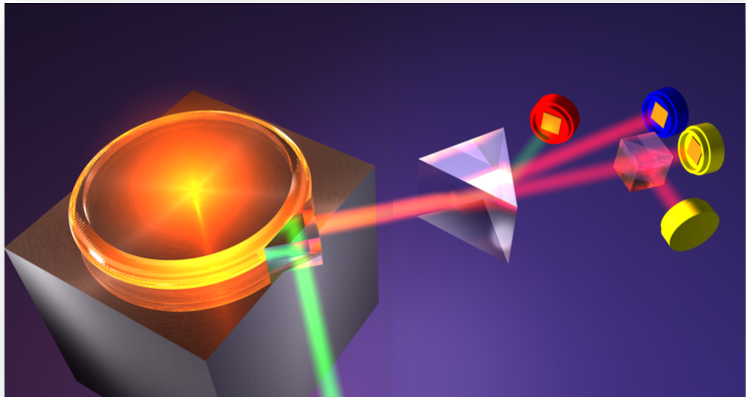
Optomechanics inside nonlinear whispering gallery resonators and quantum inspired sensing

Christoph Marquardt



Max Planck Institute for the Science of Light

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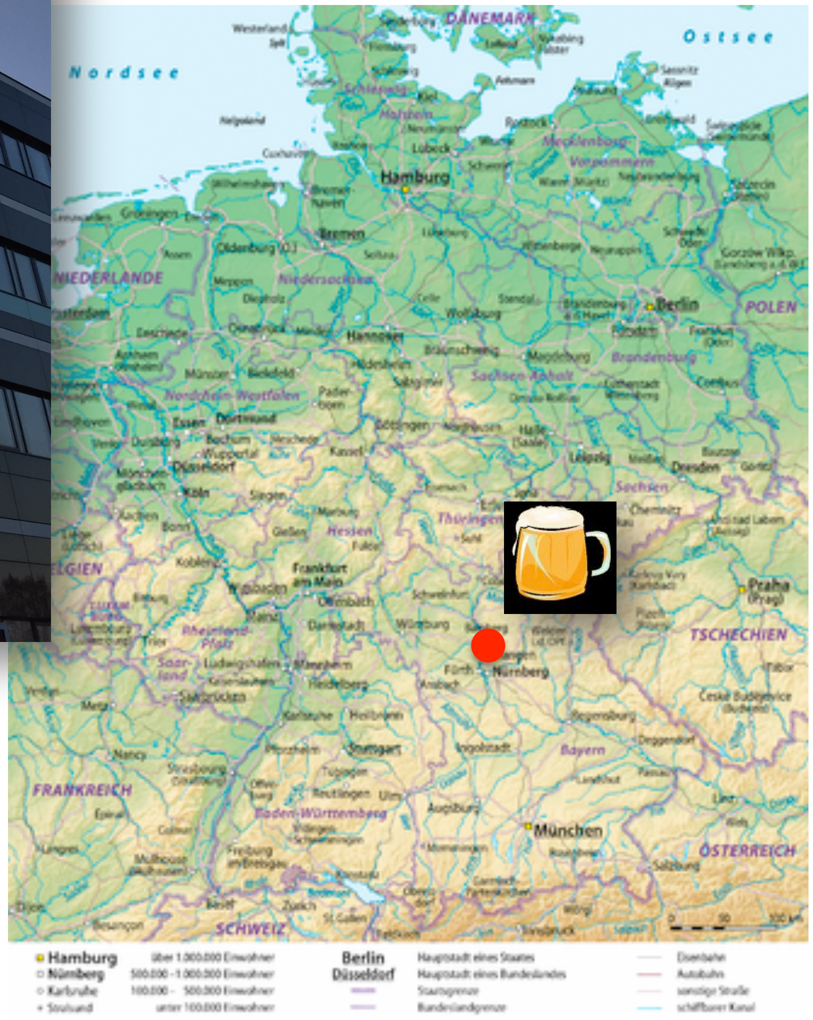
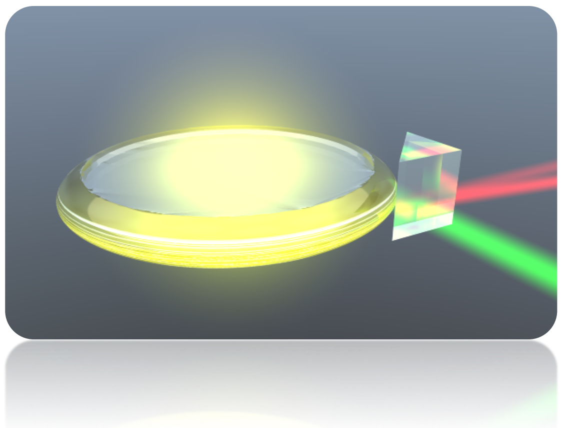
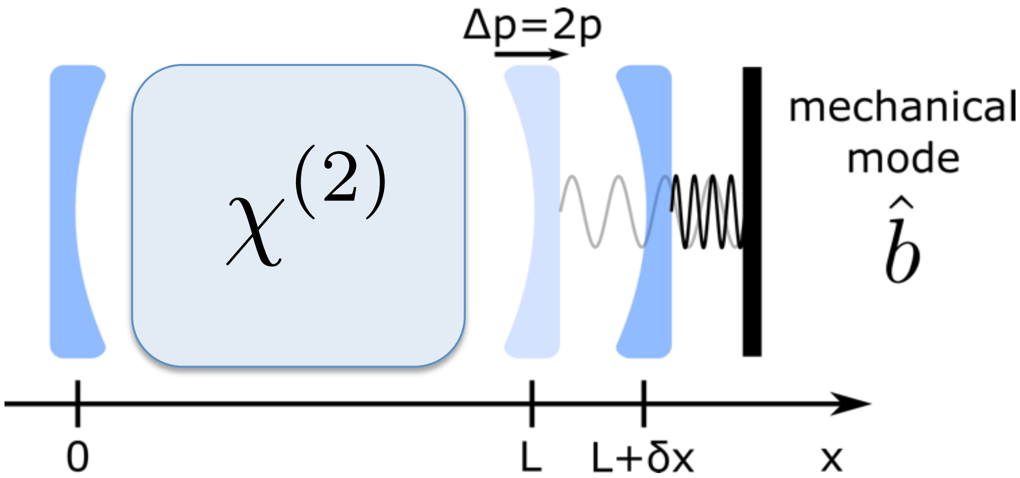


Max Planck Institute for the Science of Light:
Division G. Leuchs
Division P. St. Russell
Division V. Sandoghdar
...

Optomechanics inside nonlinear whispering gallery resonators



Optomechanics and more …



Add a second optical nonlinearity resulting in

$$\hat{H}_{\mathrm{s}} = i\hbar\sqrt{\bar{n}_{\mathrm{p}}}\nu(\hat{a}_{\mathrm{s}}^{\dagger}\hat{a}_{\mathrm{s}}^{\dagger} - \hat{a}_{\mathrm{s}}\hat{a}_{\mathrm{s}})/2$$

$$\hat{H}_{\mathrm{om}} = -\hbar G\hat{a}_{\mathrm{s}}^{\dagger}\hat{a}_{\mathrm{s}}\delta\hat{x}$$

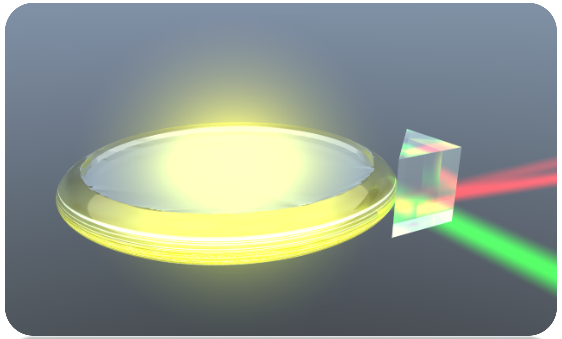
WGRs and optomechanics

Combine nonlinear optics and optomechanics

$$\hat{H}_{\mathrm{s}} = i\hbar\sqrt{\bar{n}_{\mathrm{p}}}\nu(\hat{a}_{\mathrm{s}}^{\dagger}\hat{a}_{\mathrm{s}}^{\dagger} - \hat{a}_{\mathrm{s}}\hat{a}_{\mathrm{s}})/2$$

$$\hat{H}_{\mathrm{om}} = -\hbar G\hat{a}_{\mathrm{s}}^{\dagger}\hat{a}_{\mathrm{s}}\delta\hat{x}$$

... all in one monolithic device.



WGRs and optomechanics

Enhancement of cavity cooling with parametric amplifier
S. Huang and G. S. Agarwal, PRA, 79:013821 (2009)

Optomechanical entanglement from competing nonlinearities
A. Xuereb et al., PRA, 86:013809 (2012)

Classical analysis of degenerate OPOs
F. Jiménez and C. Navarrete-Benlloch, arXiv:1412.2521 (2014)

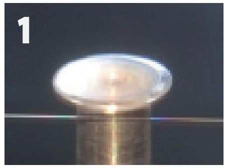
From weak to strong optomechanical coupling via nonlinear interaction
X. Lü et al., PRL, 114:093602 (2015)

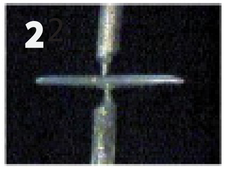
Enhancement of position detection using intracavity squeezing
V. Peano et al., arXiv:1502.06423 (2015)

...

But: all theoretical proposals so far…

WGRs and optomechanics

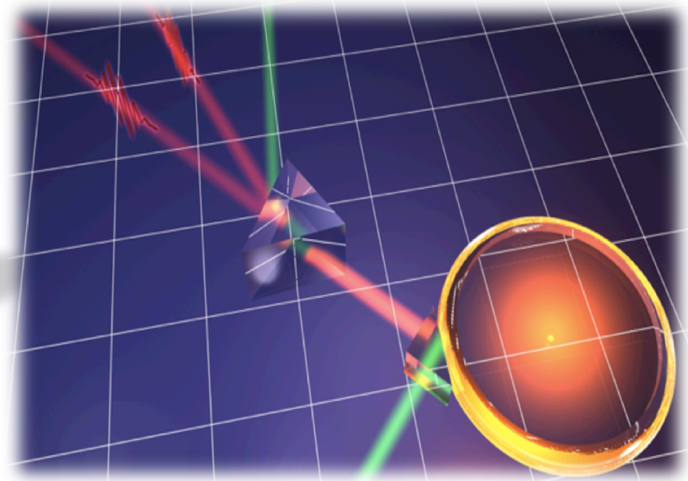




J. Hofer et al., PRA, 82:031804(R) (2010)

- LiNbO$_3$ WGMRs have shown to be a versatile source of nonclassical light:

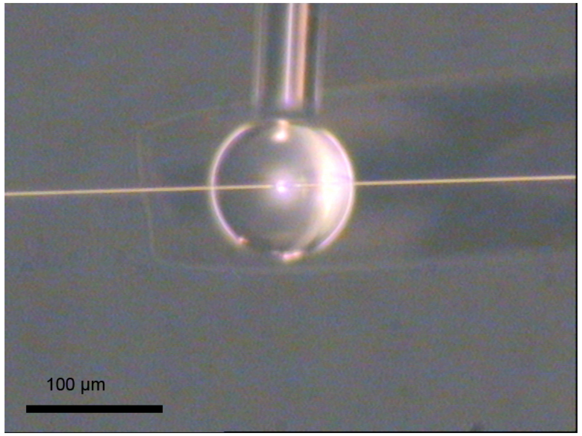
PDC: quantum correlated and individually intensity squeezed signal and idler
J. U. Fürst et al., PRL, 106:113901 (2011)



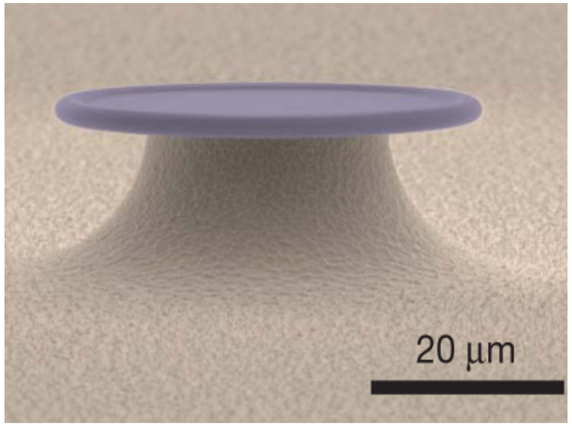
Single photon source
M. Förtsch et al., Nature Comm, 4:1818 (2013)

High wavelength tunability
G. Schunk et al., in preparation

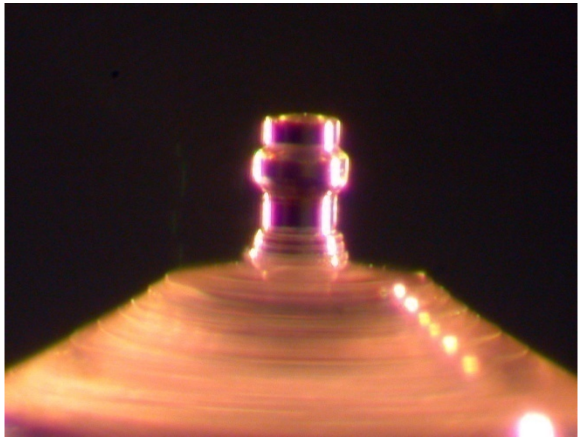
Whispering Gallery Resonators



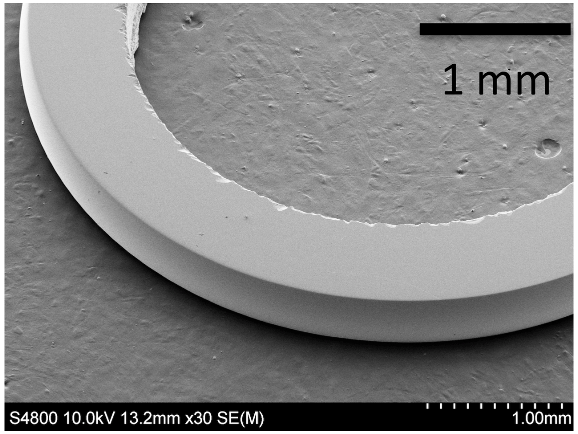
MPI for the Science of Light



Vahala group, Caltech



Jet Propulsion Laboratory

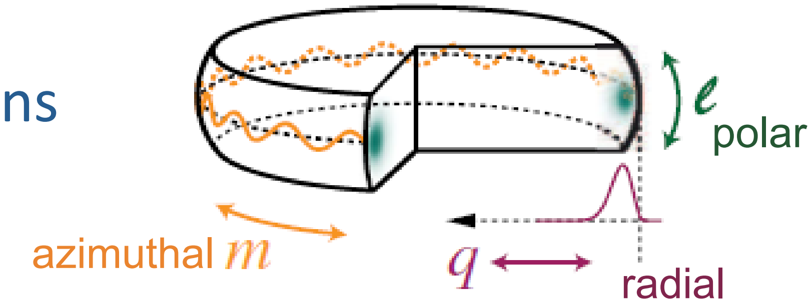


MPI for the Science of Light

amorphous materials (e.g., fused silica) can be shaped by the surface tension in a reflow process. *Only third order nonlinearity!*

crystalline materials (e.g. Lithium Niobate) typically have lower losses **and may possess second order nonlinearity,** but they need to be polished mechanically.

Whispering Gallery Modes



- Radial part: spherical Bessel functions

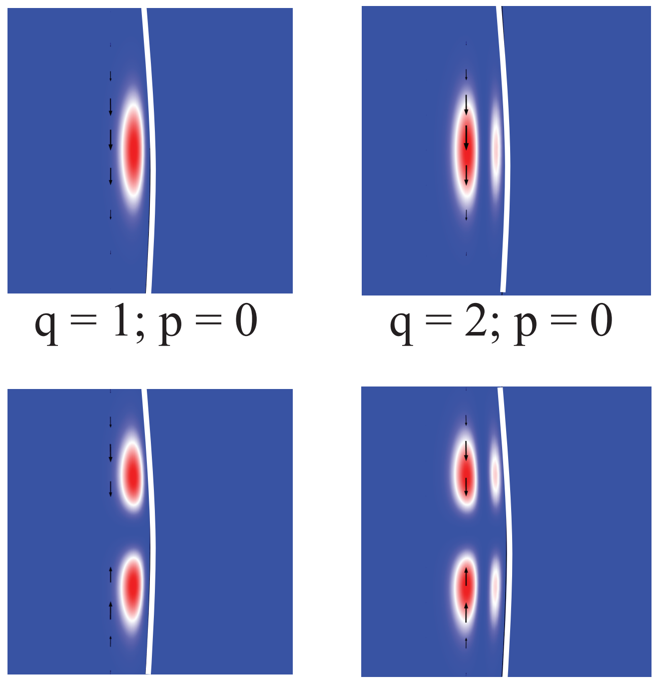
$$j(k_q r)$$

- Angular part: spherical harmonics

$$Y_{lm}(\theta, \varphi) \qquad \text{[1]}$$

- Describing mode indices

q	radial
m	azimuthal
l	polar
$(l-m)=p$	angular



q = 1; p = 0   q = 2; p = 0

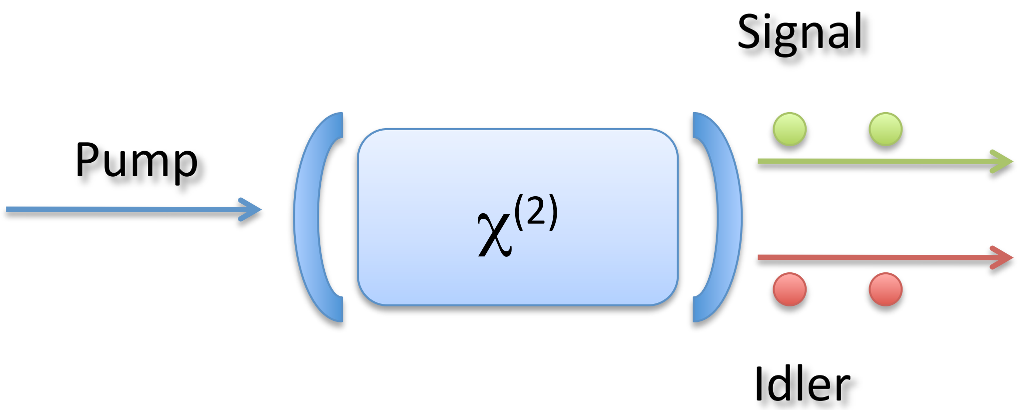
q = 1; p = 1   q = 2; p = 1

[1] P. Debye, Ann. Physik, 30, 57 (1909)

*[2] J. U. Fürst et al., Phys. Rev. Lett. **105**, 263904 (2010)*

Generation of nonclassical light

Parametric Downconversion



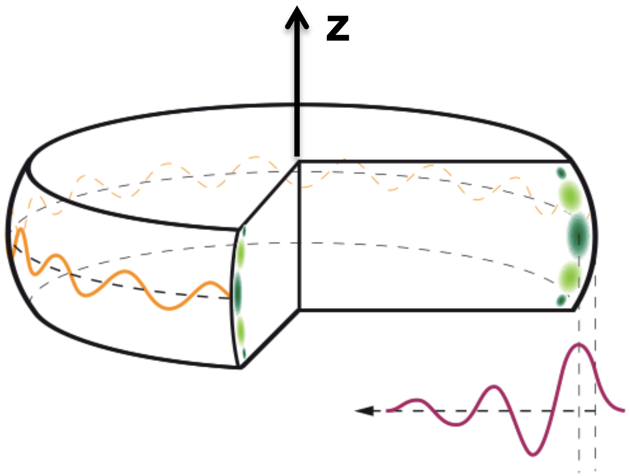
$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$

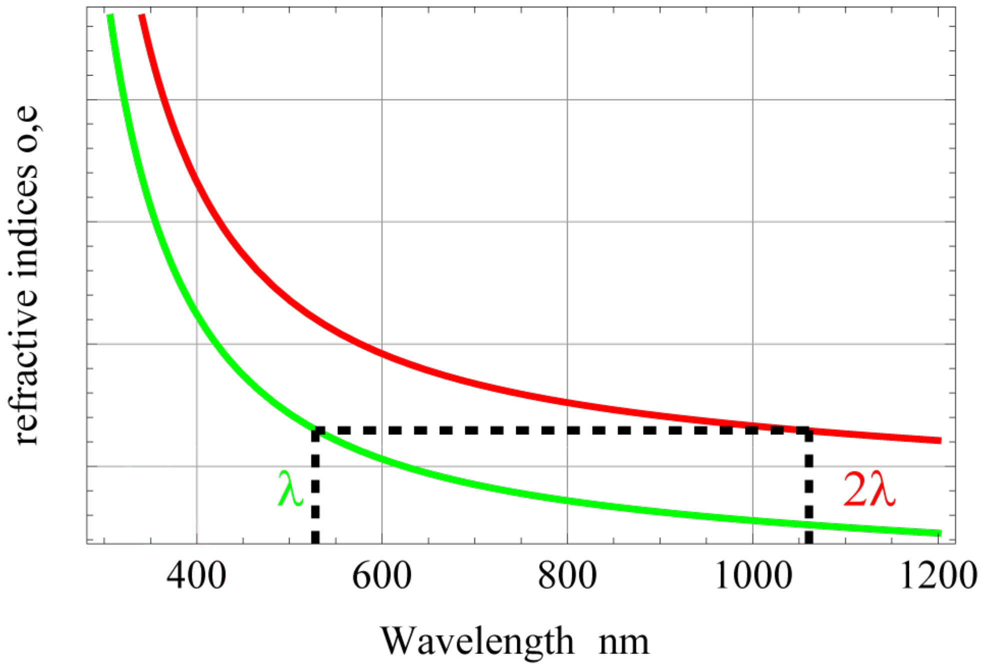
$$\vec{k}_p = \vec{k}_s + \vec{k}_i$$

Output is continuous variable entangled state.
With cavity: *Optical Parametric Oscillator (OPO) / cavity assisted spontaneous down-conversion*

Important: Nonlinearity and efficient cavity!

Wavelength tuning





- Type I natural phase matching
- z-cut crystal – phase matching of WGR modes

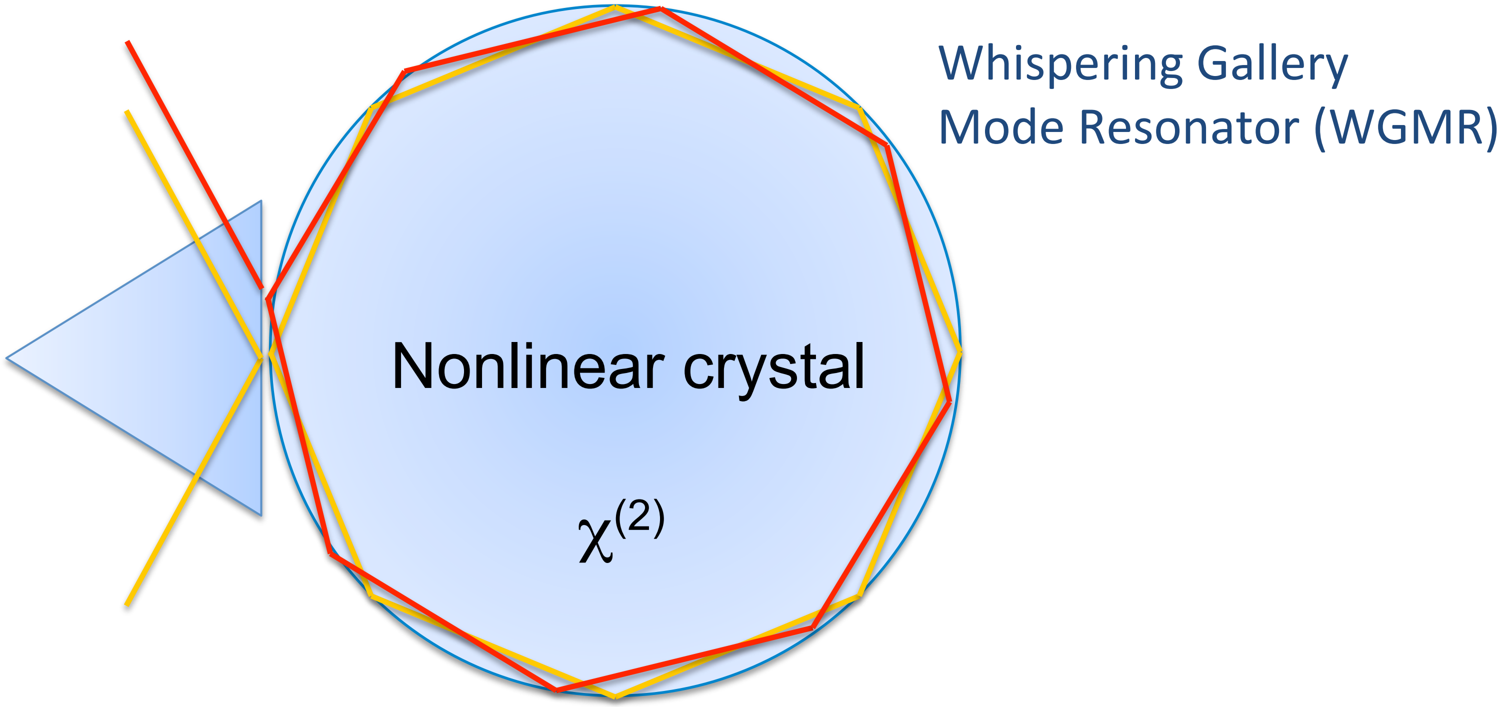
J. Fürst et al., *Phys. Rev. Lett.* 104, 153901 (2010)

Effective index of refraction depends on: Temperature, Mg doping, disk size, voltage

Alternative: periodic poling

K. Sasagawa et al., Appl. Phys. Expr. 2, 122401 (2009)
T. Beckmann et al., PRL 106, 143903 (2011)

Phase Matching in WGM



Energy conservation

$$\omega_p = \omega_s + \omega_i$$

Momentum conservation

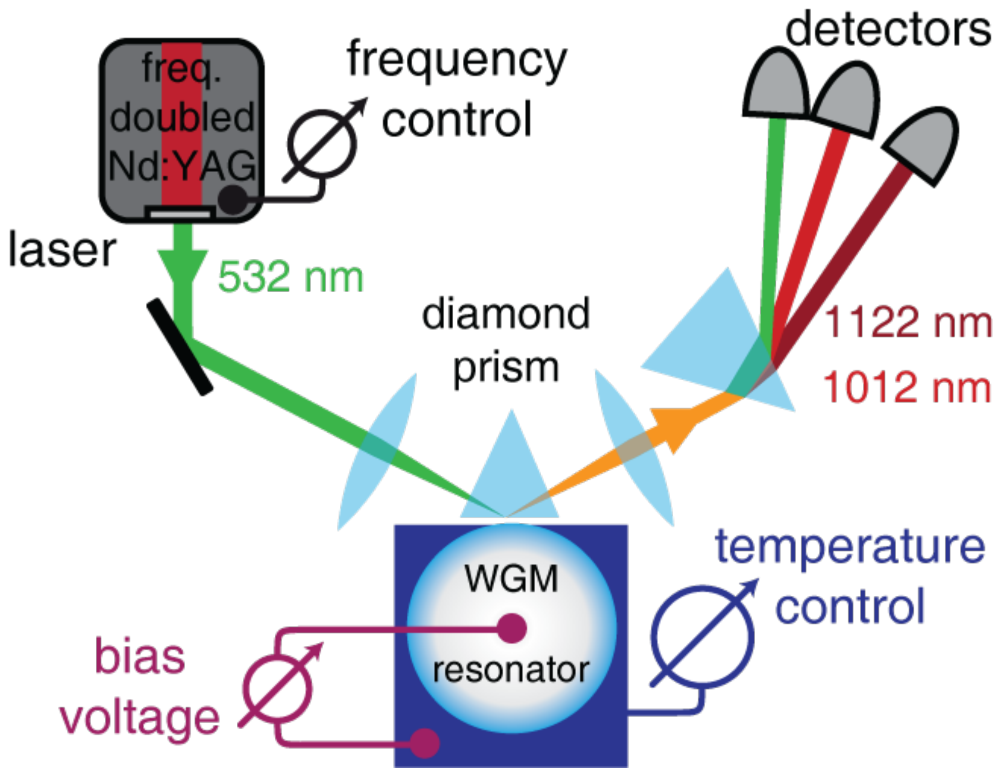
$$\vec{k}_p = \vec{k}_s + \vec{k}_i$$

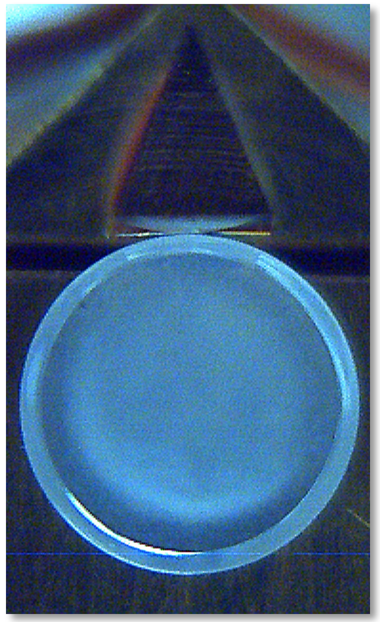
$$m_s + m_i + m_p = 0$$

$$|l_s - l_i| \leq l_p \leq l_s + l_i$$

$$l_s + l_i + l_p = 2\mathbb{N}$$

Optical Parametric Oscillator



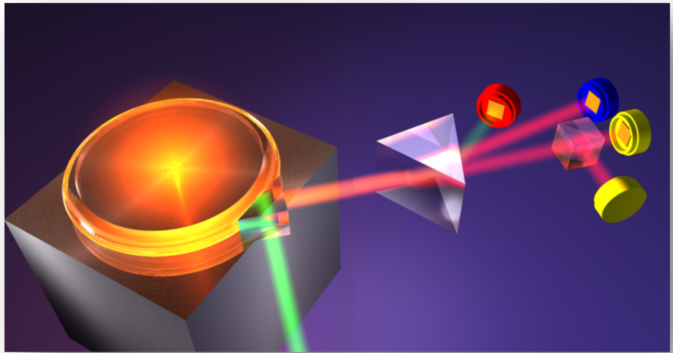


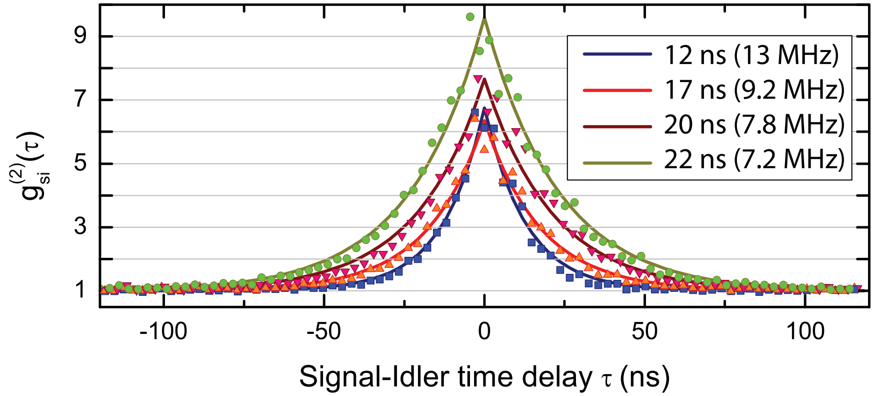
Highly efficient OPO: J. U. Fürst et al., Phys. Rev. Lett. 105, 263904 (2010)
Generation of two-mode squeezing: J. U. Fürst et al., Phys. Rev. Lett. 106, 113901 (2011)

Tunable single photon source

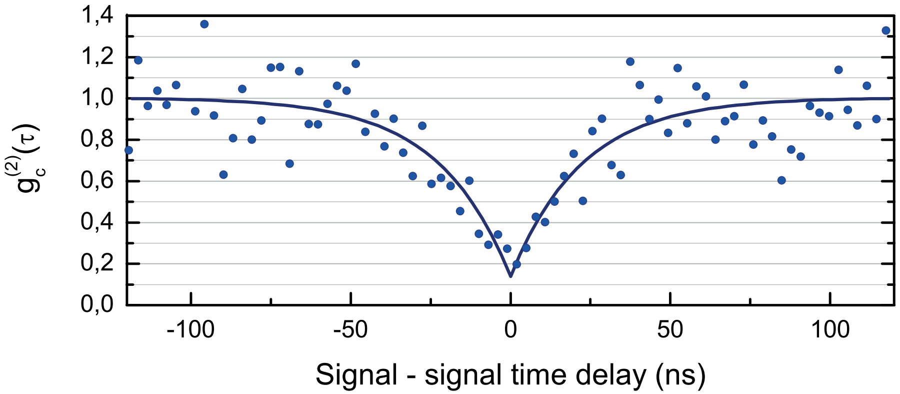
Cavity assisted SPDC

Z. Ou, Y. Lu, Phys. Rev. Lett. 83, 2556 (1999)



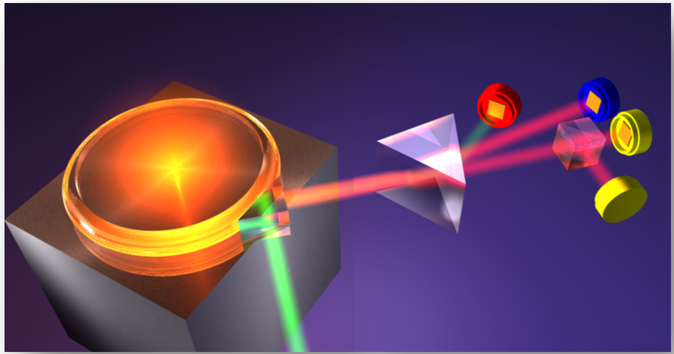


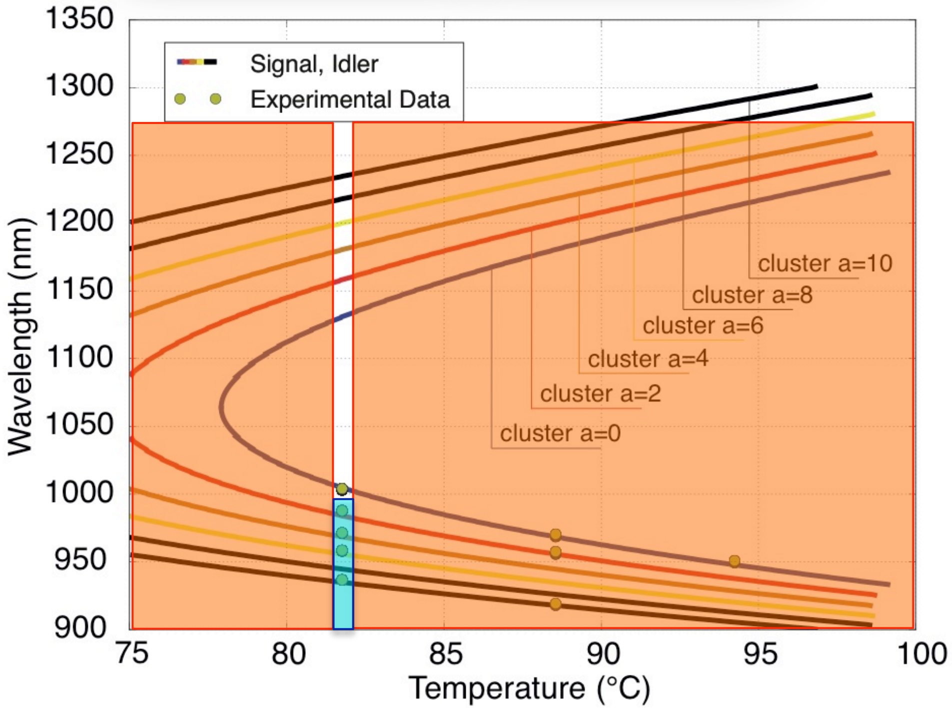
efficiency:
1.3 x 10^7 pairs/(s mW) per 13 MHz
tunable bandwidth:
7 – 13 MHz
(potentially 4 MHz – 100s of MHz)



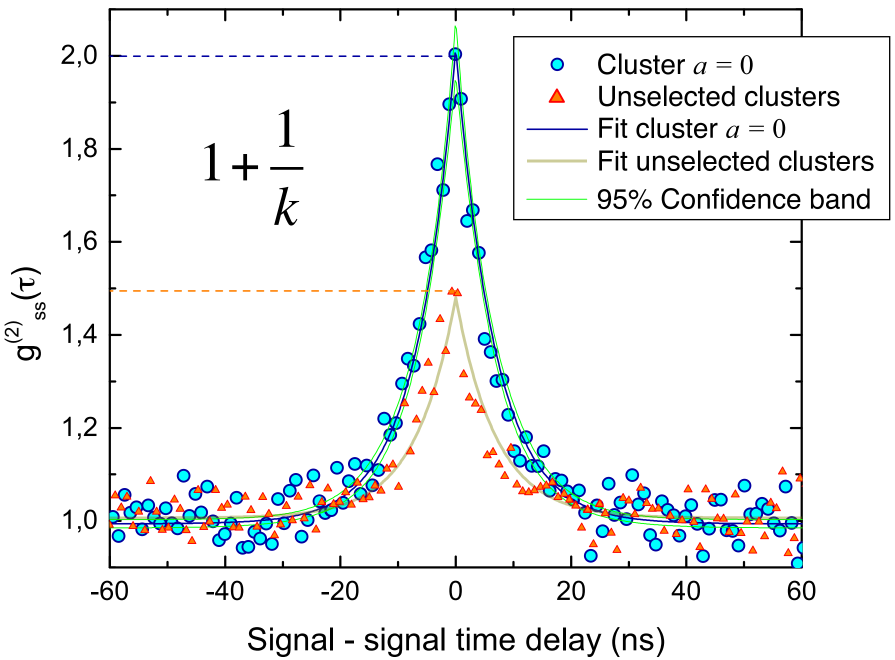
M. Förtsch et al., Nature Communications 4, 1818 (2013)

Single mode photons!



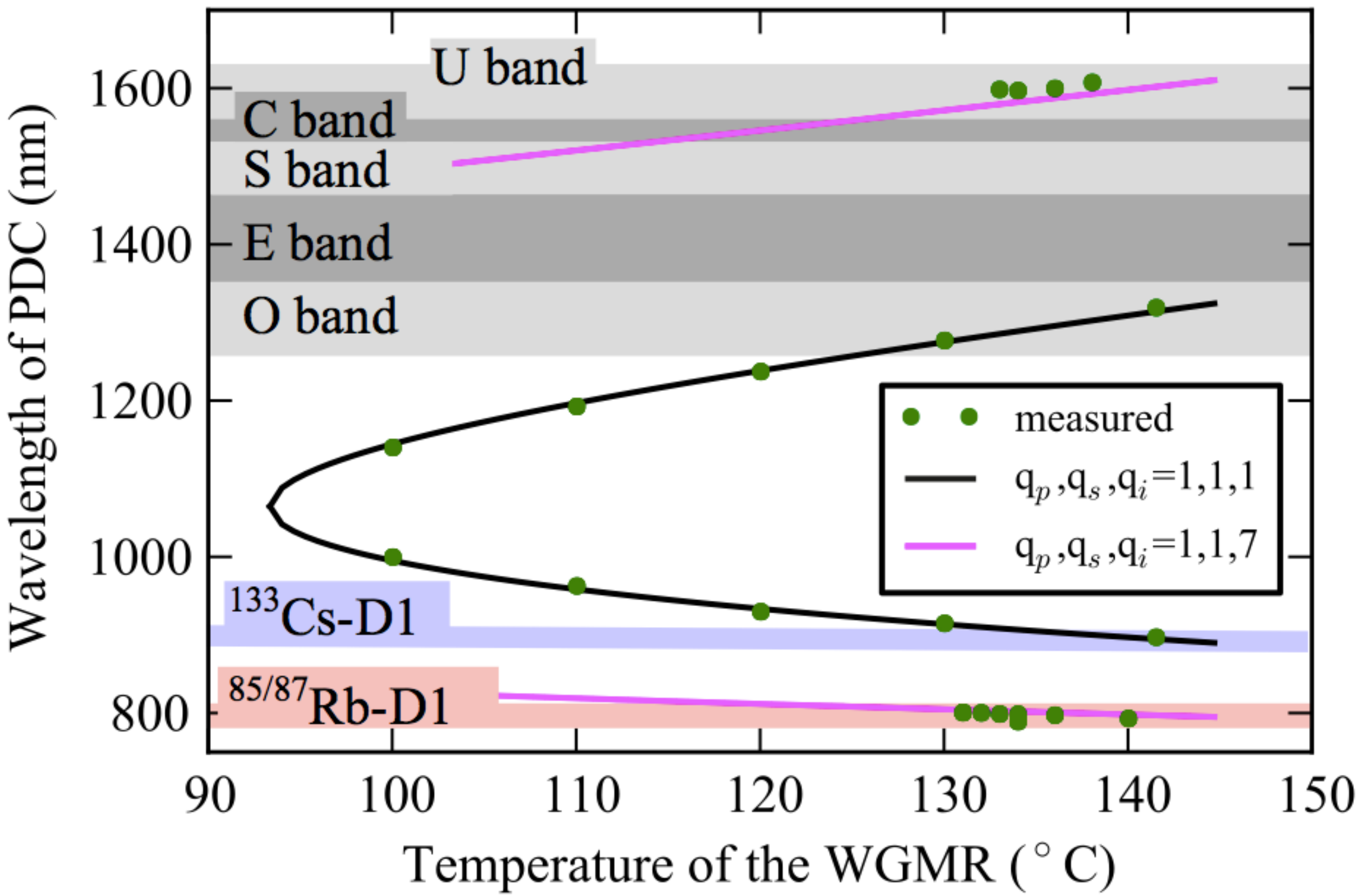


Autocorrelation function

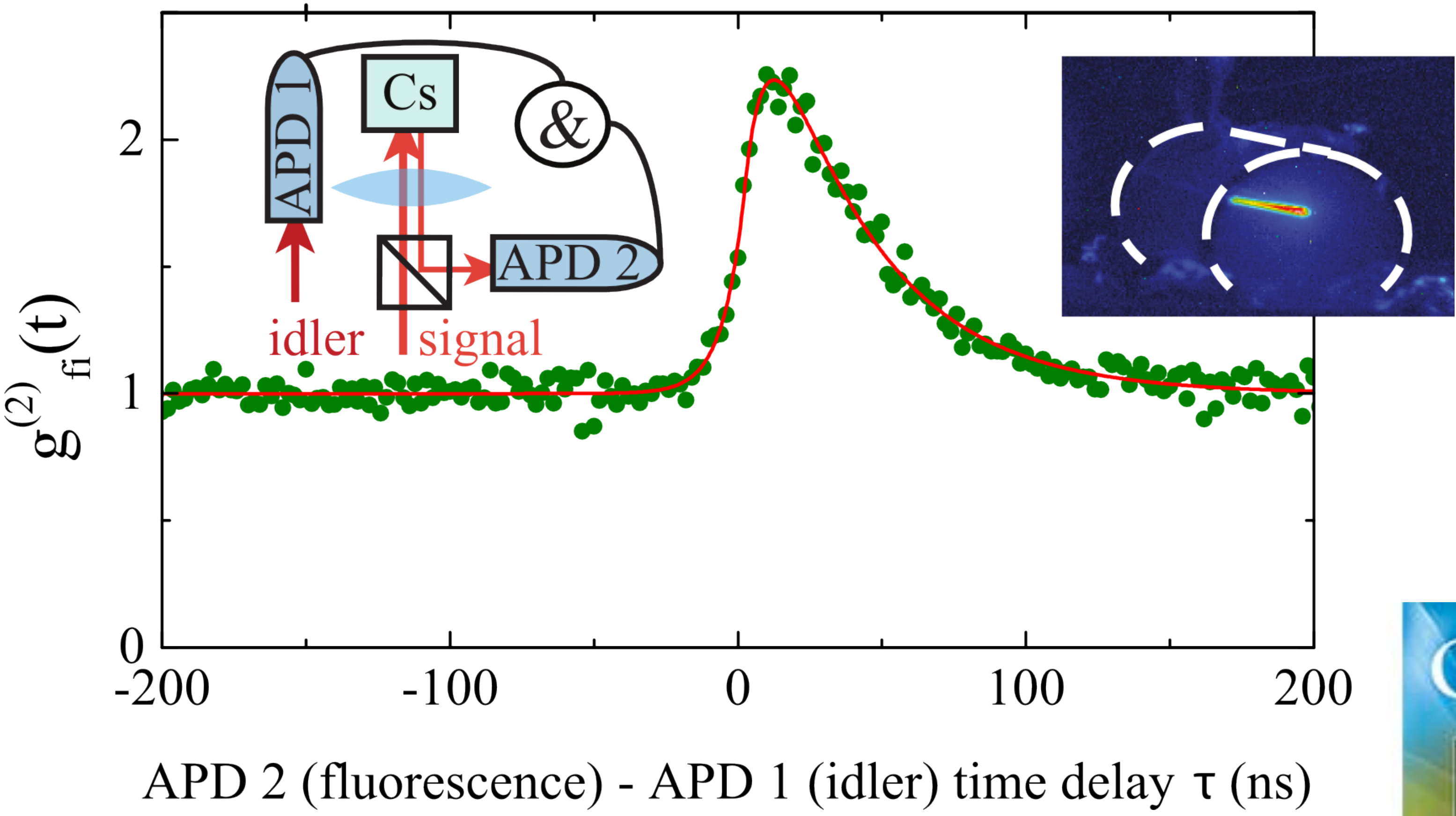


M. Förtsch et al., Phys. Rev. A 91, 023812 (2015)

Adressing atomic transitions

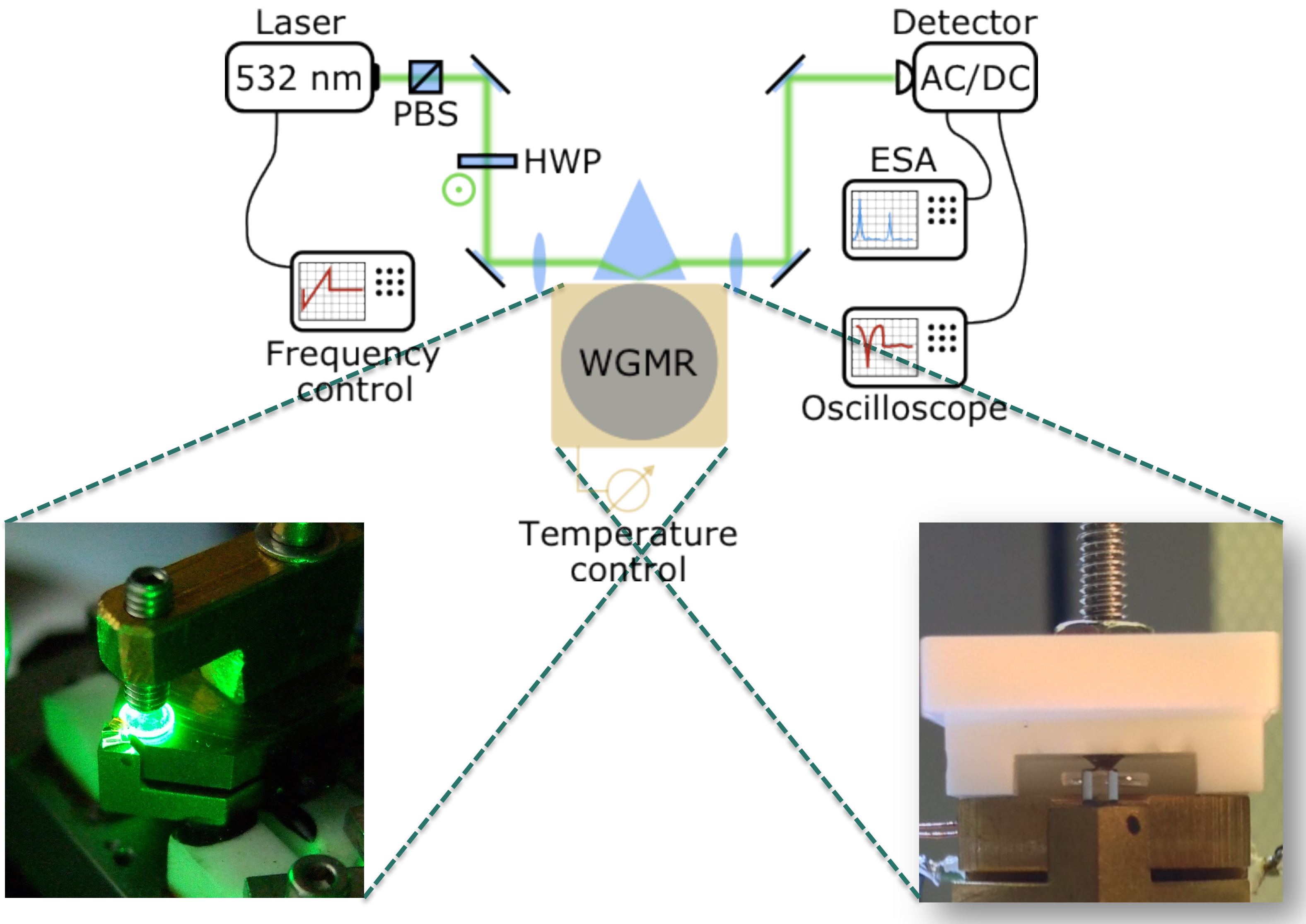


Adressing atomic transitions



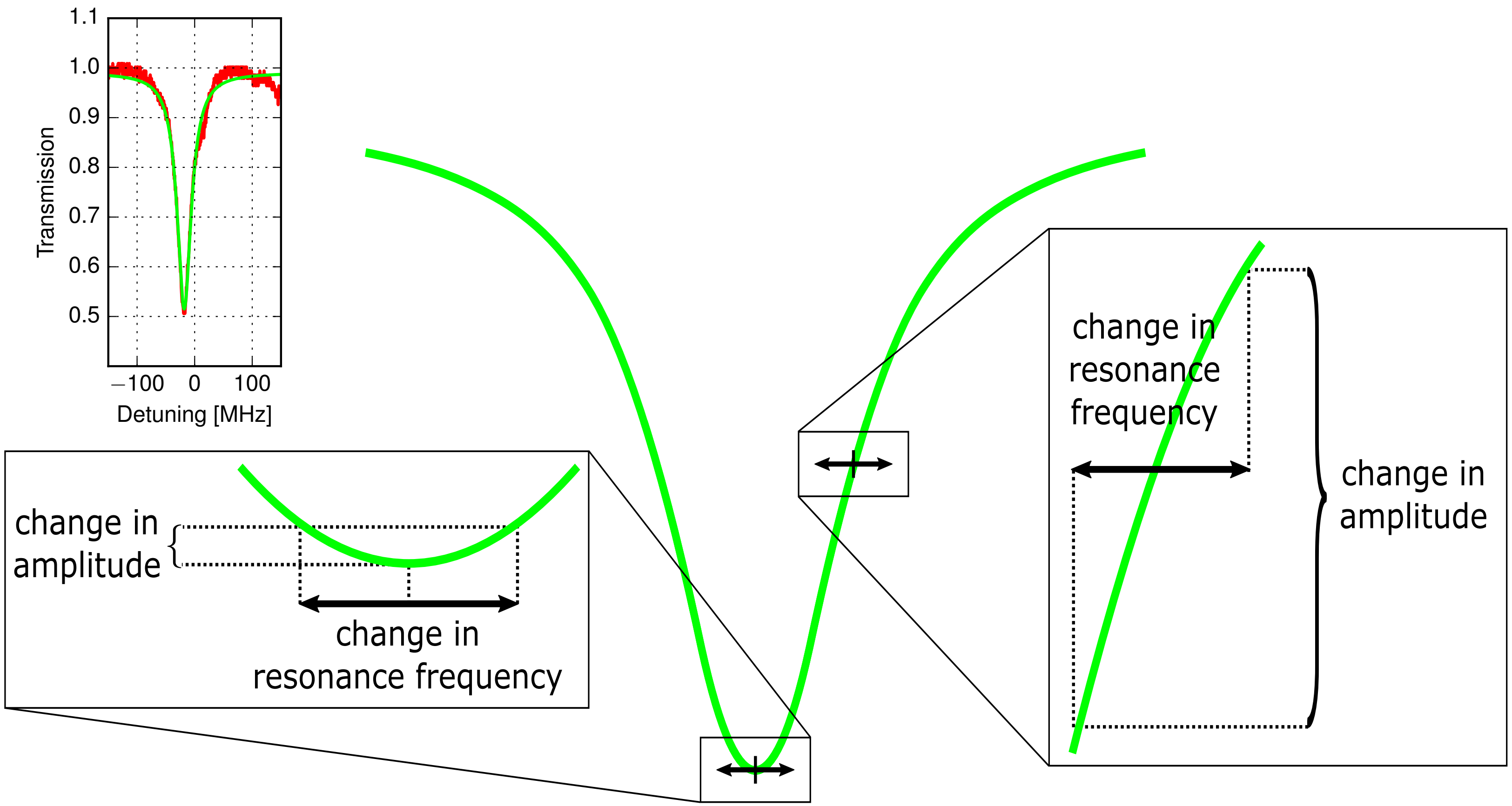
G. Schunk et al., Optica, Vol. 2, Issue 9, 773 (2015)

WGRs and optomechanics



WGRs and optomechanics

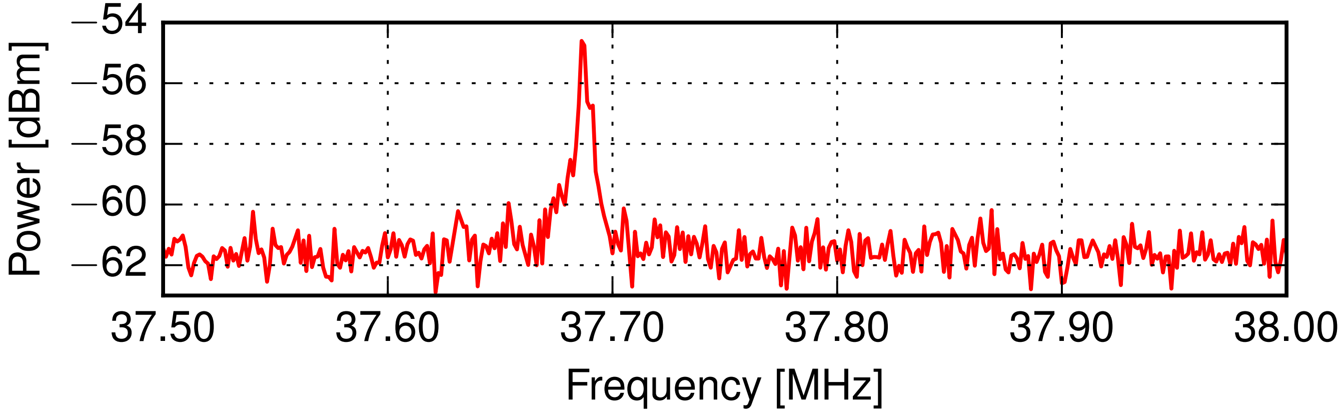
- Detectable optomechanical signature:

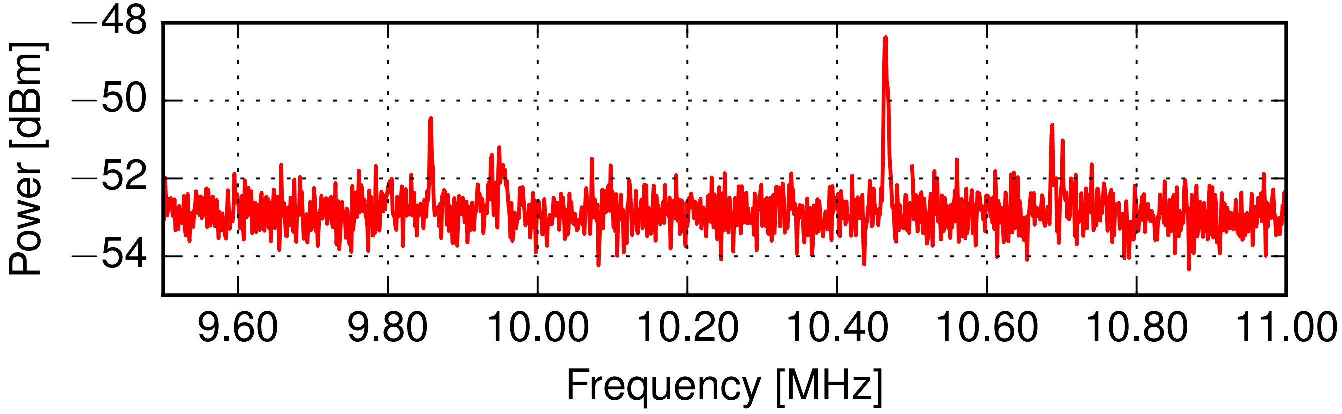


WGRs and optomechanics

- Comparison of resonator mounting techniques:

Clamped resonator

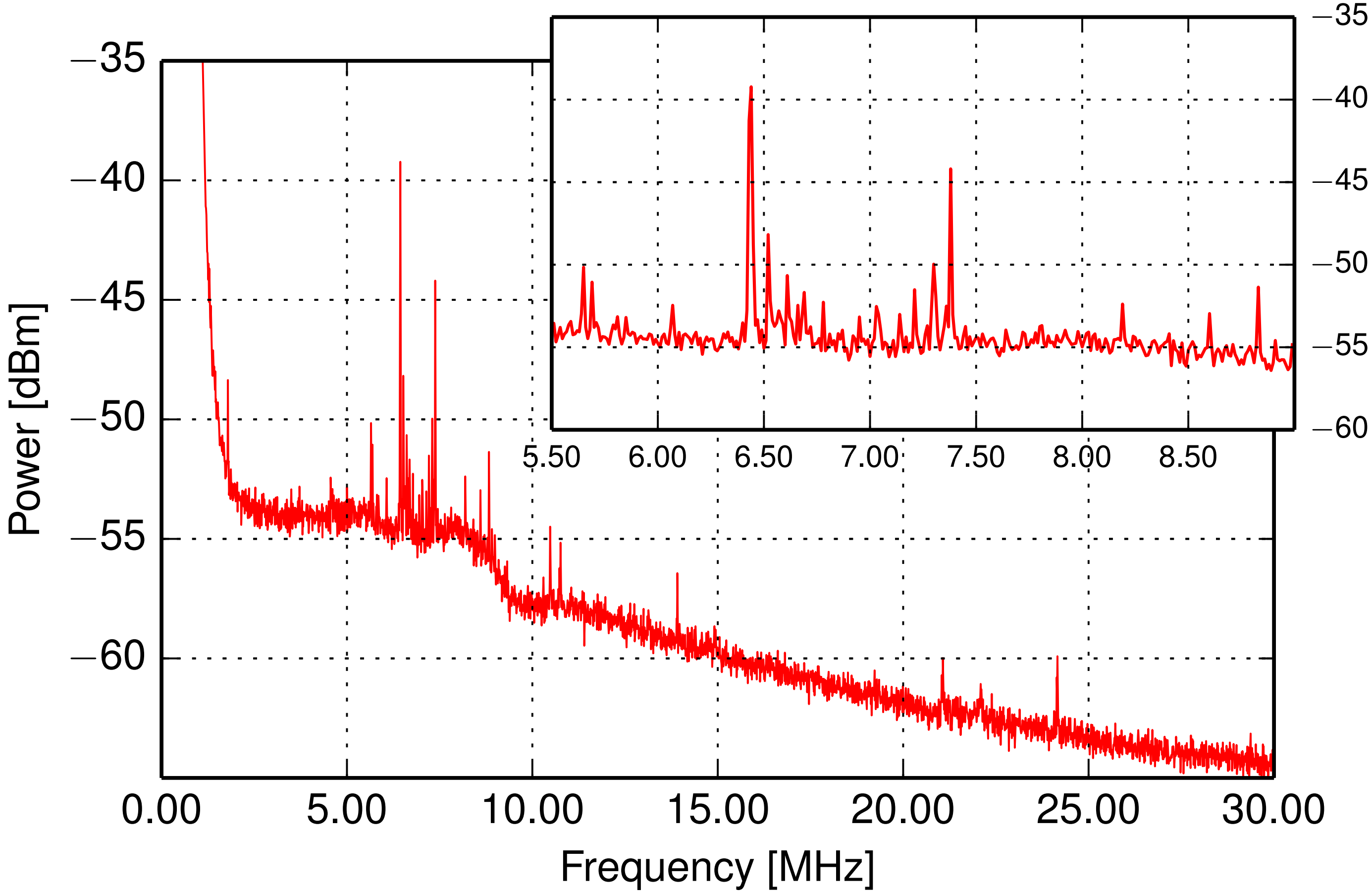




WGRs and optomechanics

- Comparison of resonator mounting techniques:

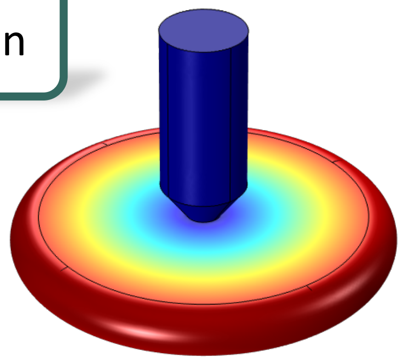
Suspended resonator



WGRs and optomechanics

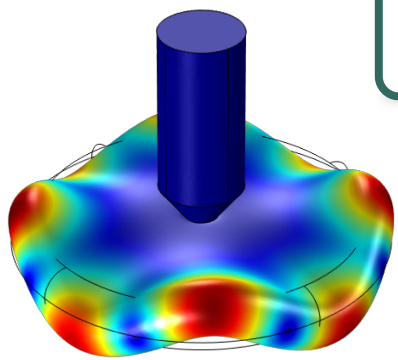
- Simulation of mechanical eigenmodes with COMSOL:

radial oscillation



$27.5\,\mathrm{kHz}$

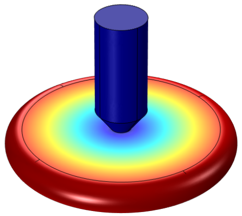
polar oscillation



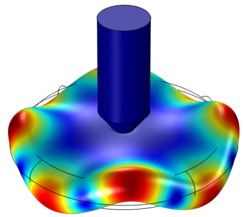
$644.7\,\mathrm{kHz}$

WGRs and optomechanics

- Simulation of mechanical eigenmodes with COMSOL:

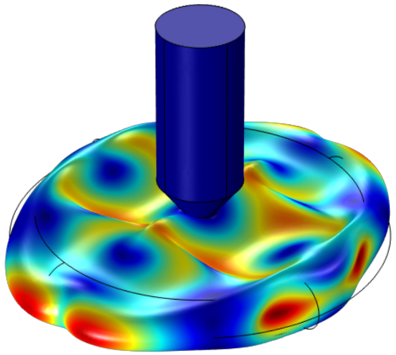


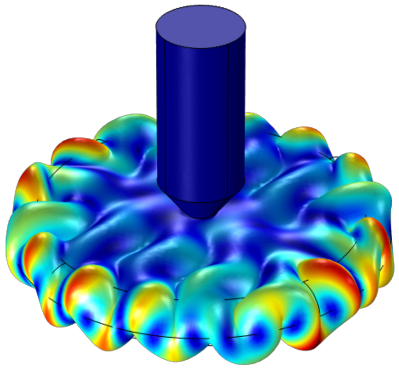
27.5 kHz



644.7 kHz

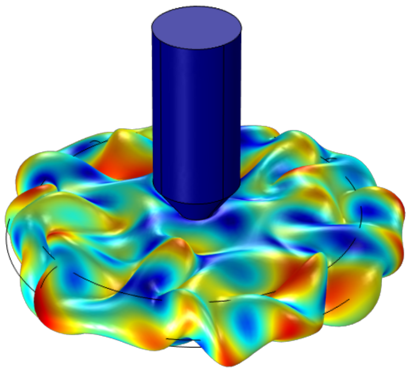
3.7 MHz

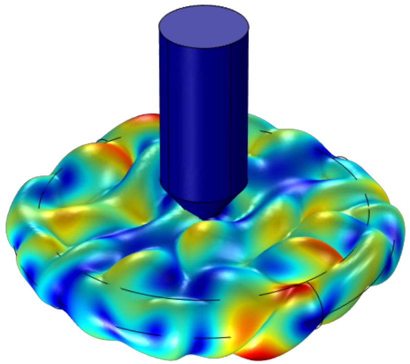




4.09 MHz

3.89 MHz



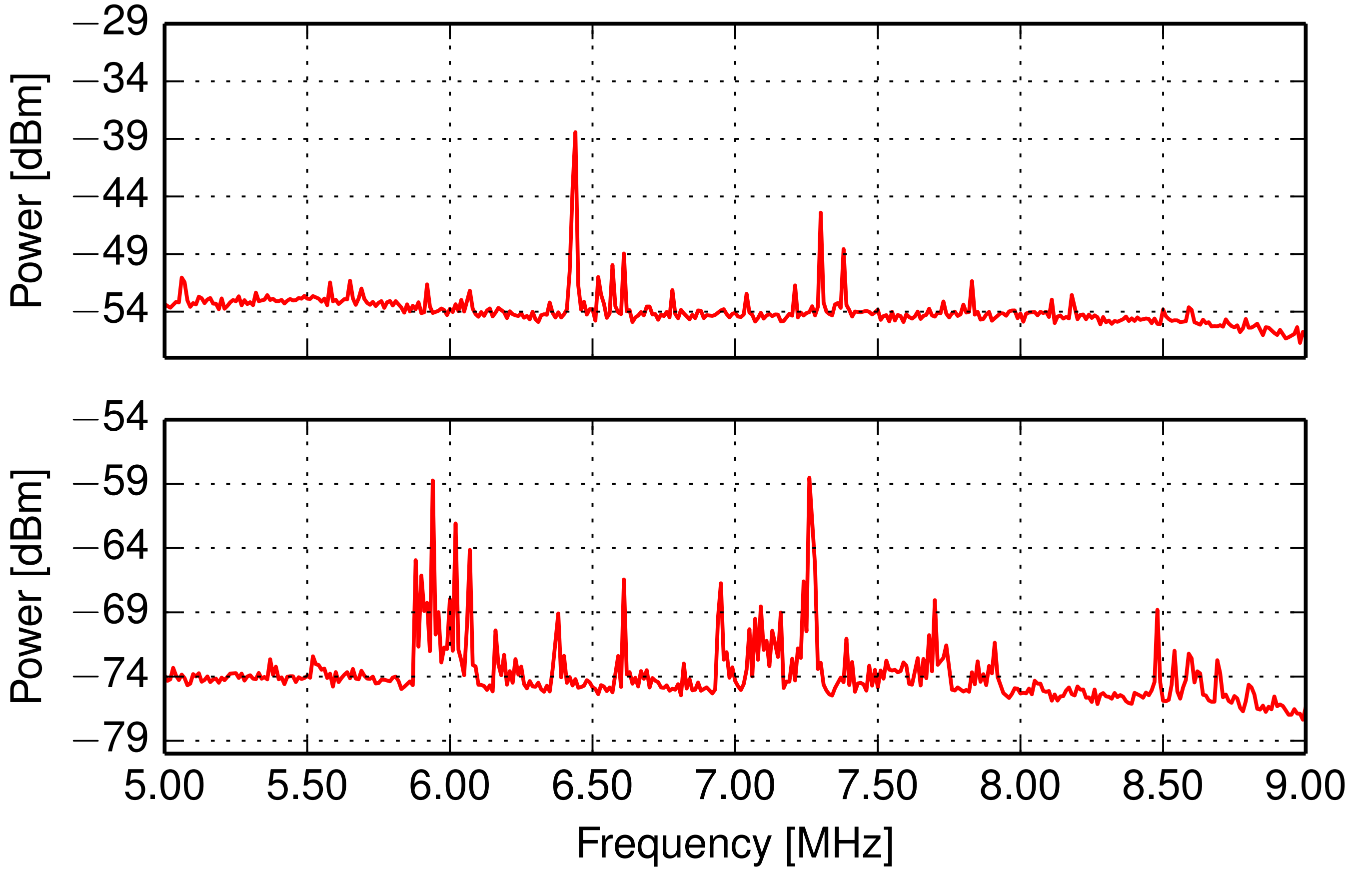


3.94 MHz

- Order of observed mechanical eigenmodes ≈200

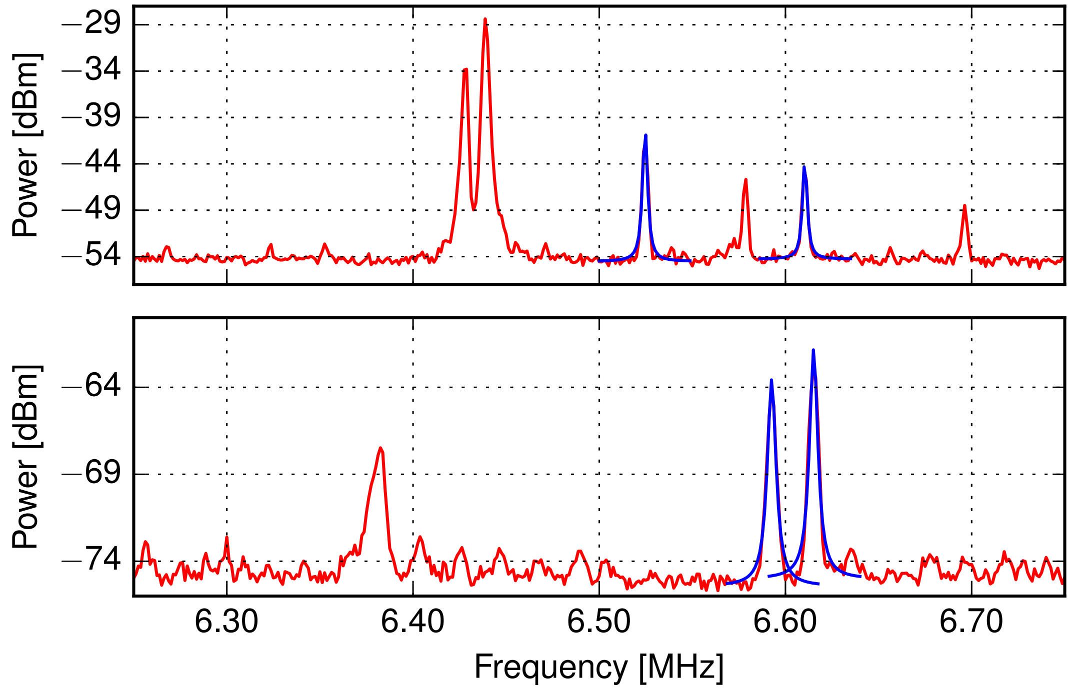
WGRs and optomechanics

- Comparison of two frequency spectra from different resonators:



WGRs and optomechanics

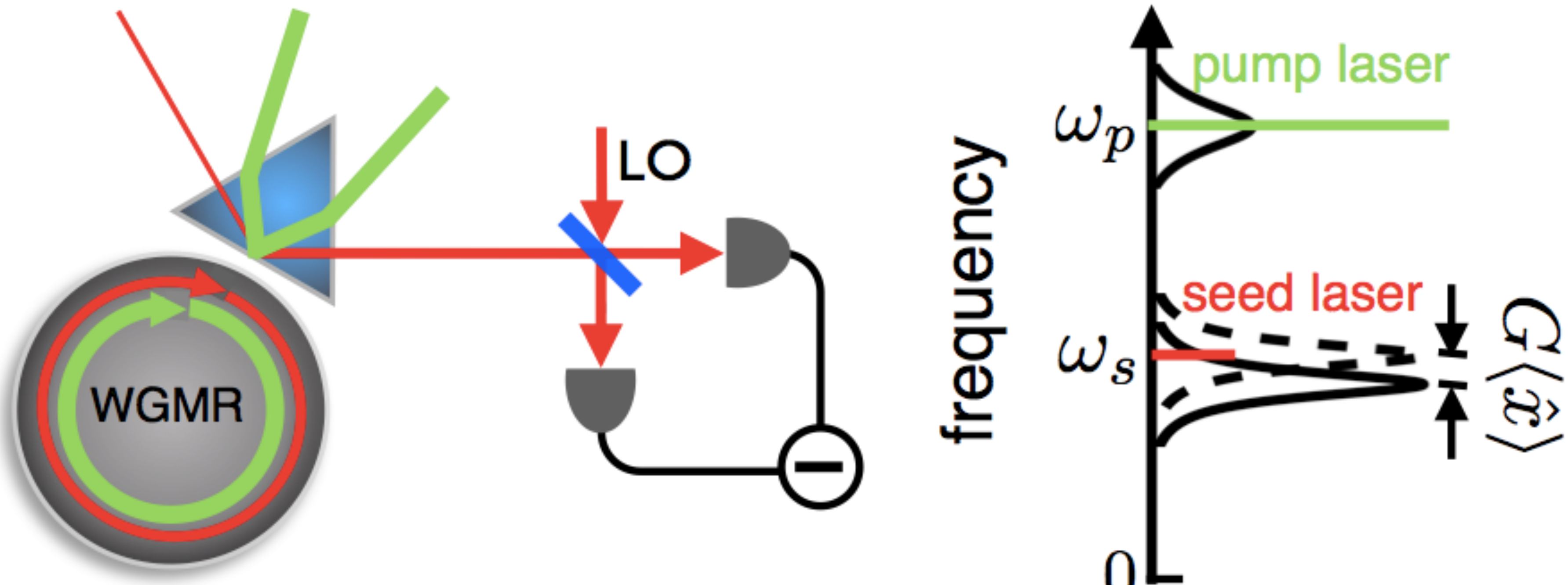
- Comparison of two frequency spectra from different resonators:



- Mechanical Q-factors up to 3000 at room temperature and higher and atmospheric pressure

WGRs and optomechanics

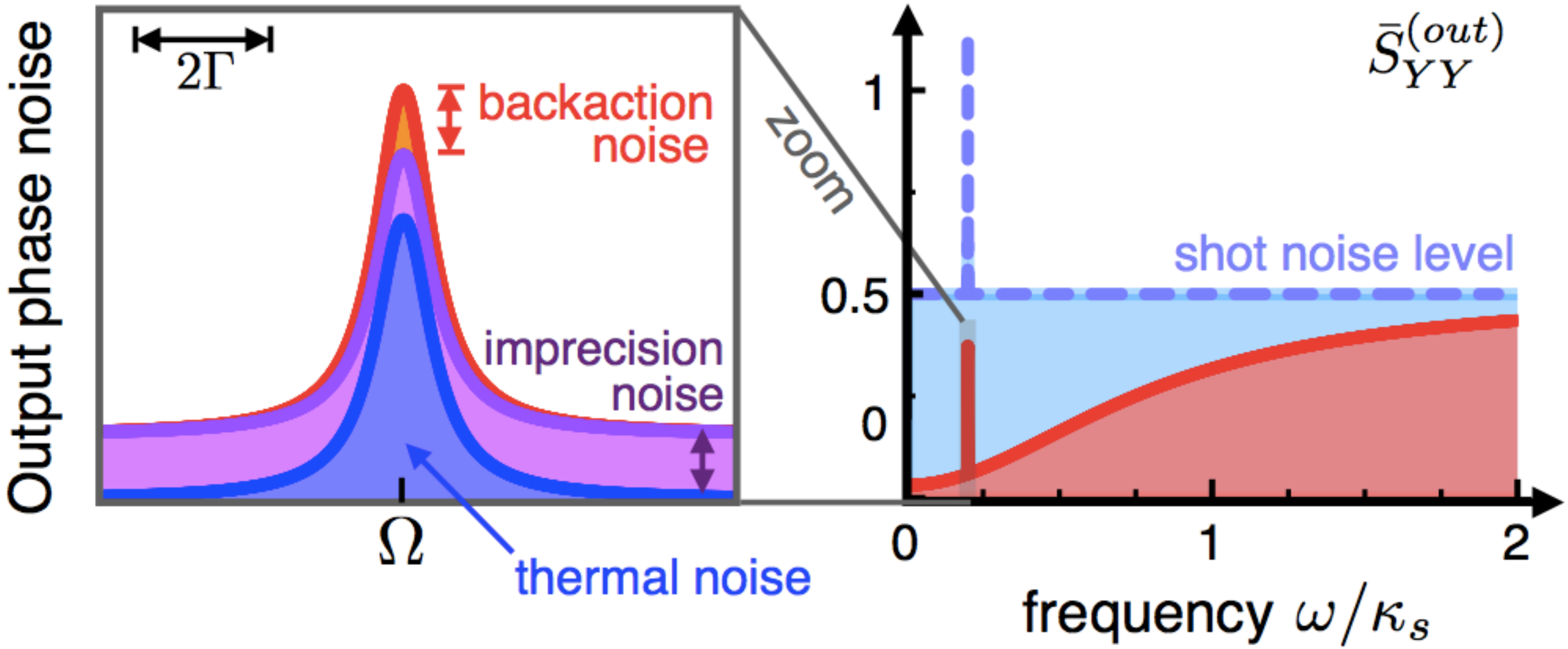
Combine nonlinear optics and optomechanics



V. Peano et al., Phys. Rev. Lett. 115, 243603 (2015)

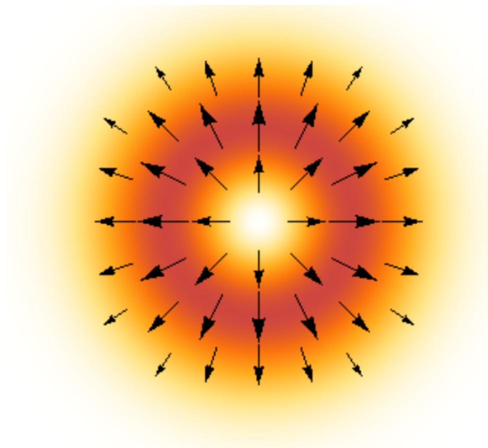
WGRs and optomechanics

Combine nonlinear optics and optomechanics

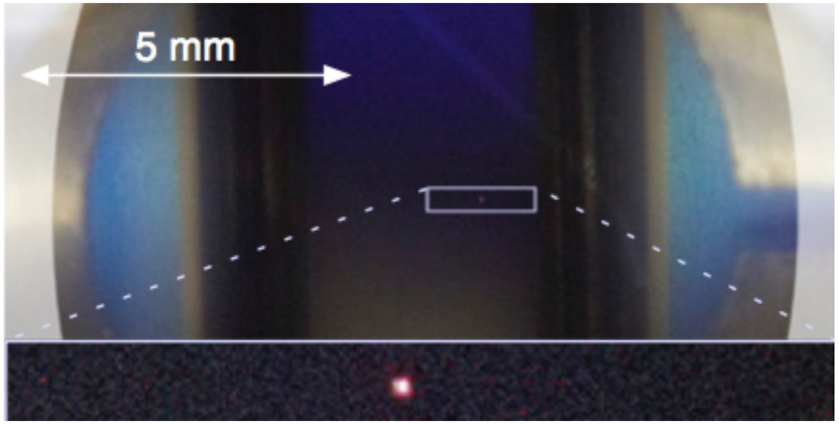


V. Peano et al., Phys. Rev. Lett. 115, 243603 (2015)

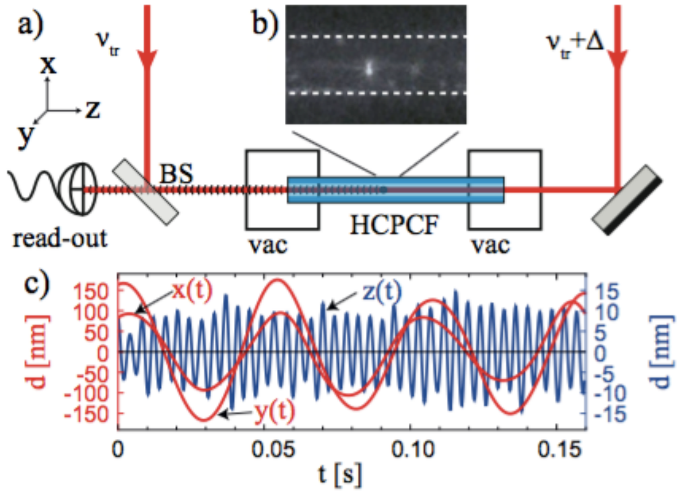
Quantum inspired sensing



Tracking of particle motion



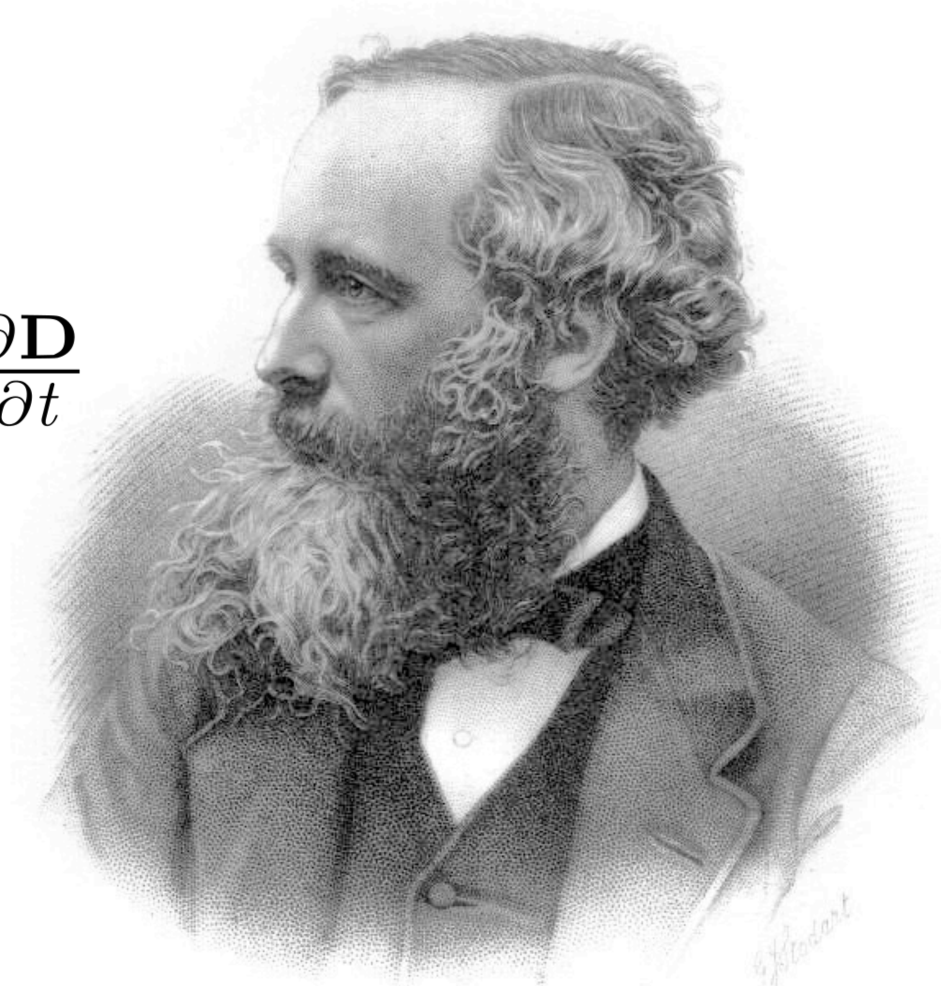
N. Kiesel et al., PNAS USA, vol. 110, 14180–14185



D. Grass et al., arXiv:1603.09393

Maxwell‘s Equations

$$\nabla \cdot \mathbf{D} = \rho$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$



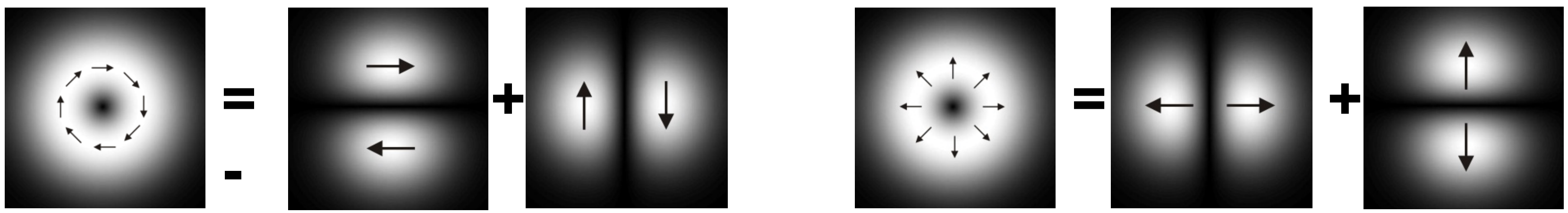
The Radial and Azimuthal Mode

- Modes can be described classically with the transverse mode functions:

$$\mathbf{u}^A = (-\mathbf{e}_H\,\psi_{01} + \mathbf{e}_V\,\psi_{10})\,/\sqrt{2}, \quad \mathbf{u}^R = (\mathbf{e}_H\,\psi_{10} + \mathbf{e}_V\,\psi_{01})\,/\sqrt{2}$$

- Or quantum mechanically with appropiate annihilation operators:

$$\hat{a}_A = \frac{1}{\sqrt{2}}(-\hat{a}_{H01} + \hat{a}_{V10}), \quad \hat{a}_R = \frac{1}{\sqrt{2}}(\hat{a}_{H10} + \hat{a}_{V01})$$



The classical radially polarized mode is not separable in its polarization and spatial degrees of freedom
- structural inseparability

C.E.R. Souza et al., Phys. Rev. Lett. 99, 160401 (2007), A. Holleczek et al, arXiv:1007.2528 (2010), A. Holleczek et al., Optics Express 19, 9714 (2011)

Classical entanglement

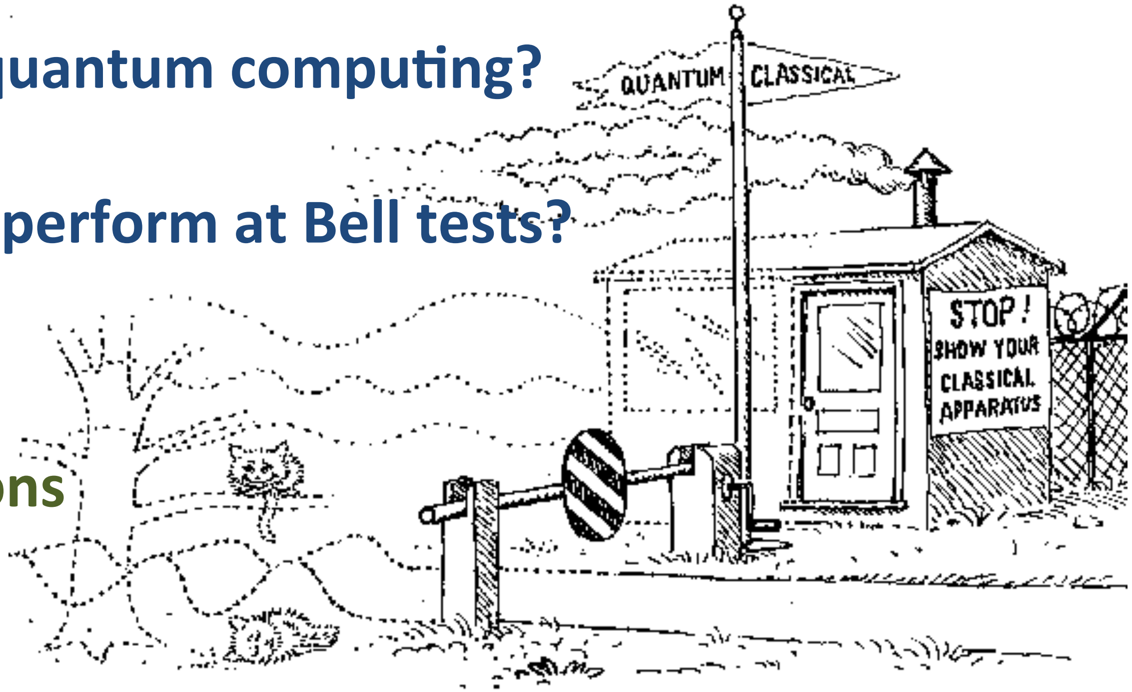
quantum – classical devide is not so obvious,

and deserves a closer look ...

What does non-classical mean?

What is really needed for quantum computing?

How do these correlations perform at Bell tests?

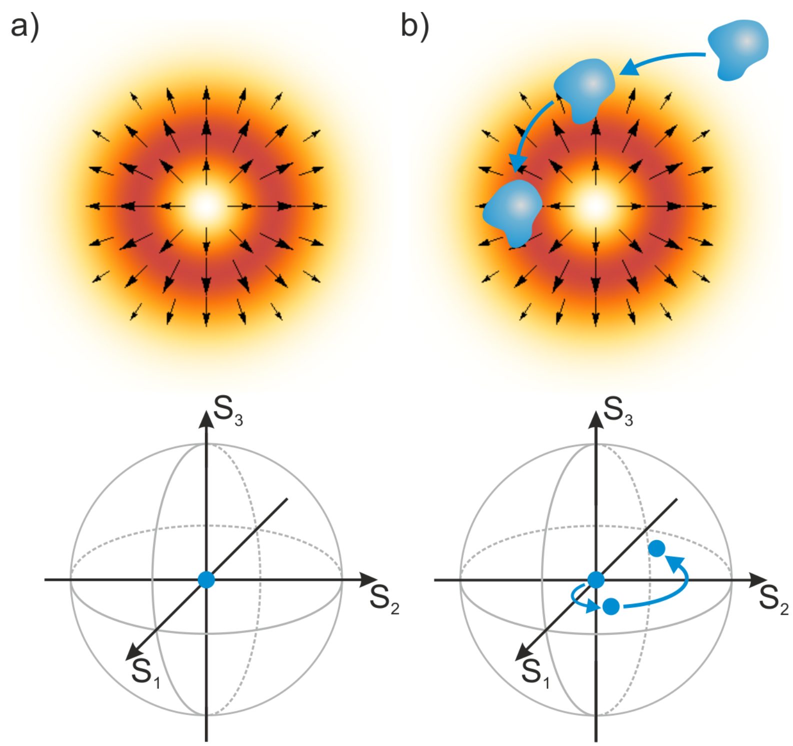


→ Operational investigations

Tracking Birds (supersonic species)

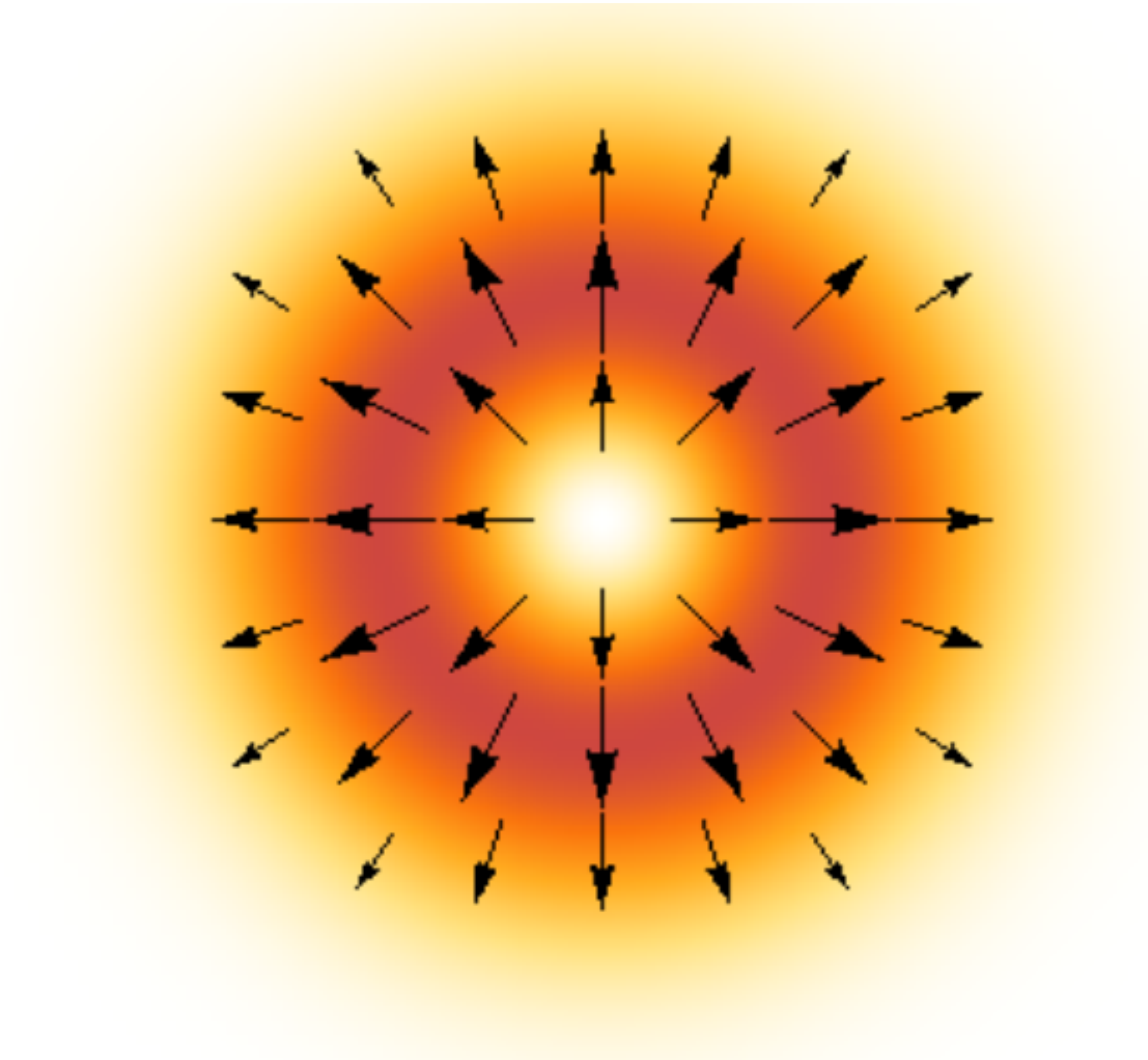
Sensing with „Classical Entanglement“

Correlations between two degrees of freedom

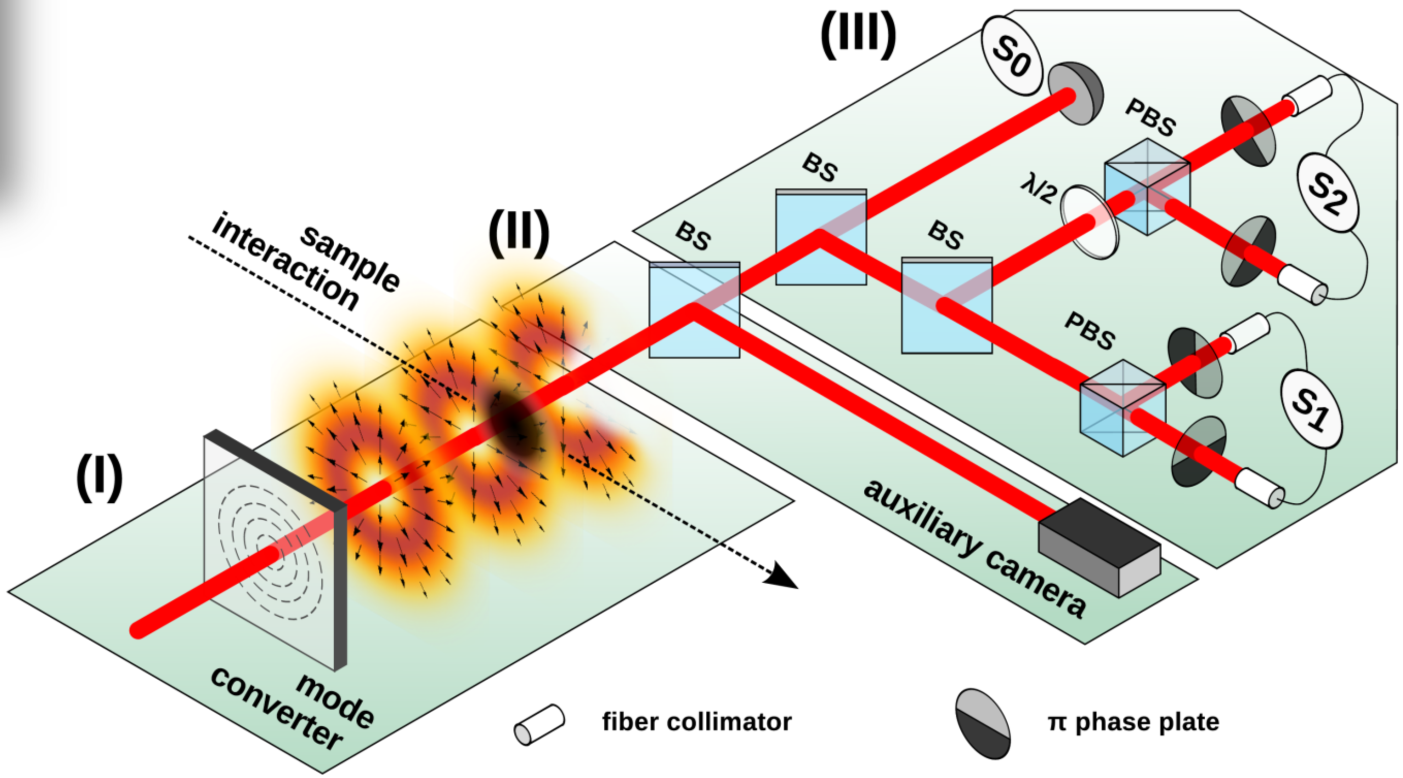


Sense spatial changes with polarization measurements.

Tracking Birds (supersonic species)

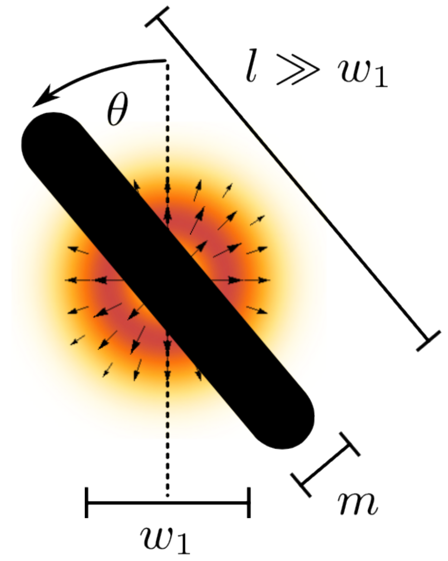


Sensing with „Classical Entanglement“

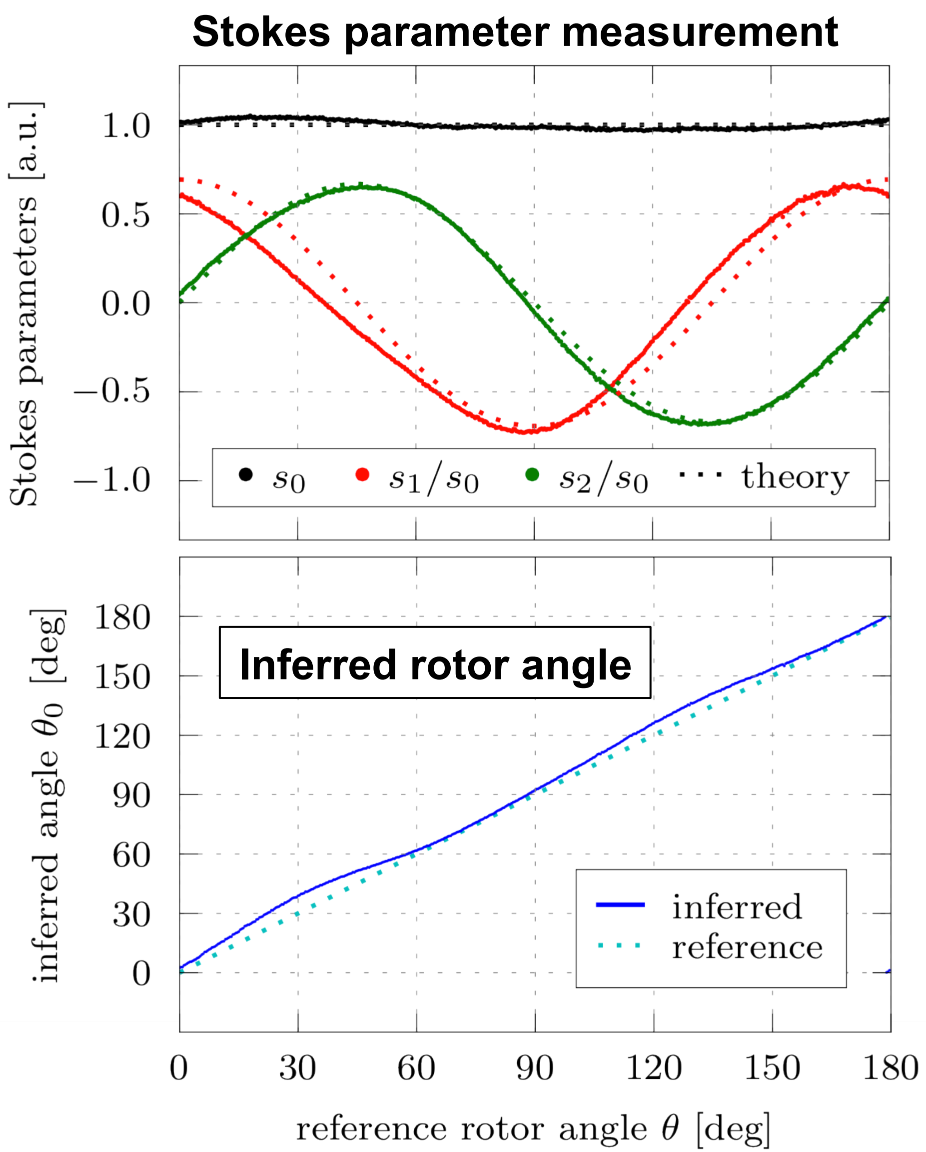


Spatial sensing with GHz bandwidth!

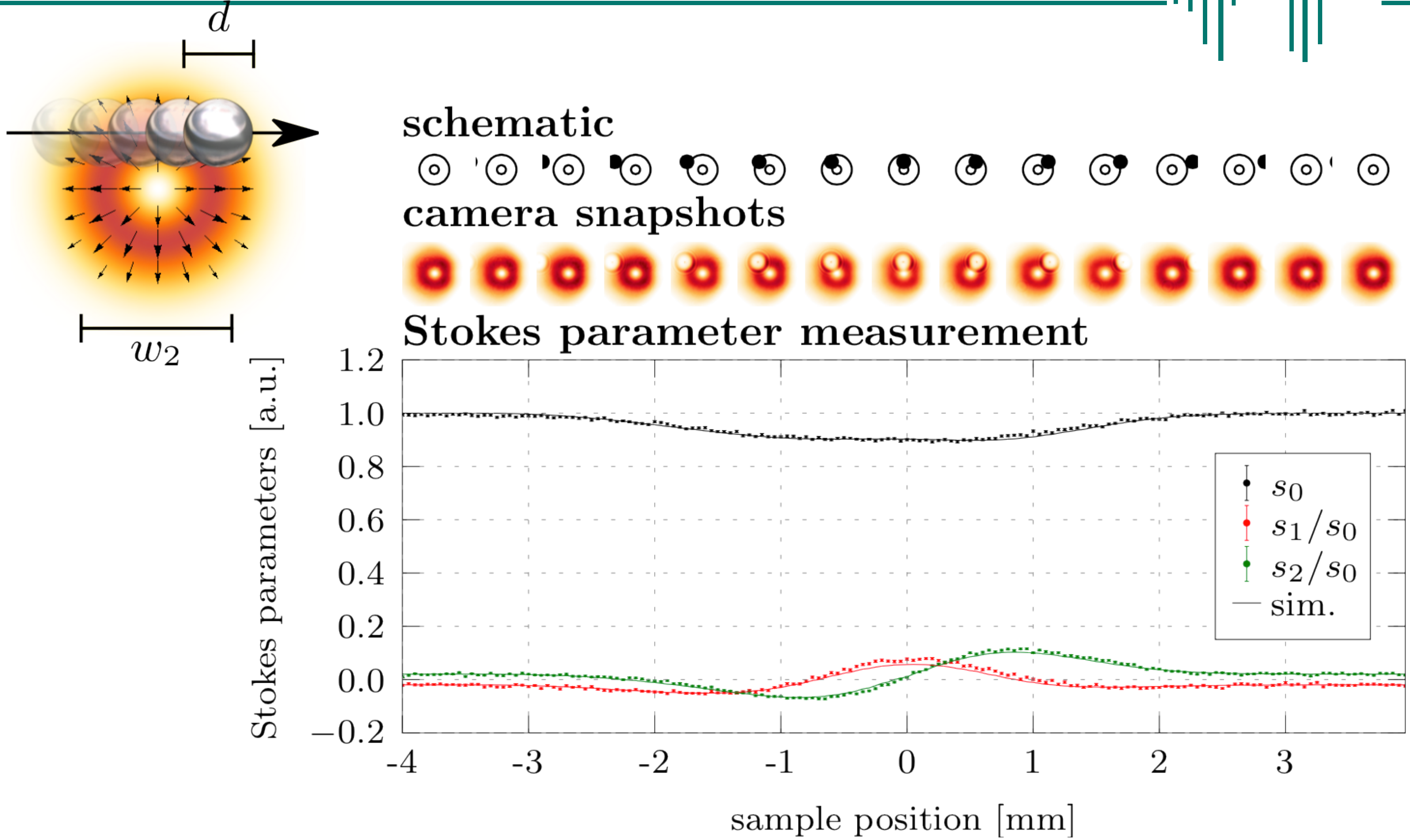
Sensing with „Classical Entanglement“



S. Berg-Johansen et al., Optica 2(10), 864 (2015)



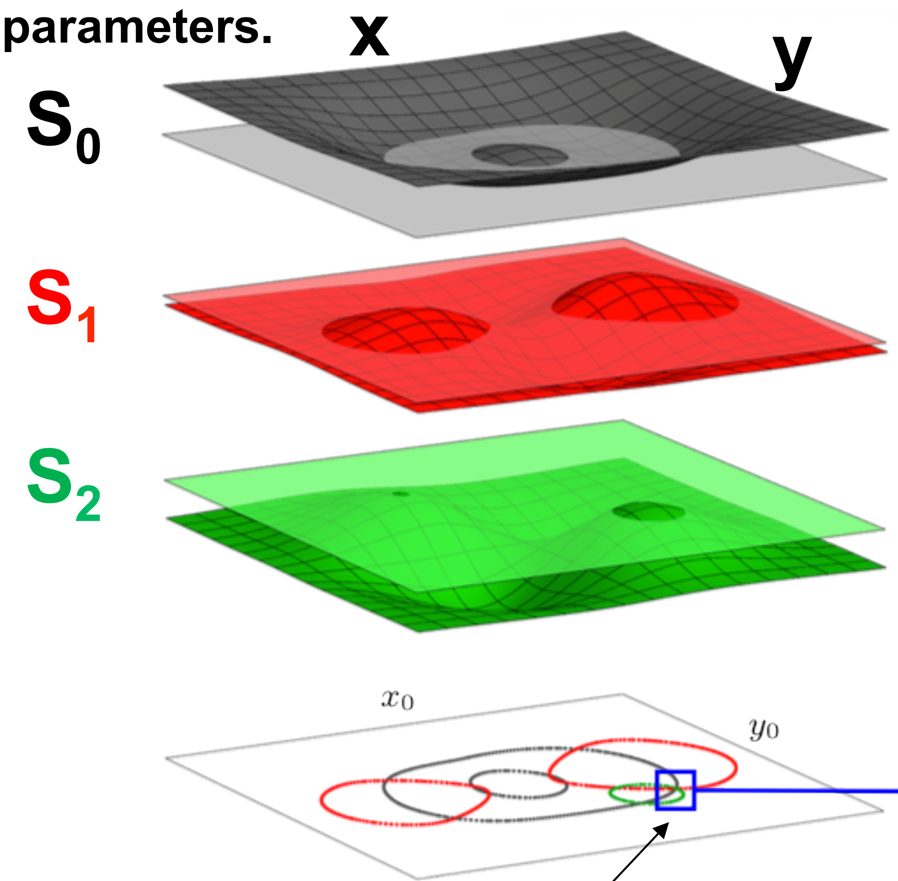
Sensing with „Classical Entanglement“



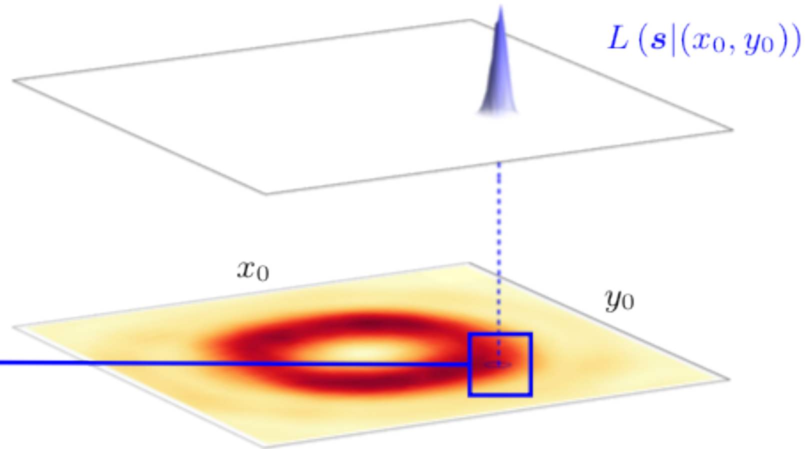
S. Berg-Johansen et al., Optica 2(10), 864 (2015)

Sensing with „Classical Entanglement“

Pre-computed surfaces describe expected Stokes parameters.



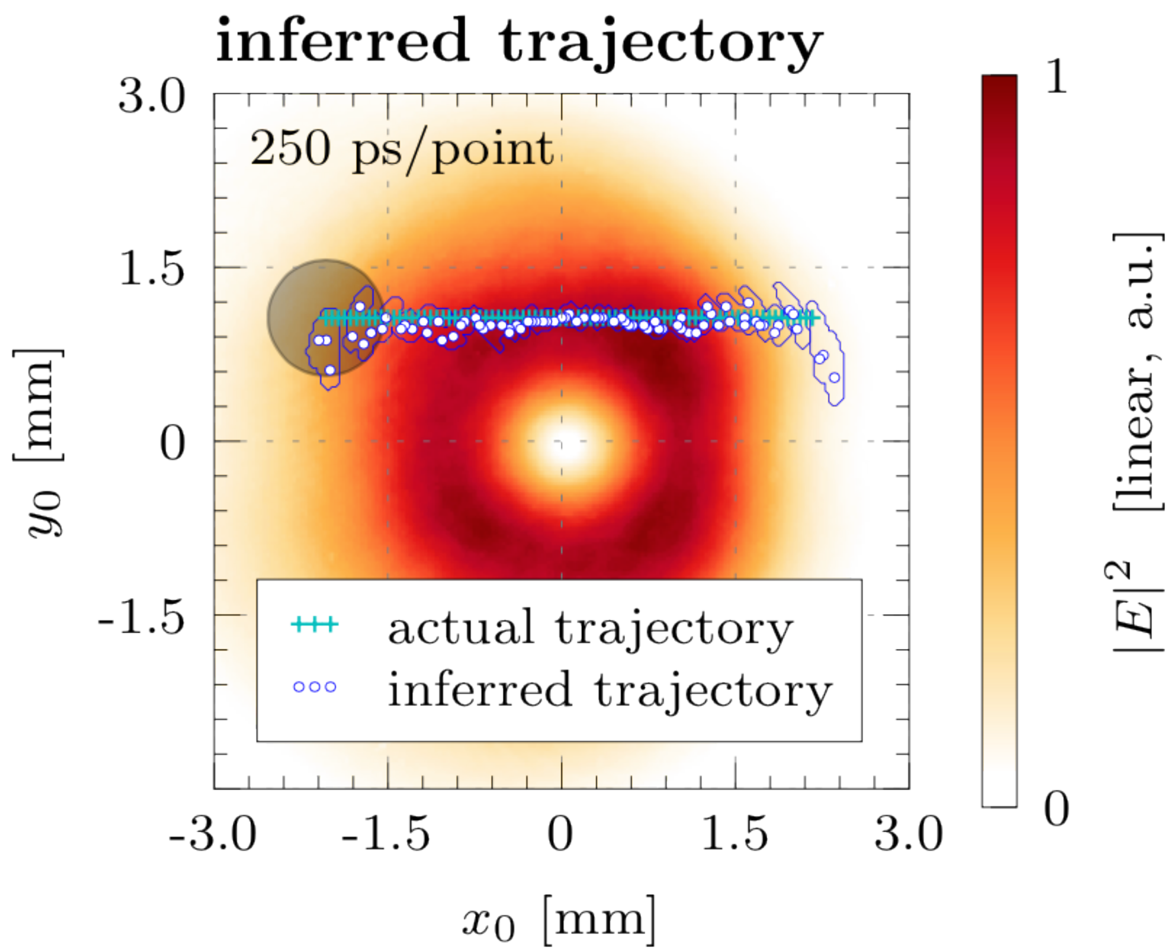
Measured Stokes parameters correspond to intersecting planes.



Intersection of contours indicates position.

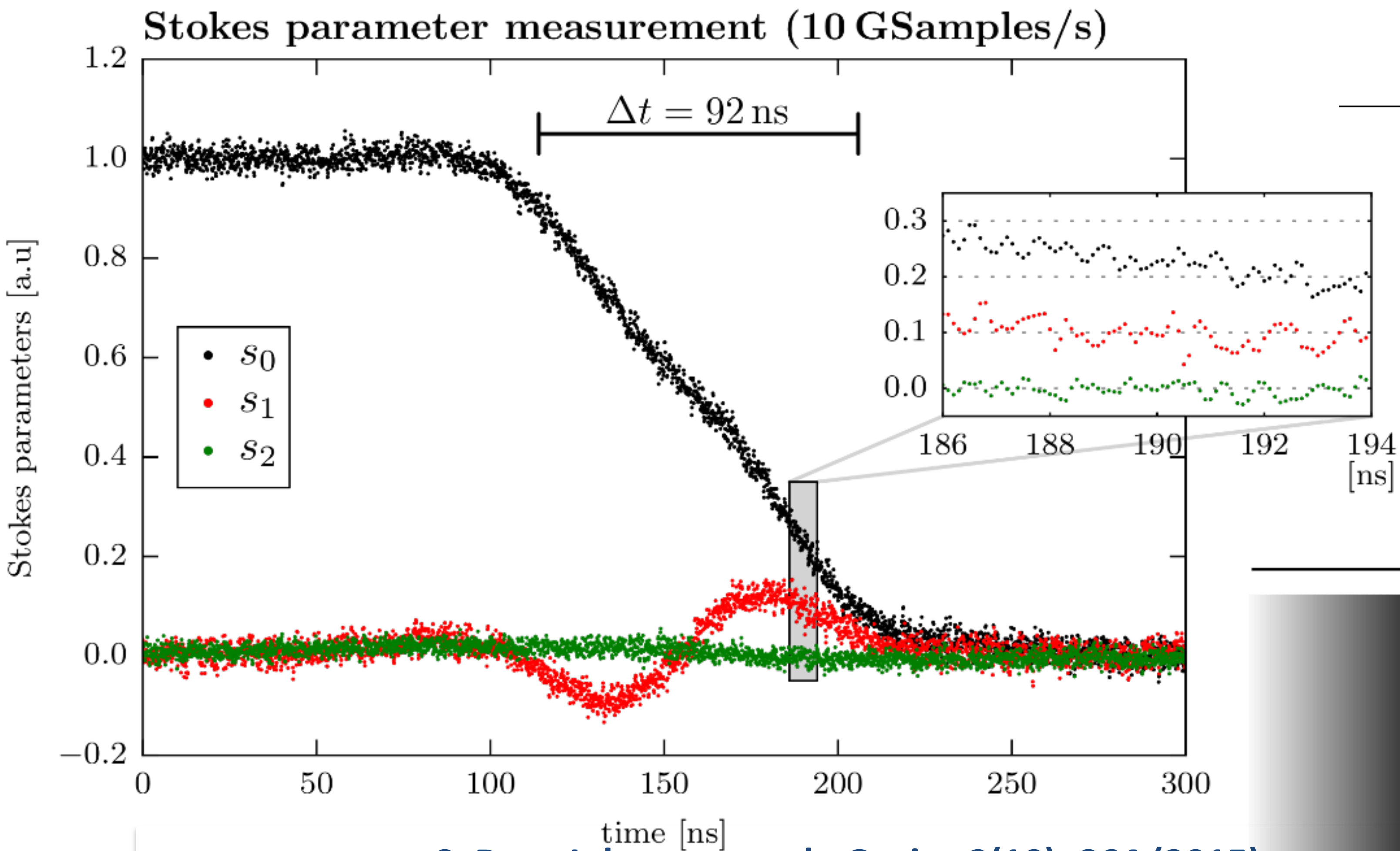
Likelihood function allows position inference in the presence of experimental noise.

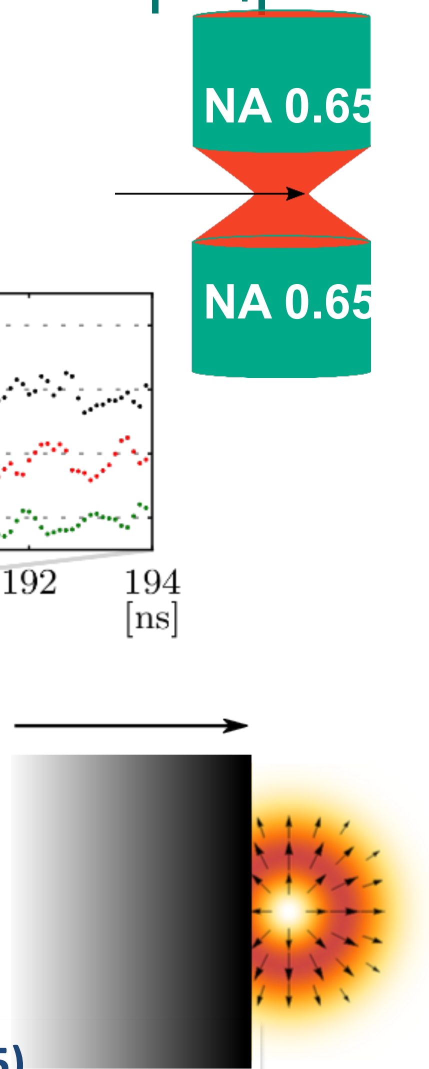
Sensing with „Classical Entanglement“



S. Berg-Johansen et al., Optica 2(10), 864 (2015)

Sensing with „Classical Entanglement“





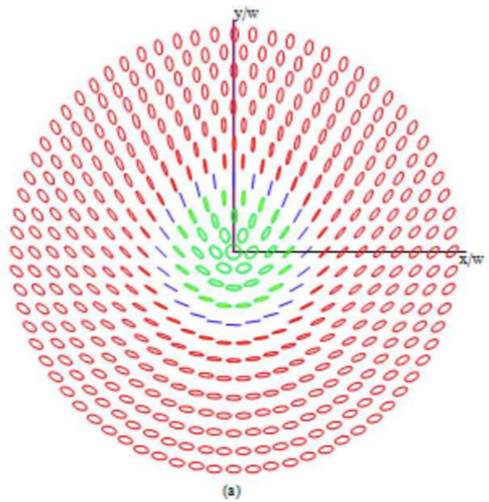
S. Berg-Johansen et al., Optica 2(10), 864 (2015)

Can be done more?

- 3D sensing (multiple beams / colours)

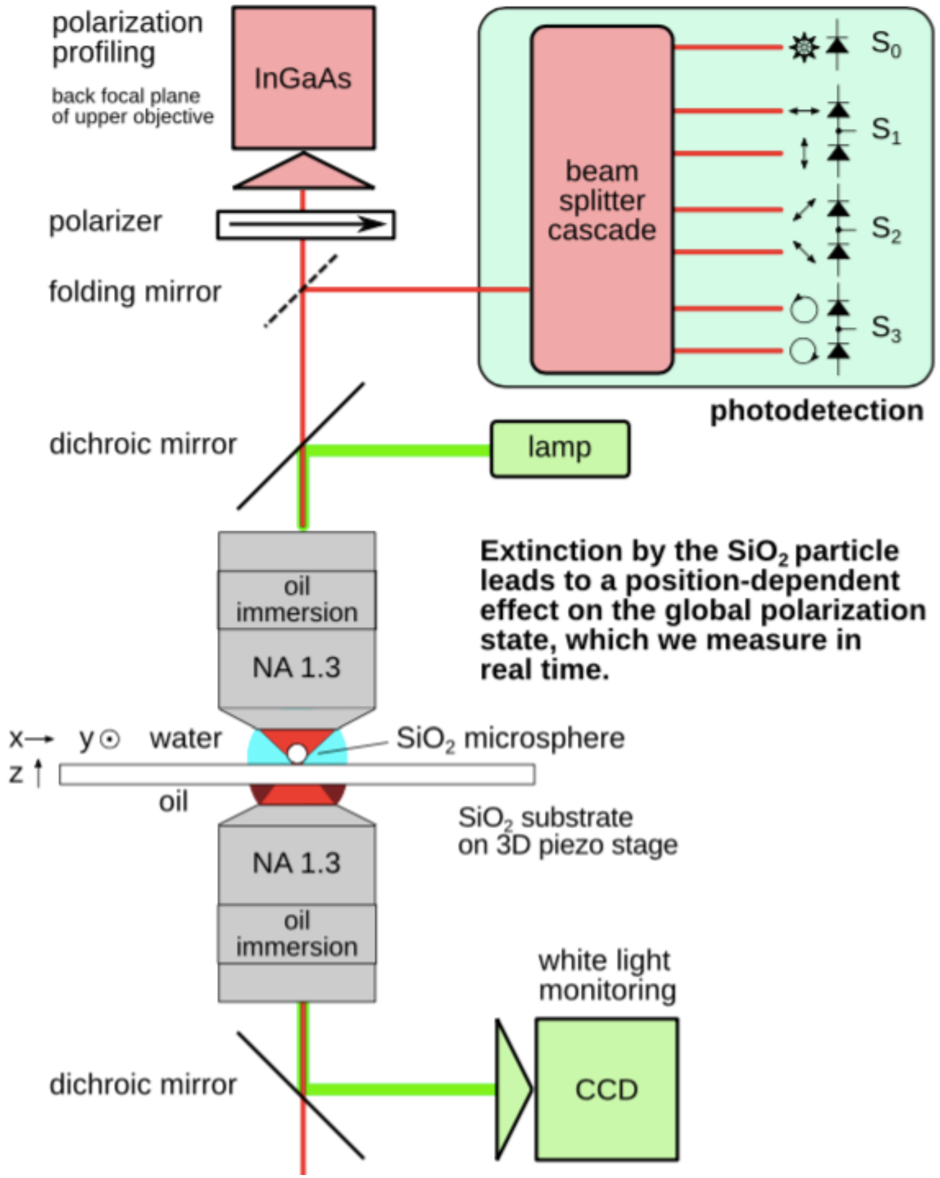
- use different classically entangled
probe beams

- quantum limits?
shot noise!



Full Poincaré beam
A.M. Beckley, Tom. G. Brown,
Miguel A. Alonso,
Optics Express 18, 10777 (2010)

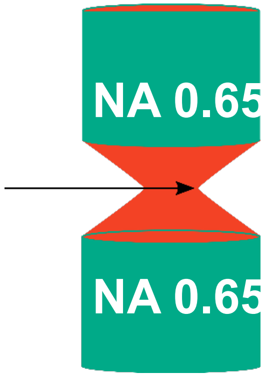
Sensing with „Classical Entanglement“

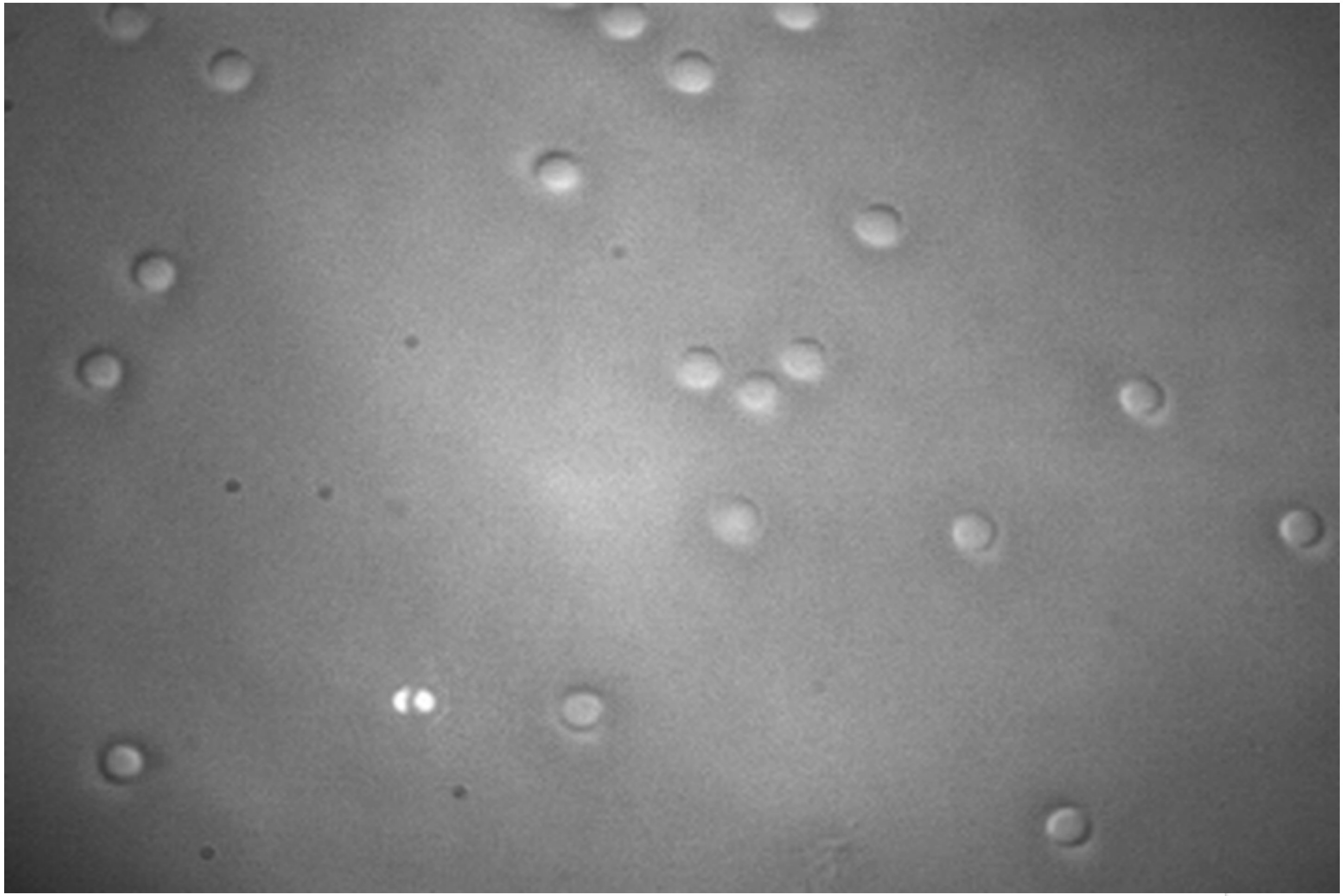


Extinction by the SiO_2 particle leads to a position-dependent effect on the global polarization state, which we measure in real time.

Sensing with „Classical Entanglement“

Track motion of particle in optical tweezer.

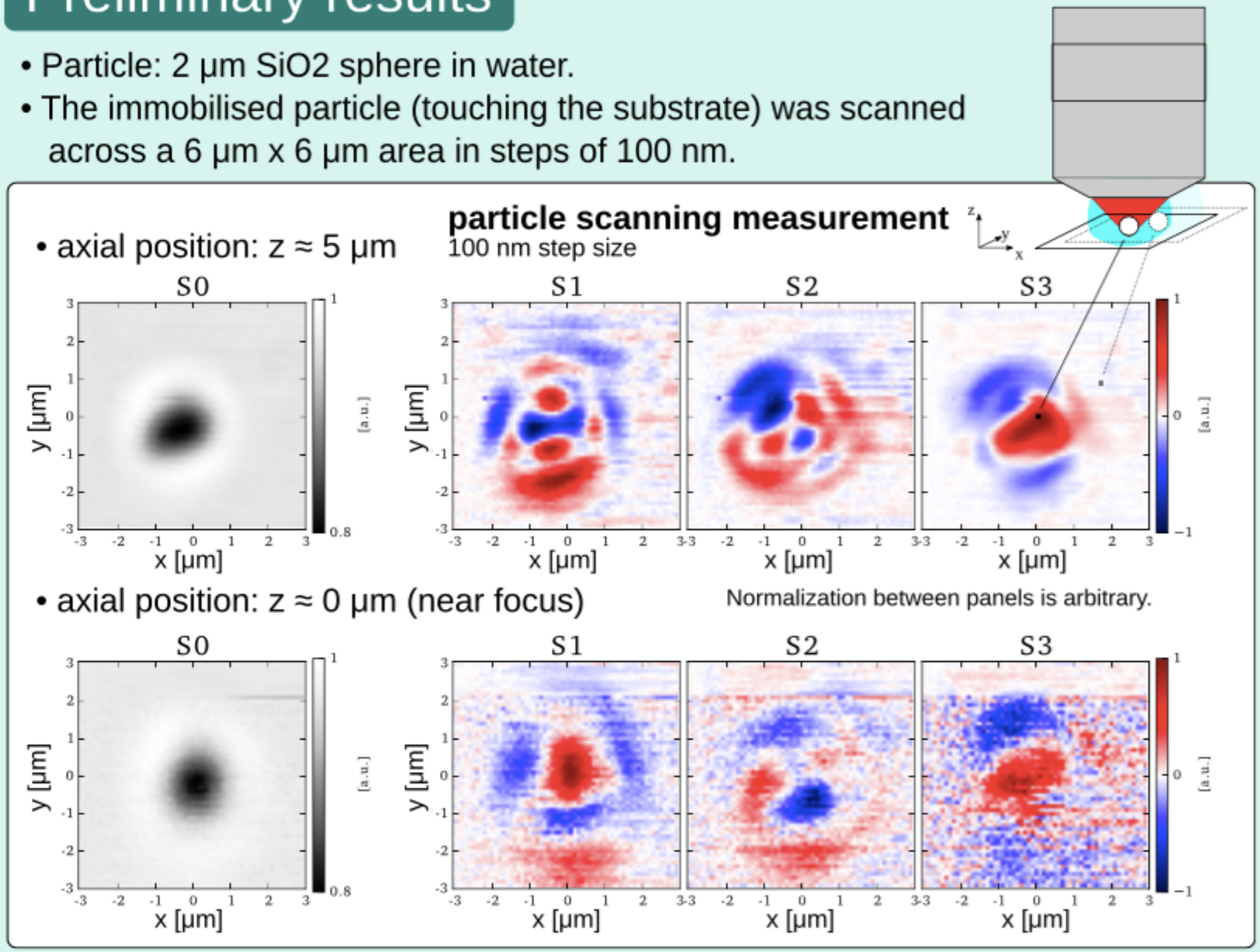




Sensing with „Classical Entanglement“

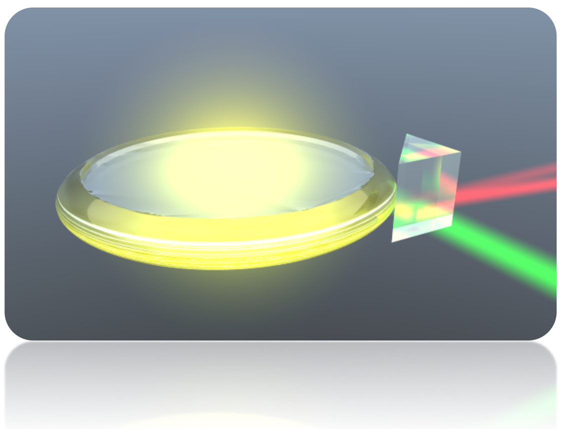
Preliminary results

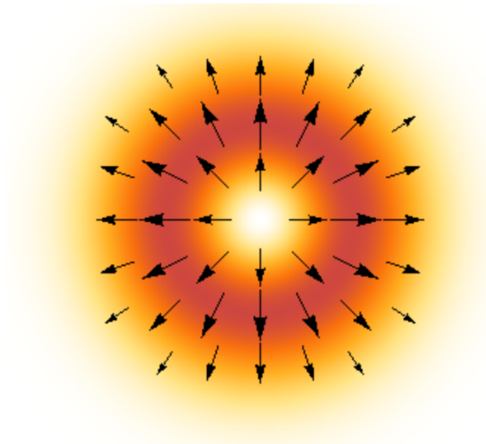
- Particle: 2 µm SiO2 sphere in water.
- The immobilised particle (touching the substrate) was scanned across a 6 µm x 6 µm area in steps of 100 nm.



Conclusion and Outlook

- Couple optomechanics and optical nonlinearity
- nonlinear crystalline whispering gallery resonators
- quantum inspired sensing for fast tracking of particle motion





QIV group – Division Leuchs

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and all the collaborators (especially Dmitry Strekalov and Harald Schwefel)