays of trapping sites



- Nanofiber diameter: 400 nm
- At most one Cs atom per trapping site
- Filling factor: up to 0.5

Trap parameters

- Atom-surface distance: 250 nm
- Trap frequencies: ~ 100 kHz
- Atoms are localized to a volume $\ll \lambda^3$

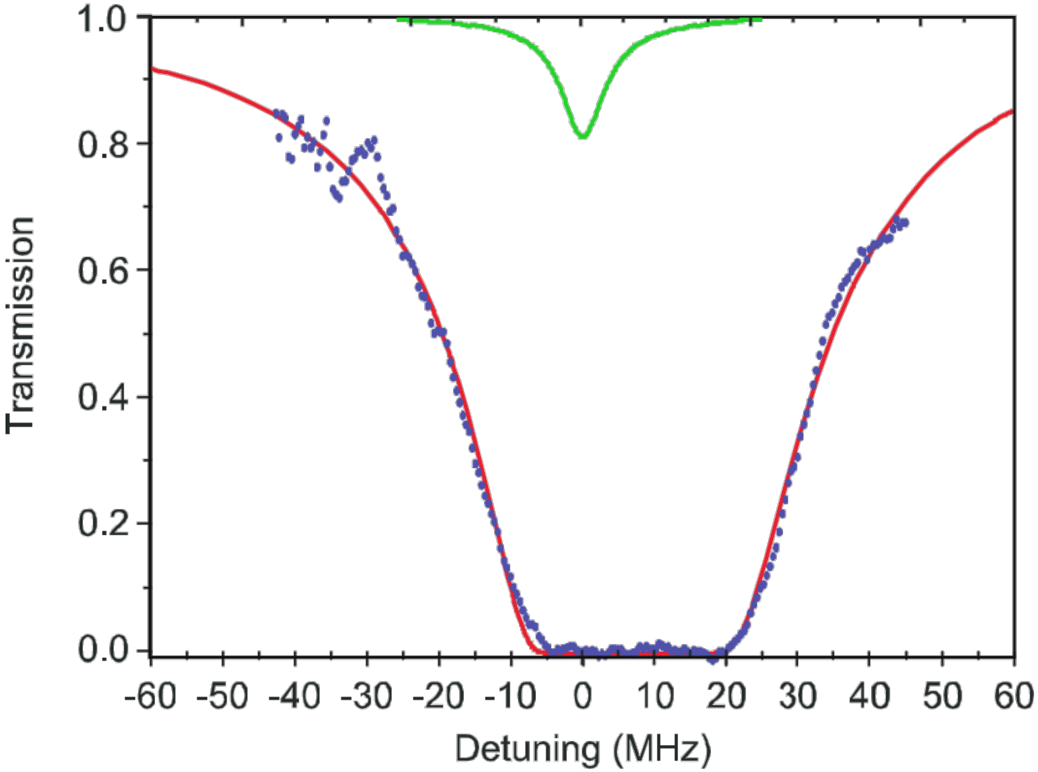
More nanofiber-based atom traps (past, present, and future):
Caltech, Niels Bohr Institute, JQI / University of Maryland, LKB Paris, Waseda University, OIST Japan, Univ. of Arizona, Swansea University, Univ. of Queensland, Univ. of Auckland, Univ. of Rochester…

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

Nanofiber-Based Optical Interface

Optical depth, $OD = -\ln(T)$

- OD per atom: $OD_{1\text{at}} \sim 0.01 - 0.1$
- Number of trapped atoms: $N_{\text{at}} = 1{,}000 - 10{,}000$
- Total OD: $OD_{\text{tot}} = N_{\text{at}} \cdot OD_{1\text{at}} \sim 10 - 1{,}000$



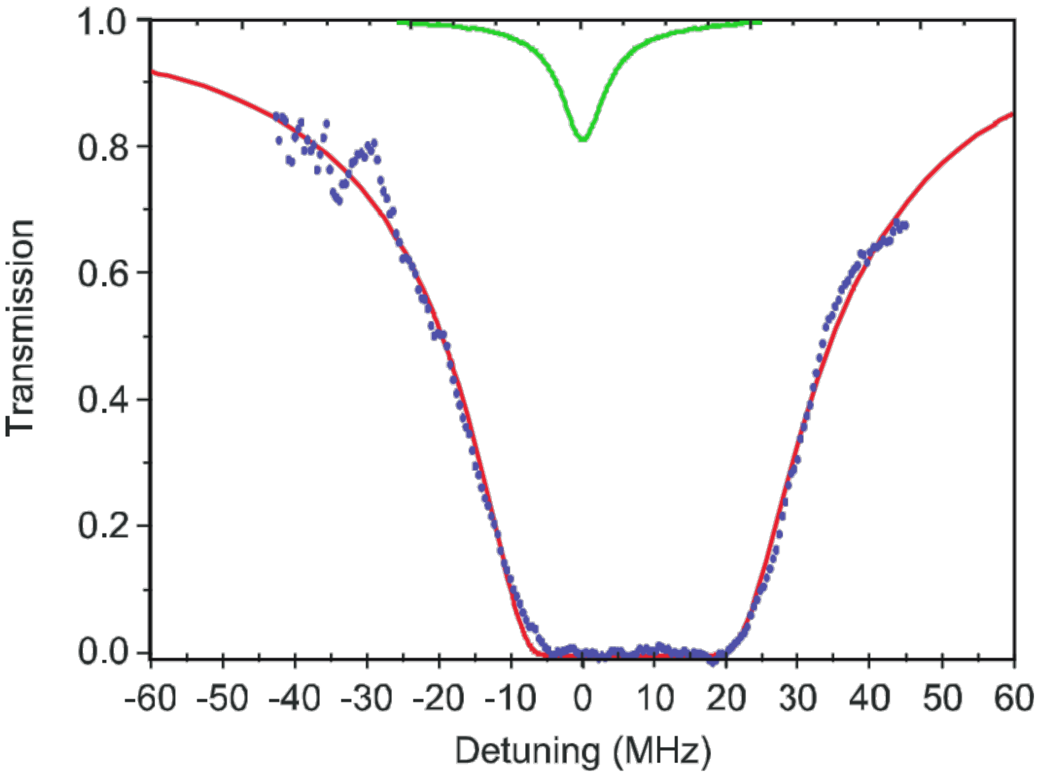
E. Vetsch et al., PRL **104**, 203603 (2010)
E. Vetsch et al., IEEE J of Quant Elec. **18**, 1763 (2012)

Nanofiber-Based Optical Interface

Optical depth, $OD = -\ln(T)$

- OD per atom: $OD_{1\text{at}} \sim 0.$
- Number of trapped atoms: N ,000 – 10,000
- Total OD: $OD_{\text{tot}} = N_{\text{at}} \cdot OD_{1\text{at}} \sim 10 - 1{,}000$

Assumes $T_{\text{tot}} = (T_{1\text{at}})^{N_{\text{at}}}$



E. Vetsch et al., PRL **104**, 203603 (2010)
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Nanofiber-Based Optical Interface

Optical depth, $OD = -\ln(T)$

- OD per atom: $OD_{\mathrm{1at}} \sim 0.01 - 0.1$
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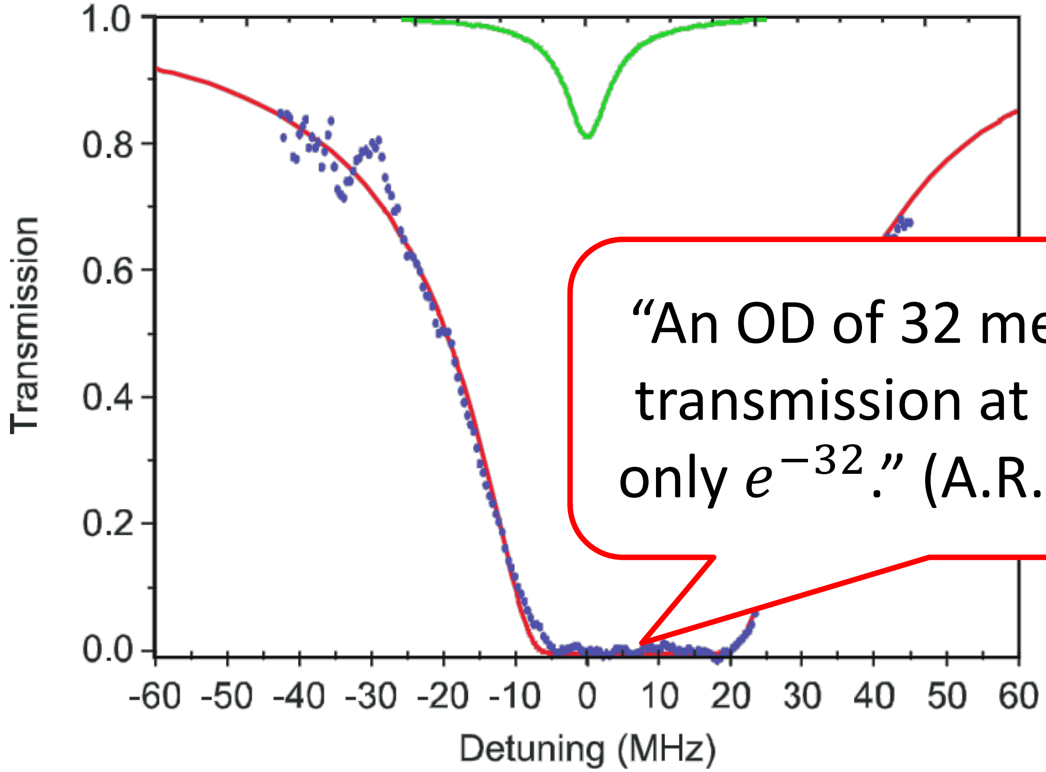

"An OD of 32 means that the transmission at resonance is only e^{-32}." (A.R. for 10 years)

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

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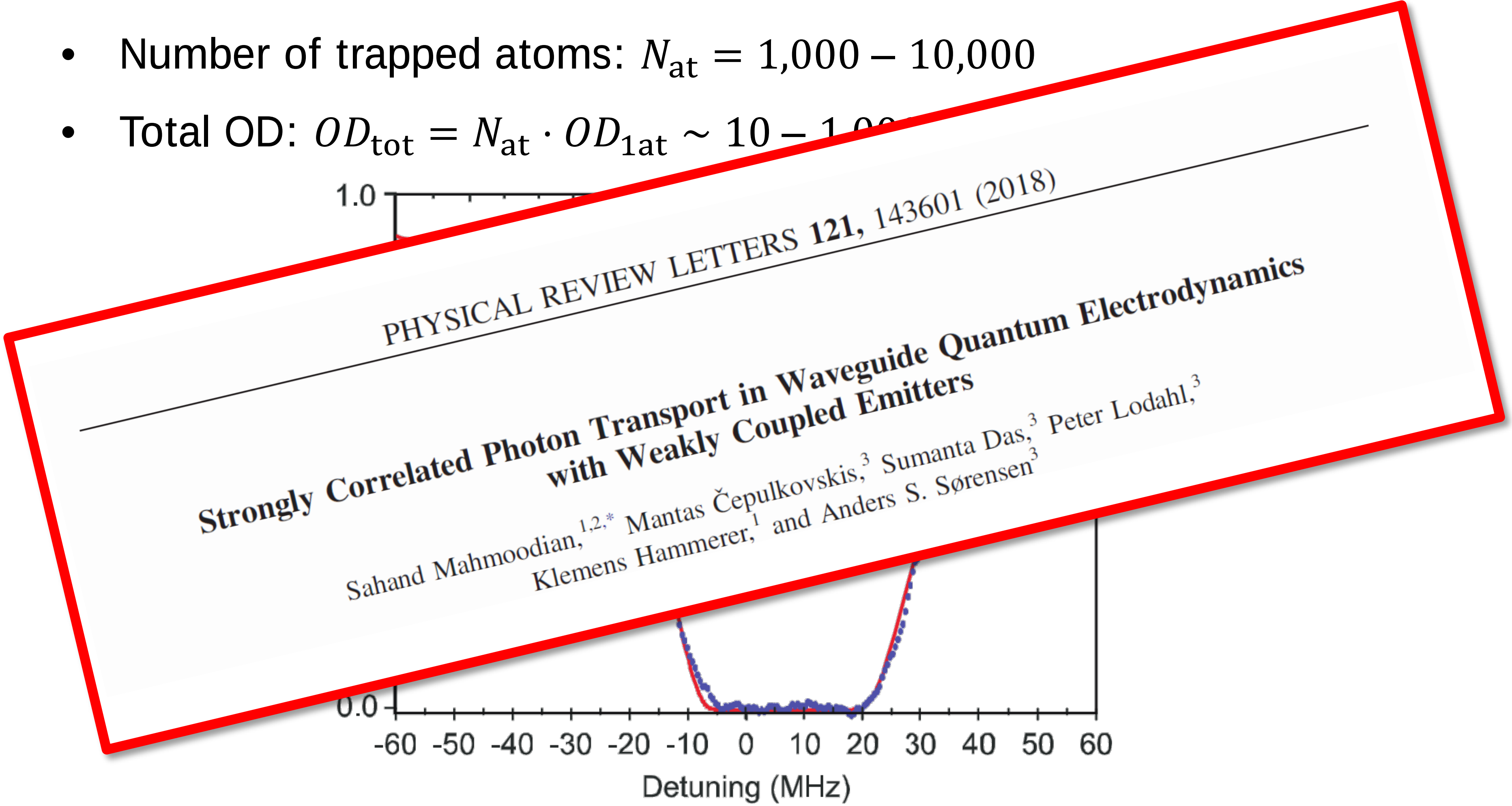


PHYSICAL REVIEW LETTERS **121**, 143601 (2018)

Strongly Correlated Photon Transport in Waveguide Quantum Electrodynamics with Weakly Coupled Emitters

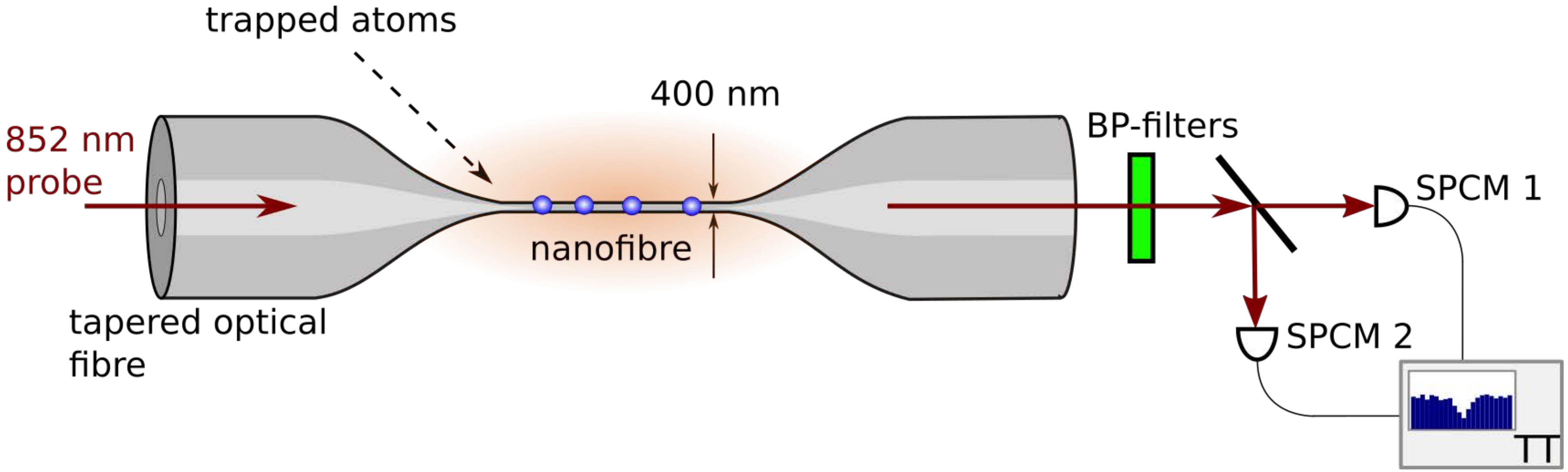
Sahand Mahmoodian,[1,2,*] Mantas Čepulkovskis,[3] Sumanta Das,[3] Peter Lodahl,[3] Klemens Hammerer,[1] and Anders S. Sørensen[3]

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

Experimental Set-Up

Experimental parameters

- Probe light resonant with cycling transition of Cs D2 line @ 852 nm
- Input power $P_{\text{in}} = 2.35$ pW ⇒ saturation parameter $S_0 = 0.02$
- Probe quasi linearly polarized ⇒ chiral light–matter coupling



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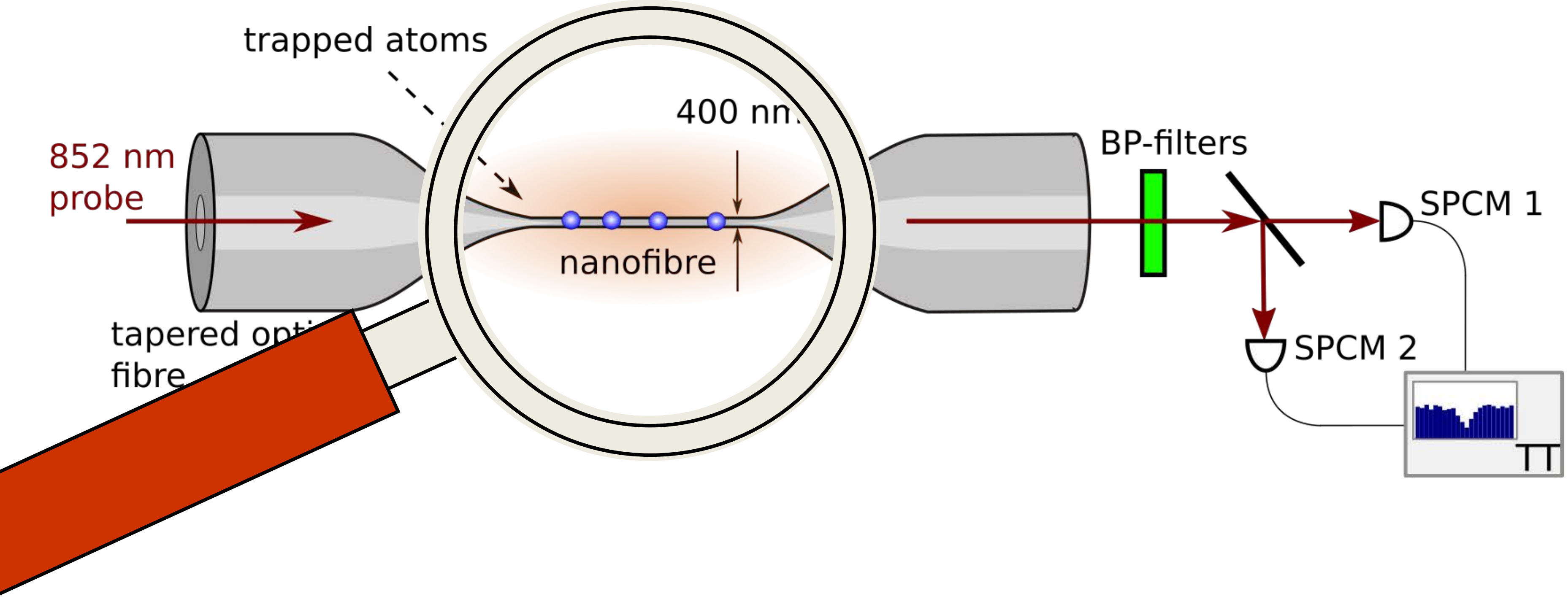
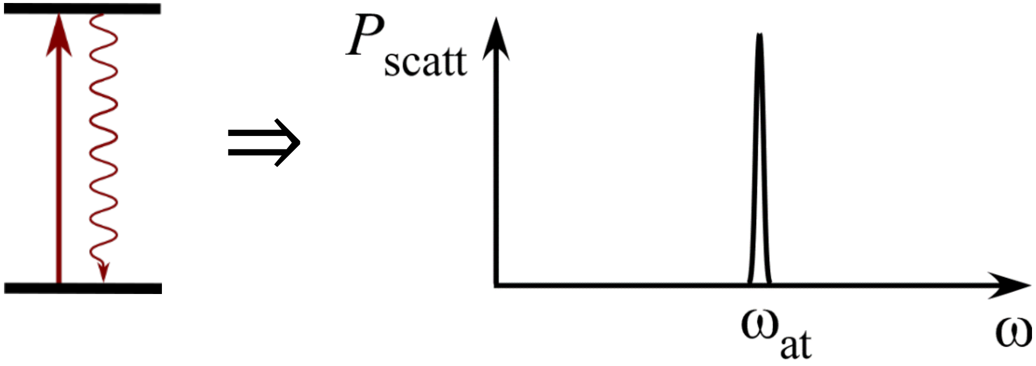


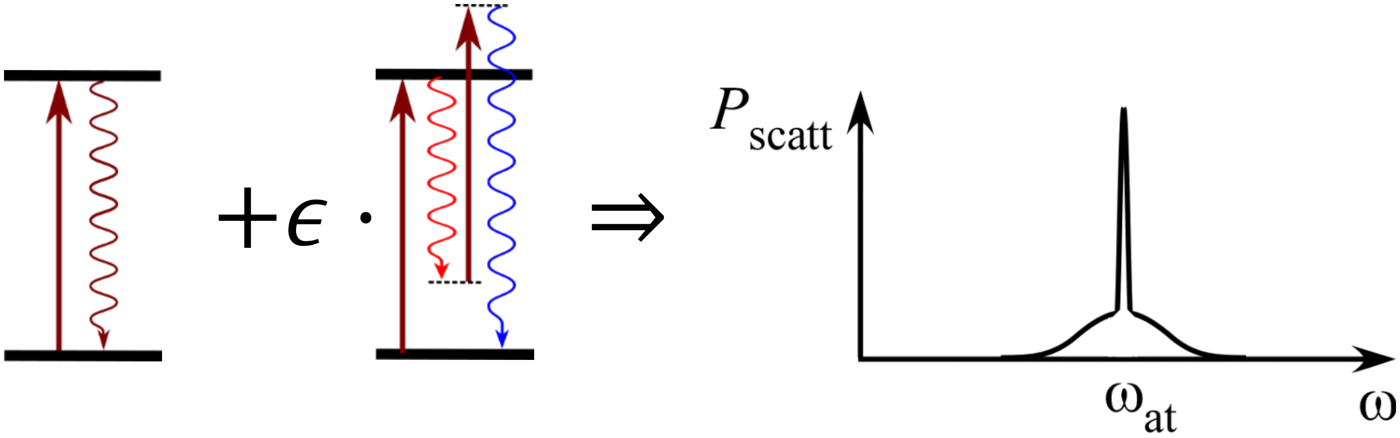
Resonance Fluorescence

Scattering of resonant light by two-level atom

- Vanishing saturation ⇒ elastic scattering

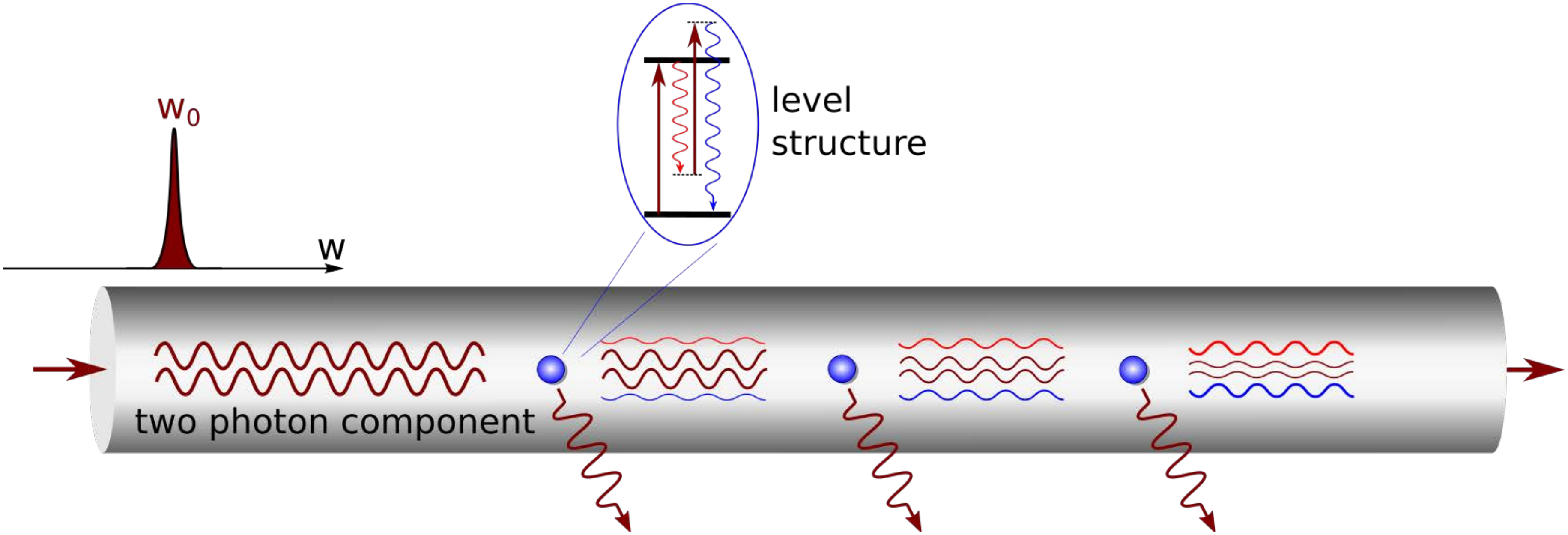


- Finite (but weak) saturation ⇒ inelastic scattering



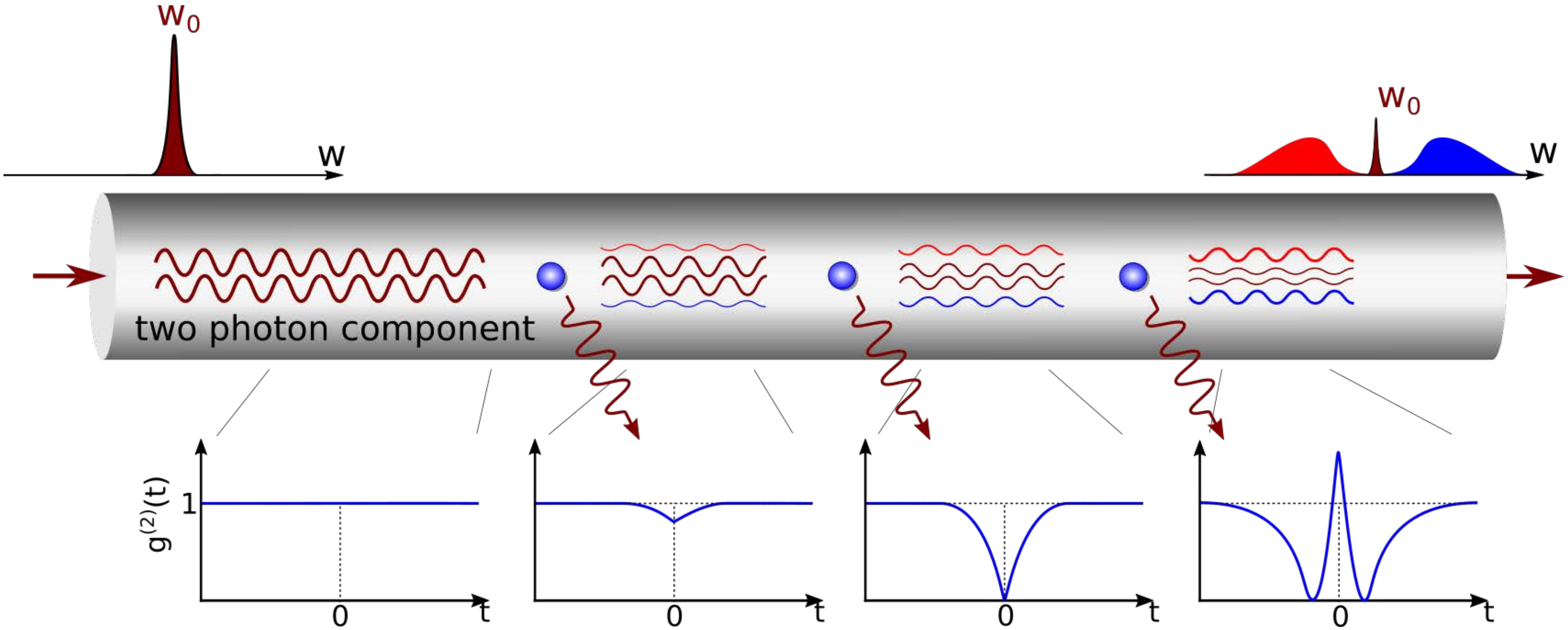
Interplay: Nonlinear Processes & Dissipation

- Two-photon scattering generates correlated photon state
- Broader spectrum ⇒ reduced absorption by rest of ensemble
- Constructive interference of scattering amplitudes from different atoms ⇒ two-photon forward scattering process is collectively enhanced
- Unscattered two-photon component subject to exponential loss
- Power-law decay (!) of correlated photon states with N_{at} for high OD



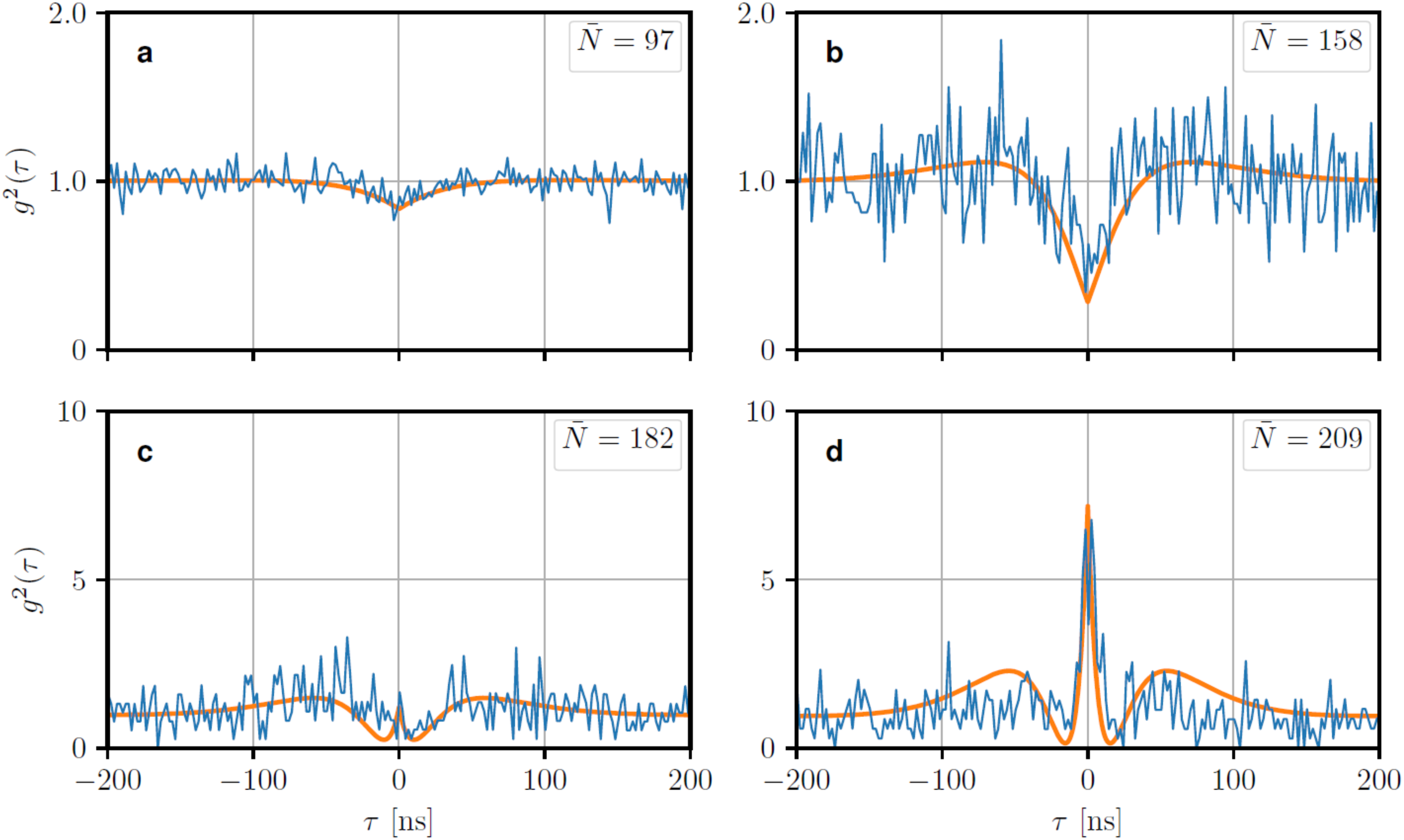
Interplay: Nonlinear Processes & Dissipation

- Scattered two-photon component π phase-shifted w.r.t. unscattered two-photon component ⇒ destructive interference
- Scattered < unscattered component @ low OD ⇒ antibunching
- Equal amplitudes @ critical OD ⇒ perfect antibunching
- All single photons are lost and only scattered two-photon component survives @ high OD ⇒ strong bunching



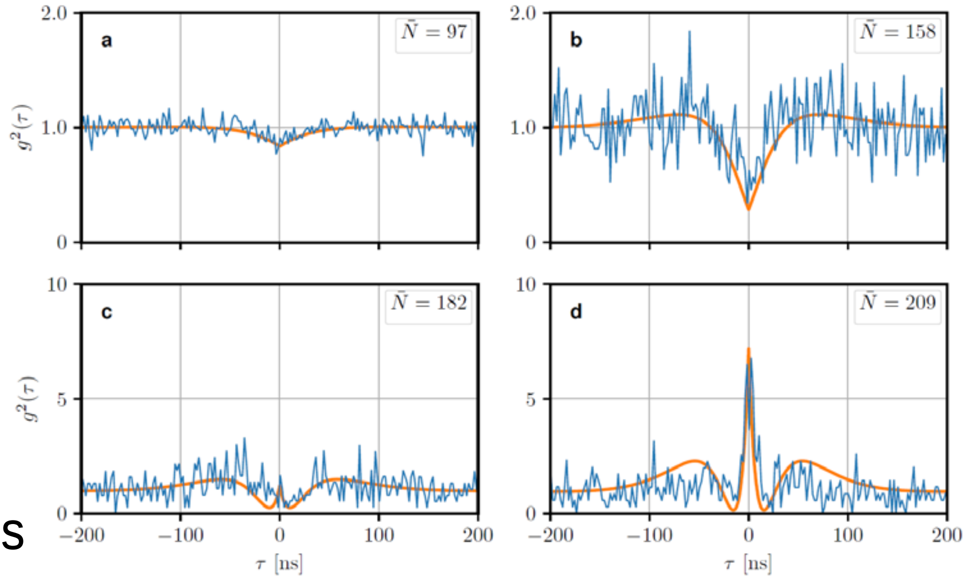
Experimental Results

Measured second order correlation functions



Experimental Results

Measured second order correlation functions

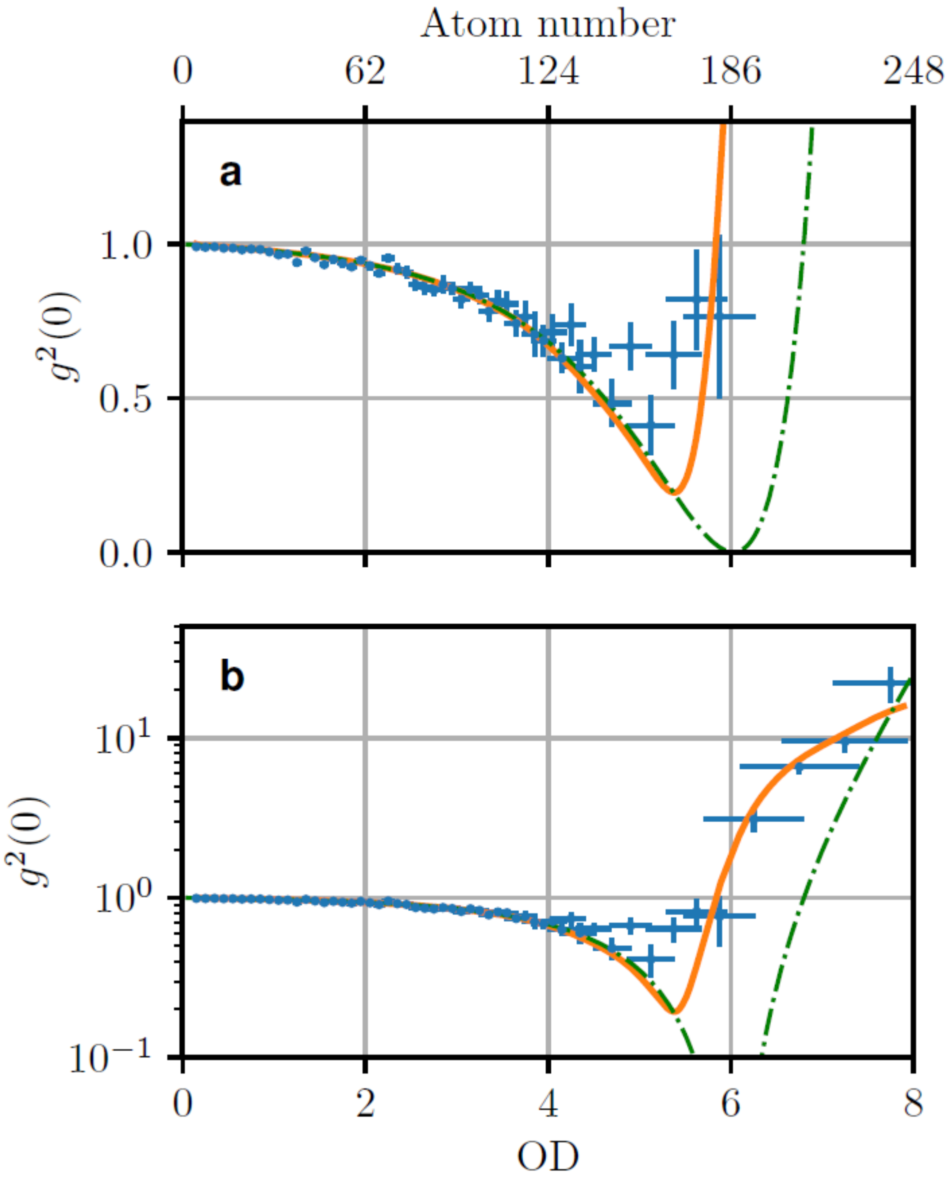


- Blue line: experimental data (2 ns binning)
- Measured optical depths
  a: $OD = 3.15$, **b**: $OD = 5.13$
  c: $OD = 5.88$, **d**: $OD = 6.75$
- Orange line: theory prediction for our experimental parameters
- Main experimental imperfection: variation in atom number distribution
- Assumed atom–waveguide coupling strength: $\beta = 0.81\,\% \pm 0.02\,\%$ (derived from fitting $g^{(2)}(\tau = 0)$ vs. OD with β as only fit parameter)
- Both antibunching and bunching are clearly apparent

Experimental Results

$g^{(2)}(\tau=0)$ vs. OD

- Exp. data determined from maximum likelihood fits to individual correlation functs.
- Orange line: theory predictions accounting for exp. uncertainty in OD estimation with coupling strength β as only fitting parameter
- Green dashed line: theory prediction without uncertainty in atom number for same β
- Strongest antibunching for $N_{\mathrm{at}} = 158$, bunching for $N_{\mathrm{at}} > 180$



Summary and Perspectives

Summary

- Ensembles of weakly coupled atoms can be used to realize strongly correlated many-body states of photons.
- Underlying dynamics is based on an interplay of weak optical nonlinearities, collective enhancement, and finite dissipation.

Perspectives

- Our results extend the use of collective enhancement into the regime of non-Gaussian operations.
- This significantly broadens the range of possible applications, in particular for quantum information science.
- Fundamentally new approach to realizing single photon sources [Patent pending (PCT/EP2019/075386)].

Funding

SFB
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MARIE CURIE ACTIONS

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Thank you for your attention!