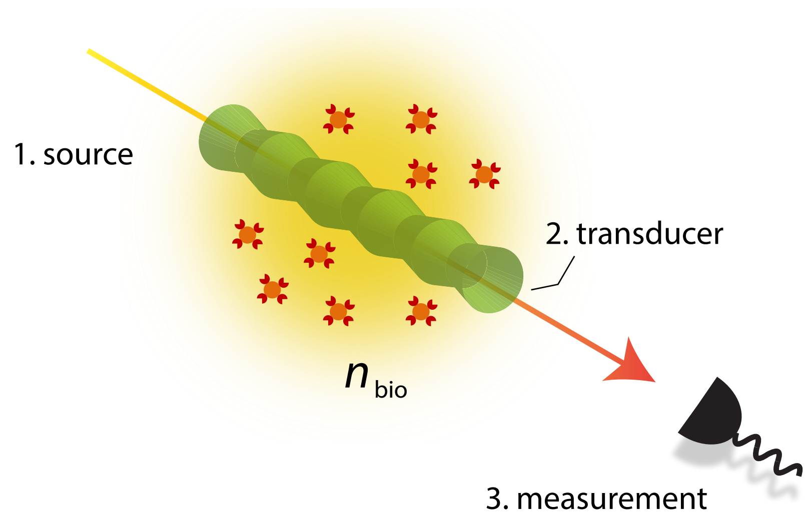
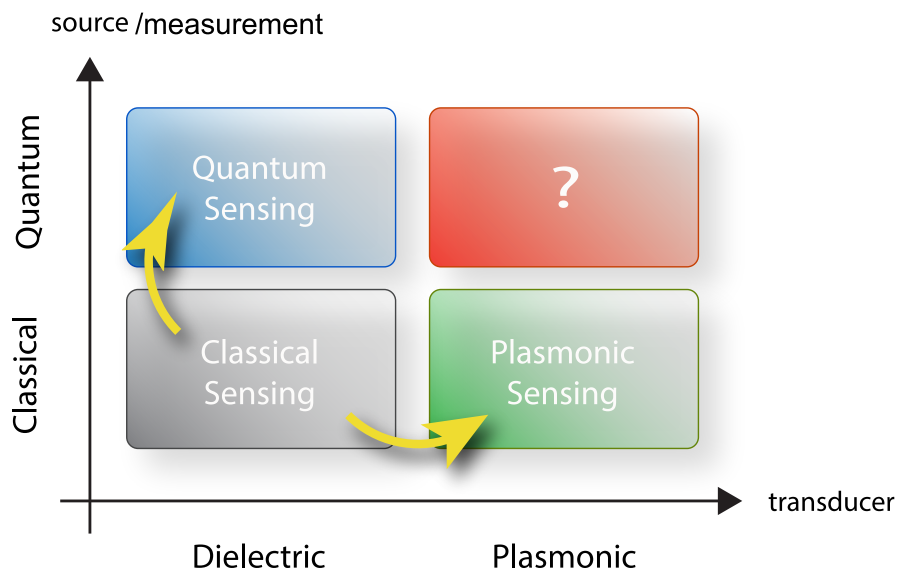
# Quantum plasmonic sensing

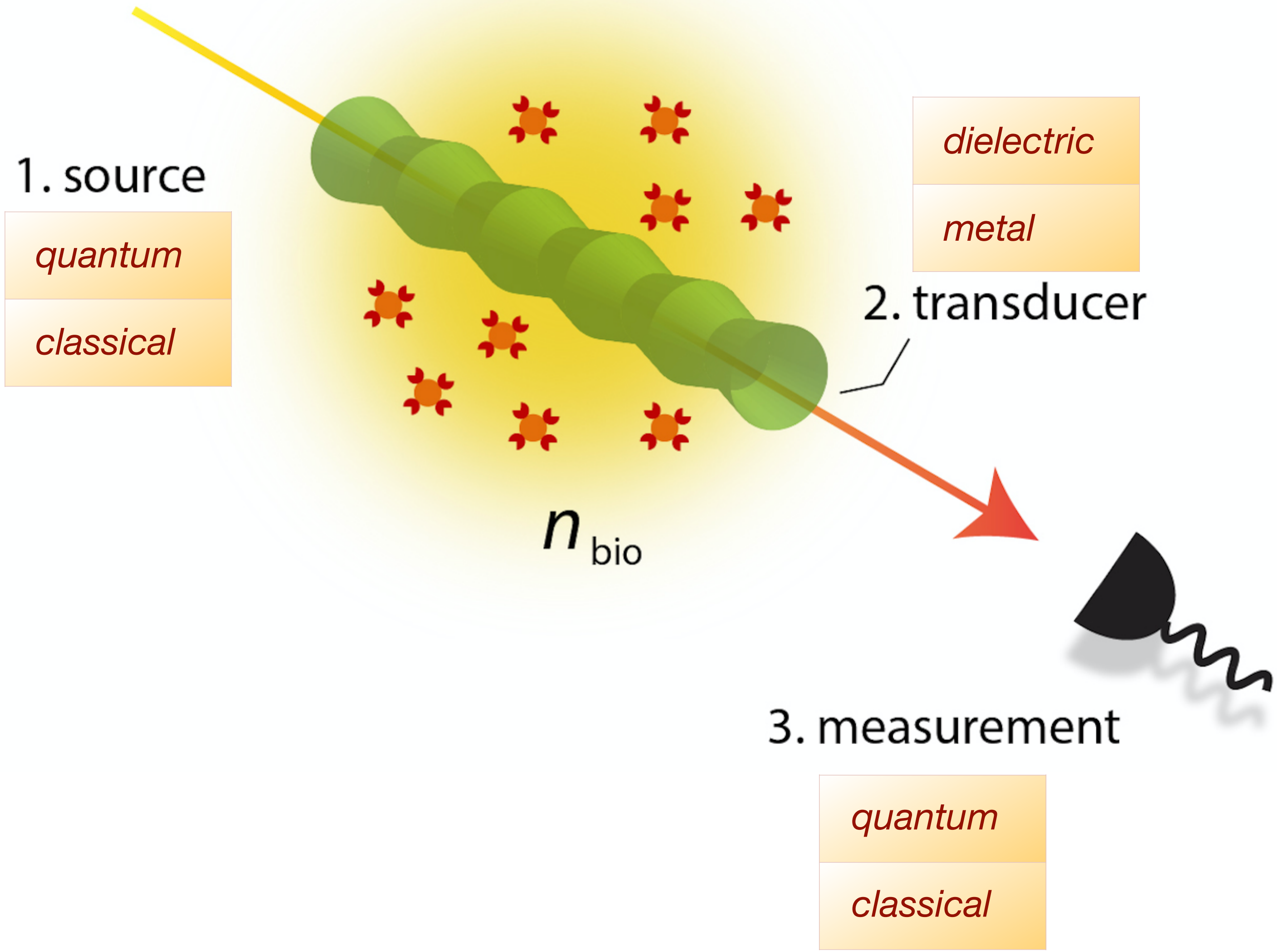
Changhyoup Lee

Institute of Theoretical Solid State Physics



# Photonic sensing



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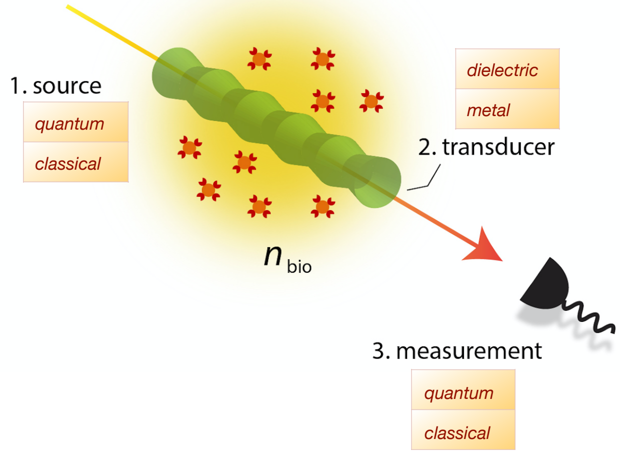
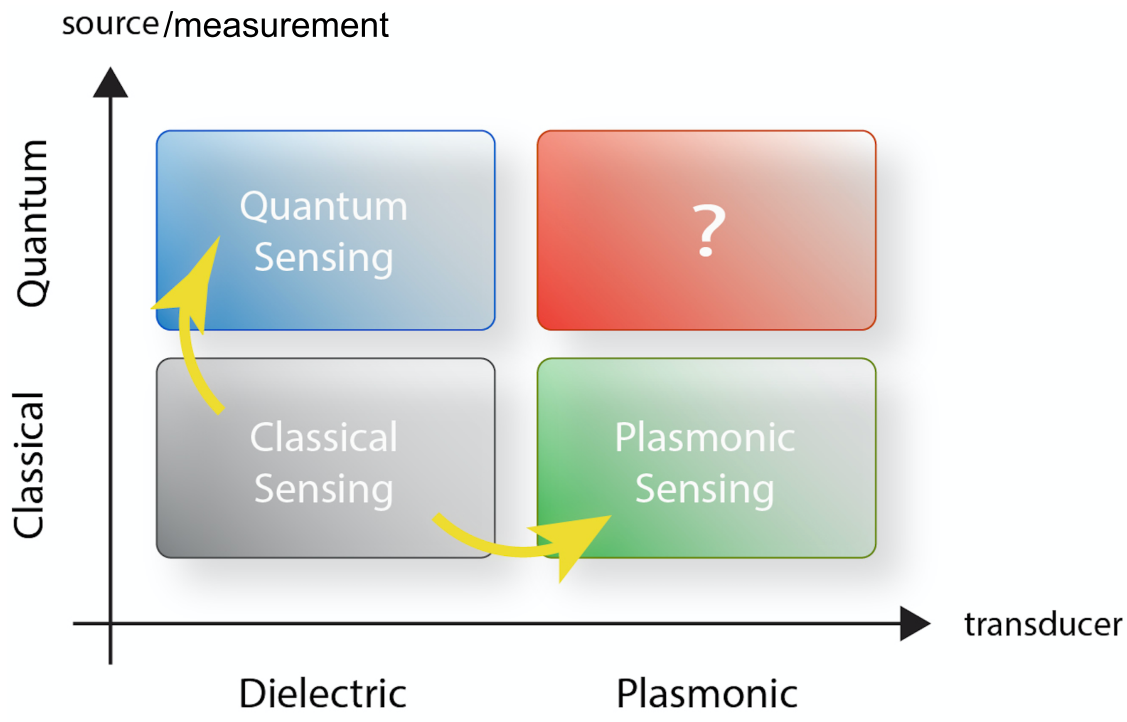
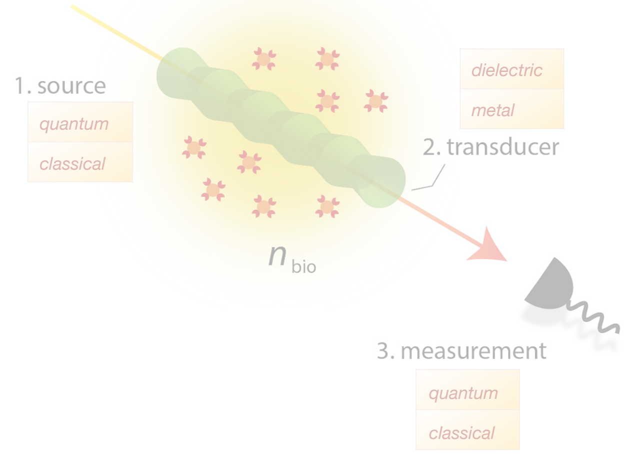
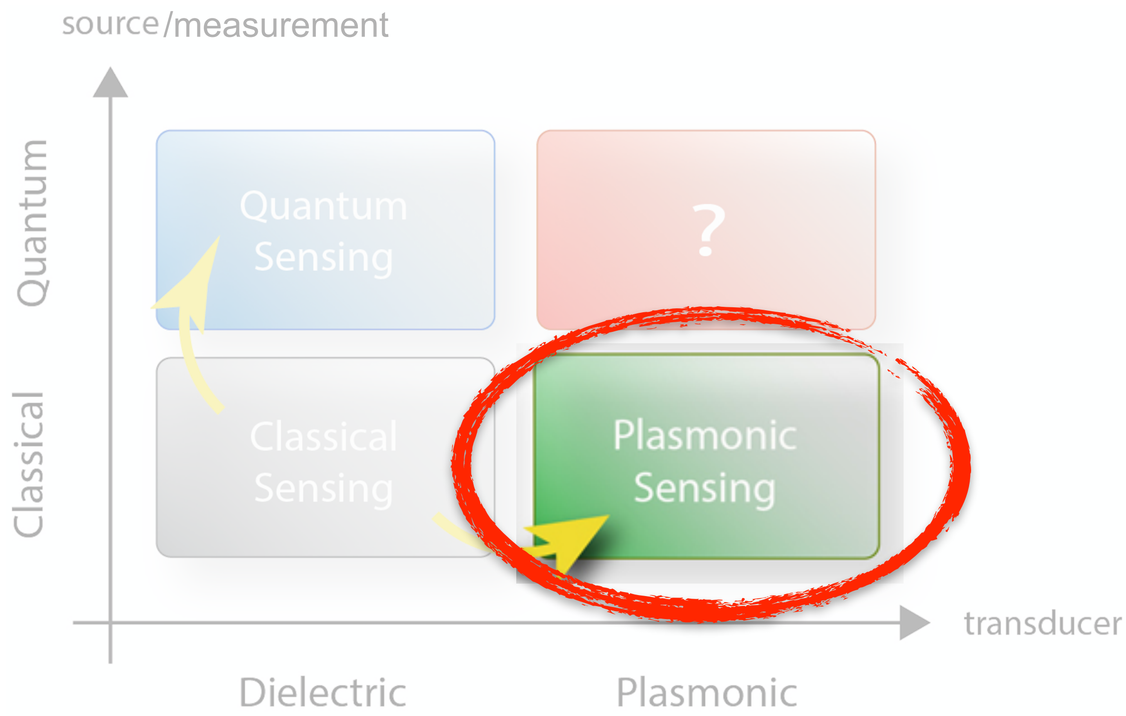



C. Lee et. al., ACS Photonics, 3, 992 (2016)

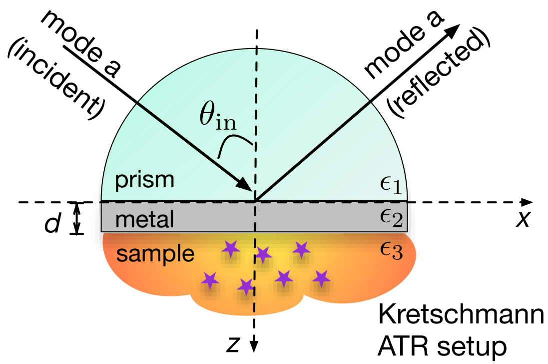
# Photonic sensing

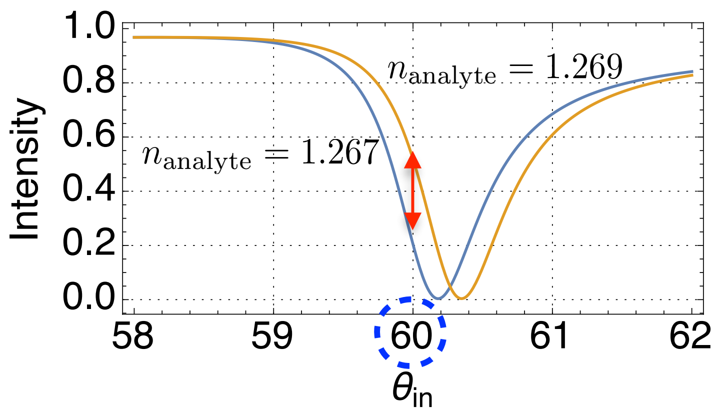


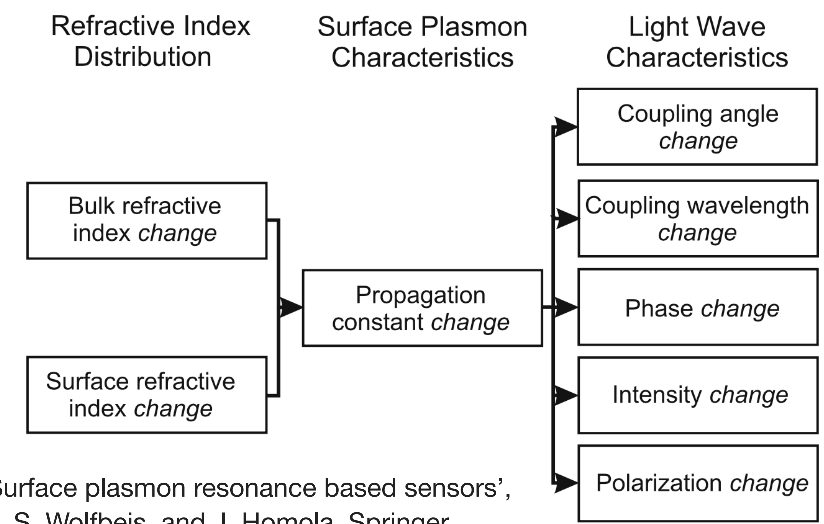
# Plasmonic sensing

- Example: intensity-sensitive ATR sensing




- Various sensing mechanisms




'Surface plasmon resonance based sensors', O. S. Wolfbeis, and J. Homola, Springer

- Various figures of merit for sensing performance
  - Sensitivity
  - Resolution
  - Accuracy
  - Precision
  - etc..

$$S = \frac{\delta Y}{\delta n_{ef}} \frac{\delta n_{ef}}{\delta n}$$

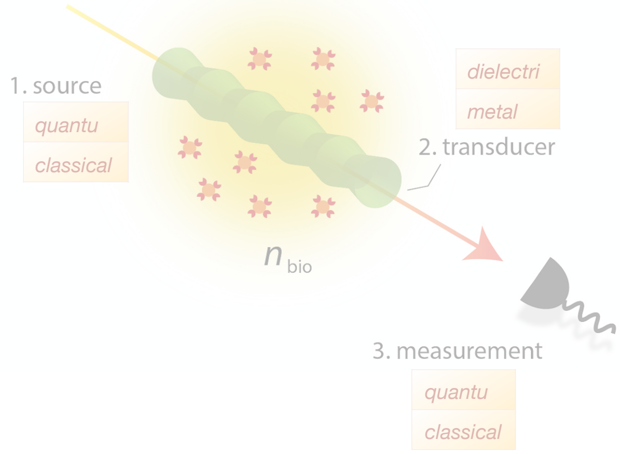
$$\sigma_{RI} = \frac{\sigma_{so}}{S}$$

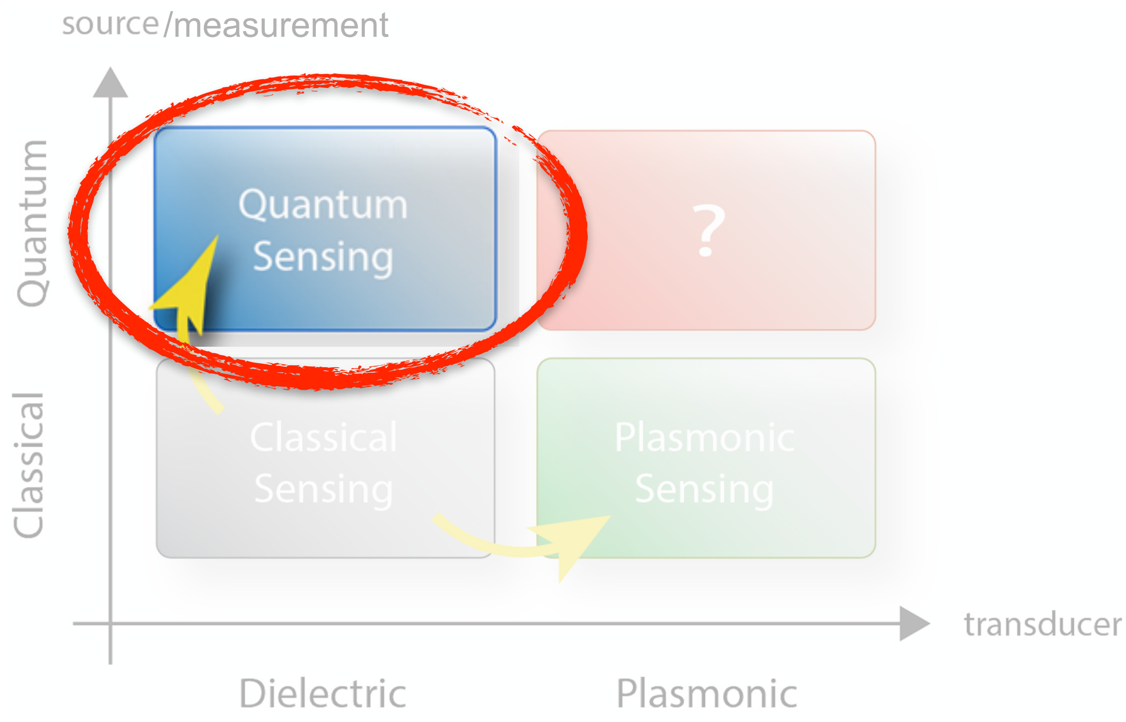
standard deviation

✓ **beyond the diffraction limit**

✓ **enhanced sensitivity**

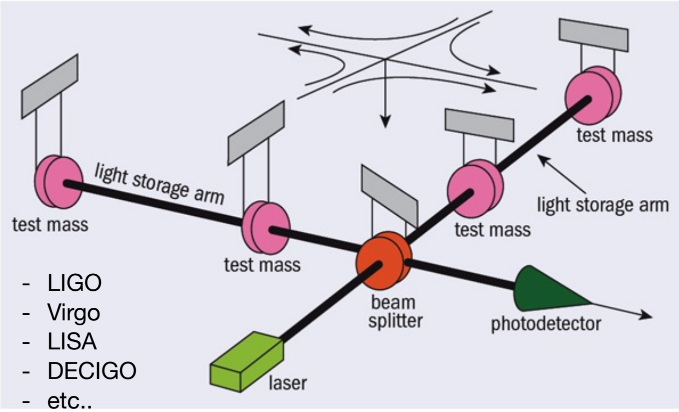
# Photonics sensing



# Quantum sensing (quantum metrology)

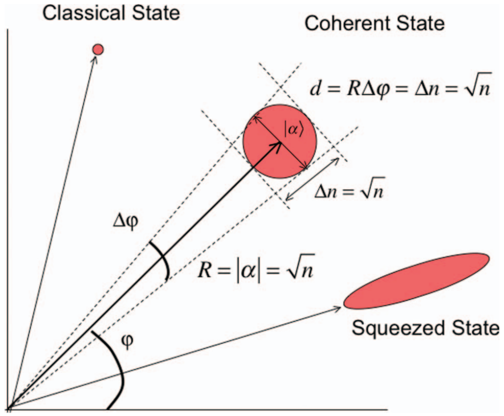
- Original idea: Gravitational wave detector




$\frac{\delta L}{L} \sim 10^{-21}$ strain induced by neutron star binary

C. Caves, PRL 45, 75, (1980)
C. Caves, PRD 23, 1693 (1981)

- The use of quantum state of light

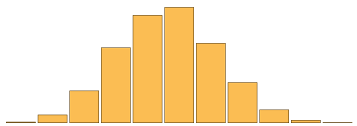


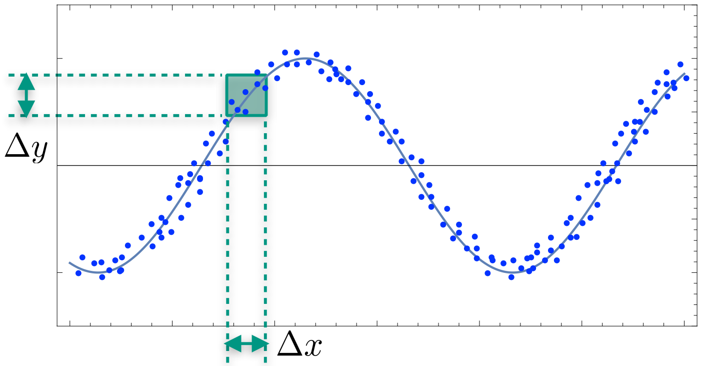

J. P. Dowling, Contemporary physics, 49, 125 (2008)

- The use of classical laser (coherent state of light)

$$|\alpha\rangle = e^{-|\alpha|^2/2} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$

*Poisson distribution*

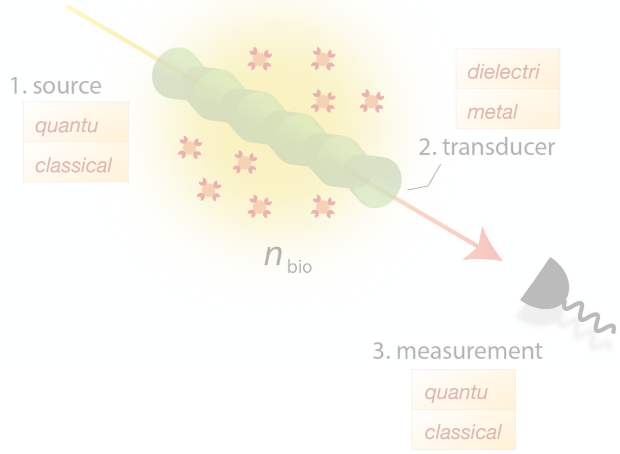


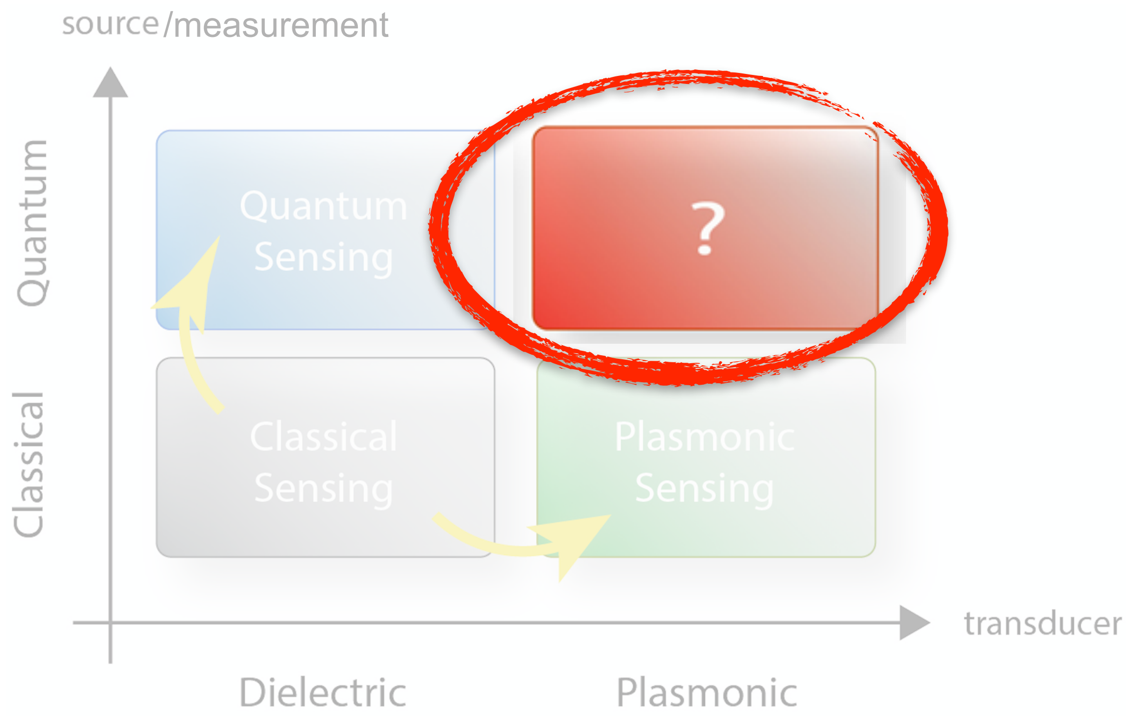



→ *shot-noise limited*

→ **✓ beats the shot-noise limit**

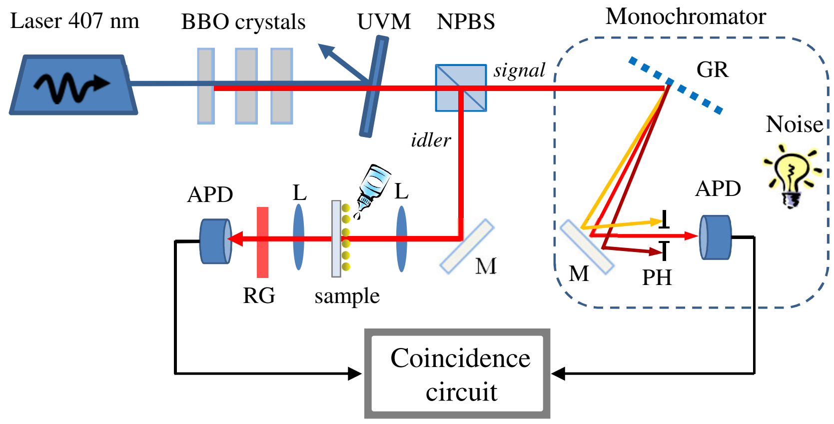
# Photonic sensing



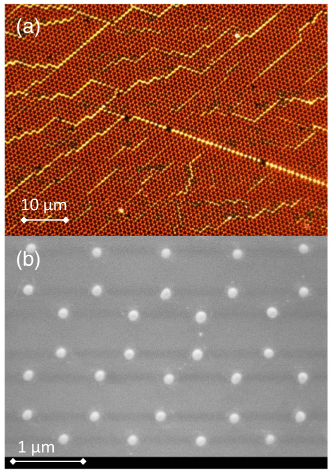



# Experiment I on quantum plasmonic sensing

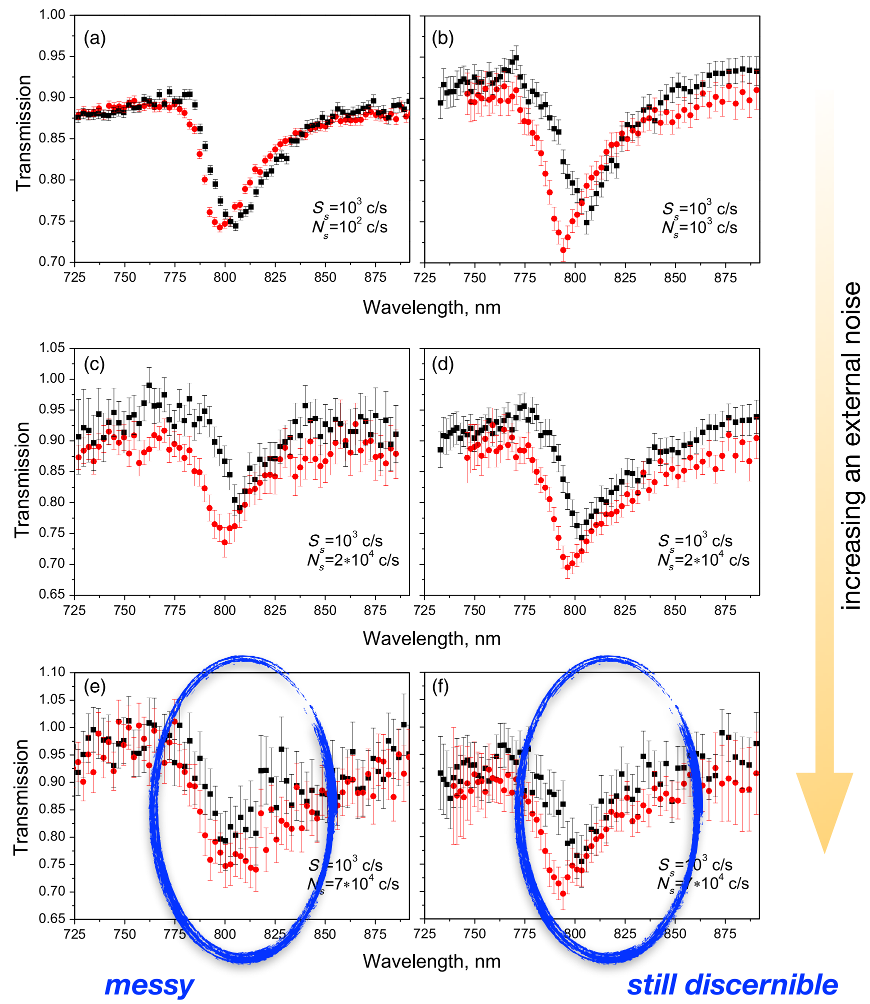
- Experimental setup




- Platform: nanoparticle arrays




- Classical source
- Quantum source




D. A. Kalashnikov et. al., PRX, 4, 011049 (2014)

# Experiment II on quantum plasmonic sensing

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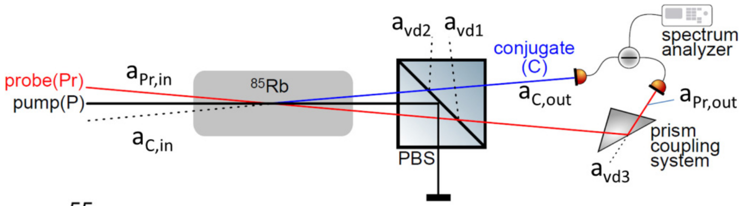
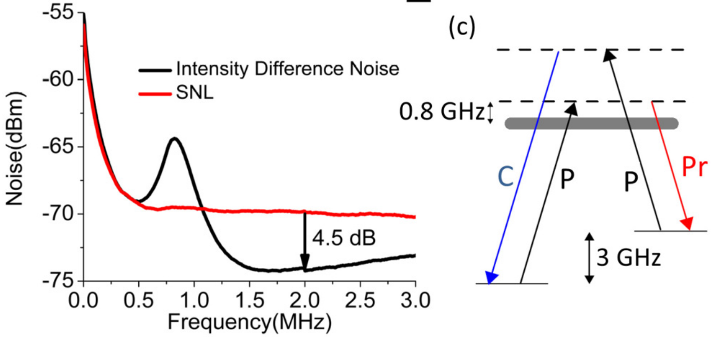
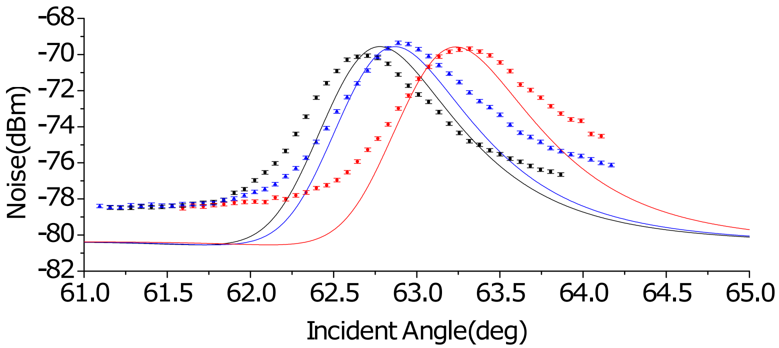
## Experimental setup

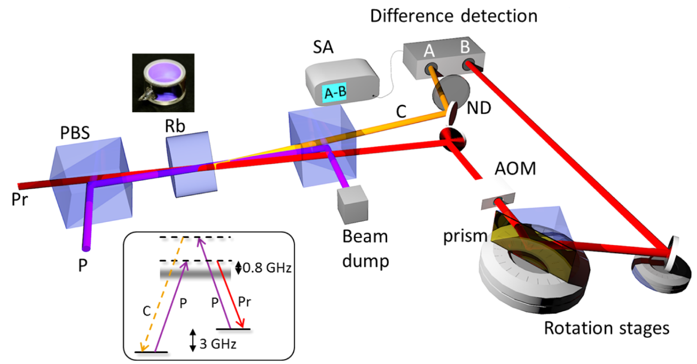


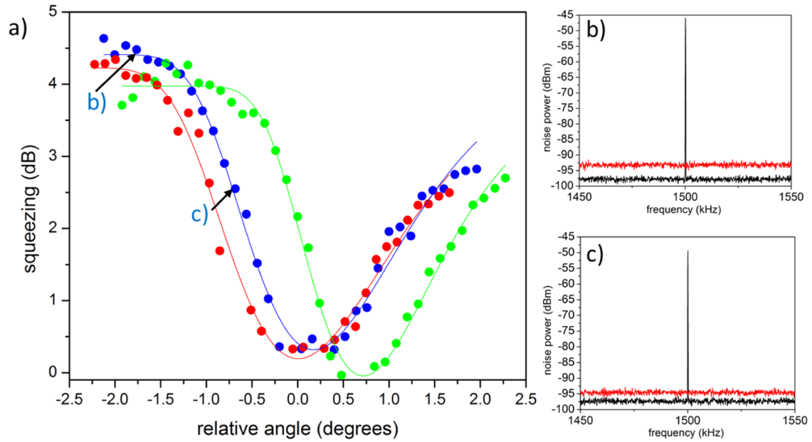




W. Fan et. al., PRA, 92, 053812 (2015)

## Experimental setup

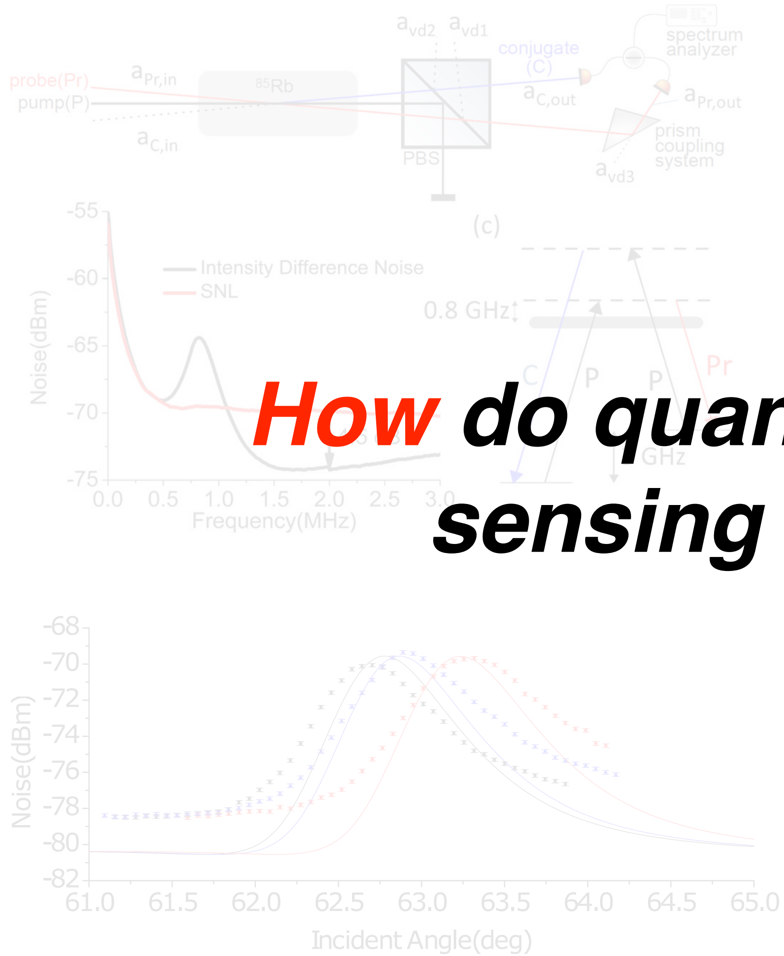



R. C. Pooser, and B. Lawrie, ACS Photonics, 3, 8 (2016)

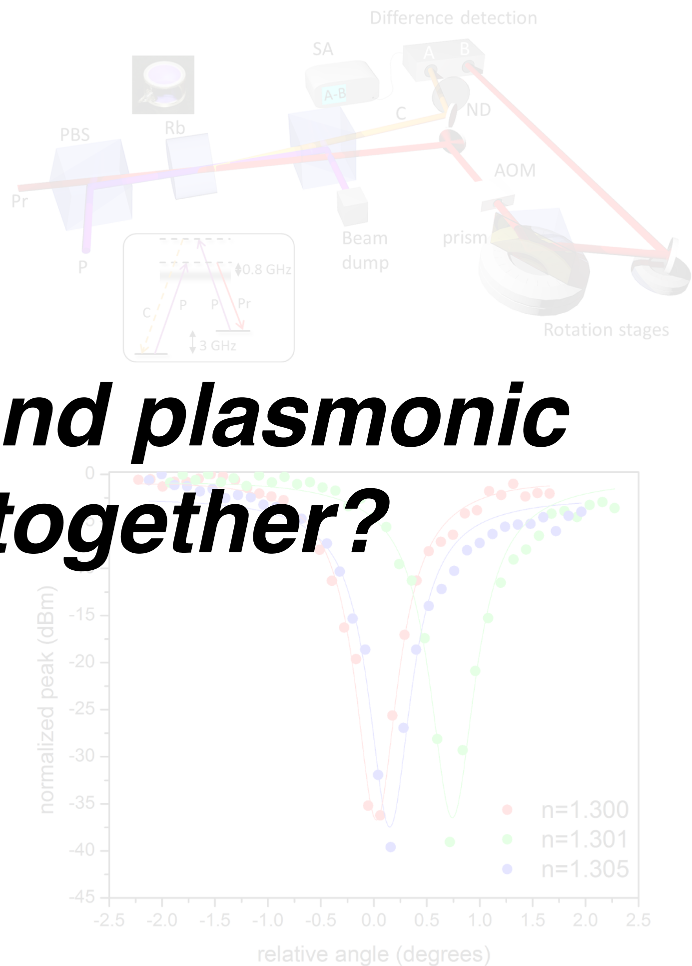
# Experiment II on quantum plasmonic sensing

- Experimental setup




W. Fan et. al., PRA, 92, 053812 (2015)

- Experimental setup




R. C. Pooser, and B. Lawrie, ACS Photonics, 3, 8 (2016)

***How** do quantum and plasmonic sensing work together?*

# Quantum plasmonic sensing

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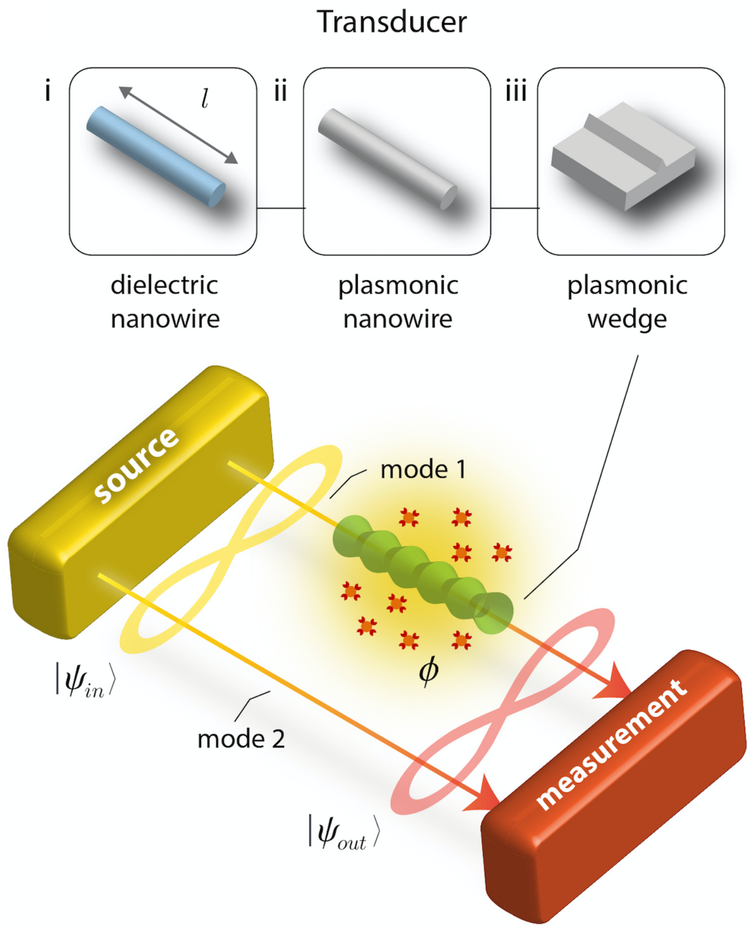
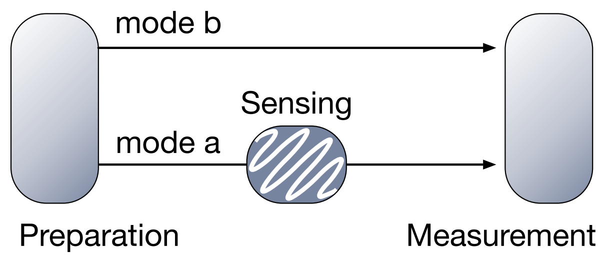
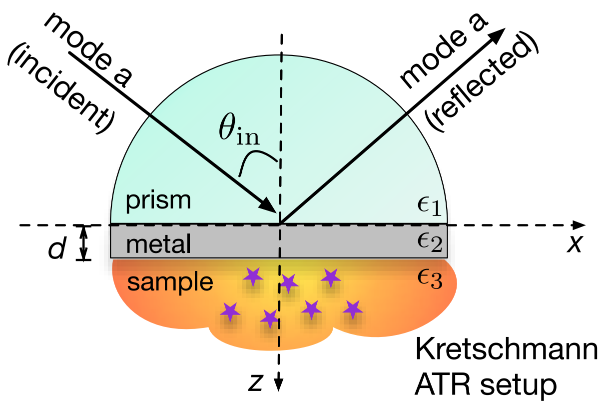
## Phase-sensitive nanowire sensing




C. Lee et. al., ACS Photonics, 3, 992 (2016)

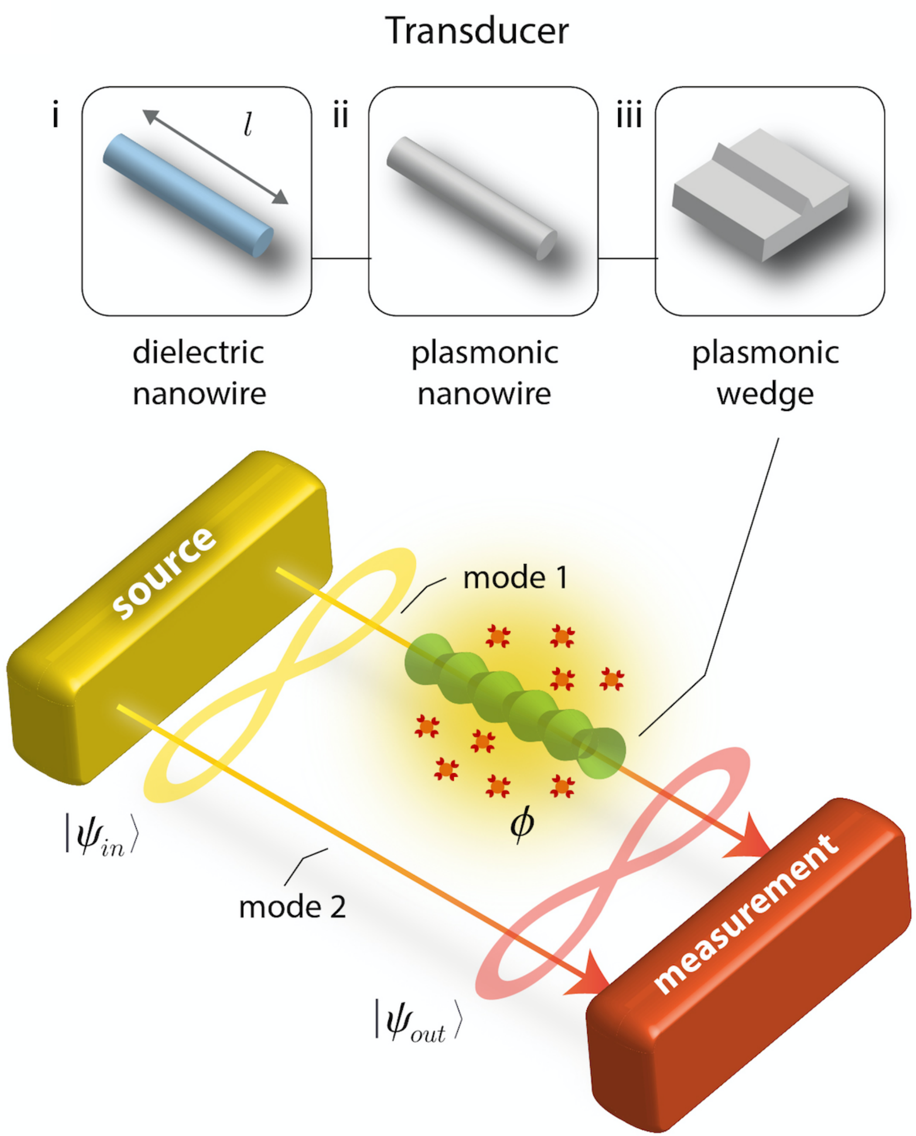
## Intensity-sensitive prism sensing



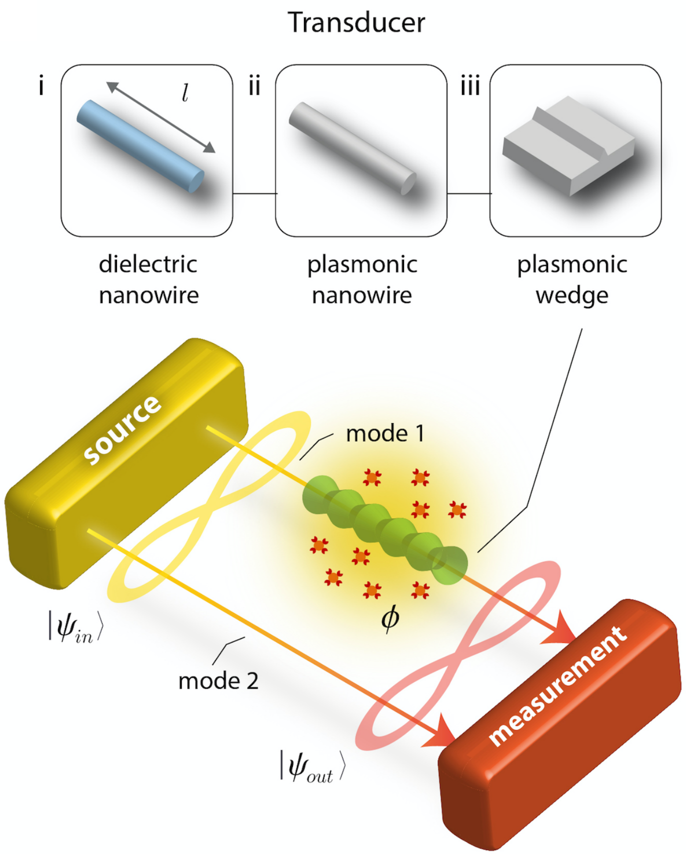

(in preparation)

# Two-mode interferometric nanowire sensing




C. Lee et. al., ACS Photonics, 3, 992 (2016)

# Two-mode interferometric nanowire sensing




- Classical reference (shot-noise limited)

$$|\alpha\rangle = e^{-|\alpha|^2/2} \sum_{m=0}^{\infty} \frac{\alpha^m}{\sqrt{m!}} |m\rangle$$

$$\hat{M} = \hat{I}_a - \hat{I}_b$$

- Quantum example (Heisenberg limited)

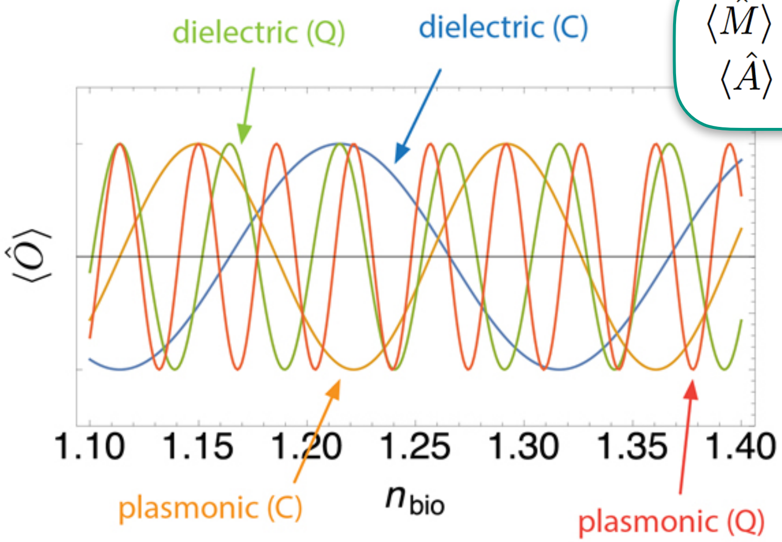
$$|\psi_{\rm in}\rangle = \left(|N0\rangle_{12} + |0N\rangle_{12}\right)/\sqrt{2}$$

$$\hat{A} = |0,N\rangle\langle N,0| + |N,0\rangle\langle 0,N|$$

- Monitored output: expectation values

$$\langle\hat{M}\rangle = M_0 \cos(\phi(n_{\rm bio}))$$

$$\langle\hat{A}\rangle = A_0 \cos(N\phi(n_{\rm bio}))$$




C. Lee et. al., ACS Photonics, 3, 992 (2016)

# Two-mode interferometric nanowire sensing

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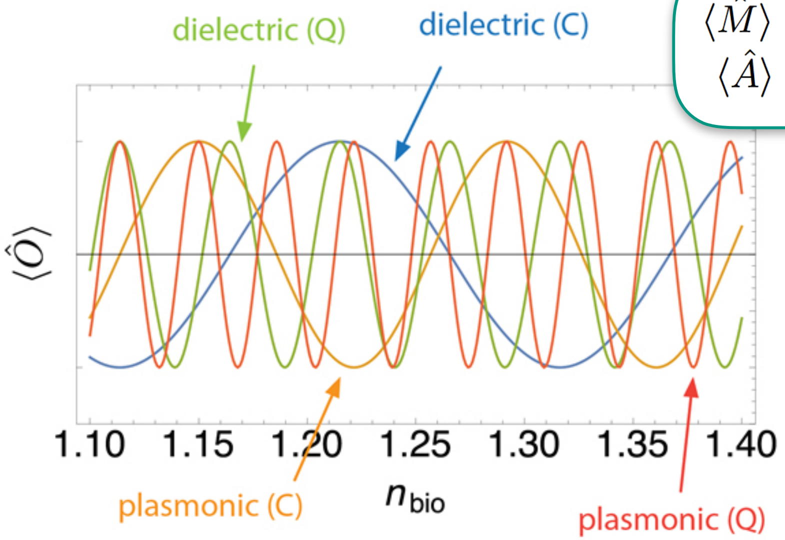
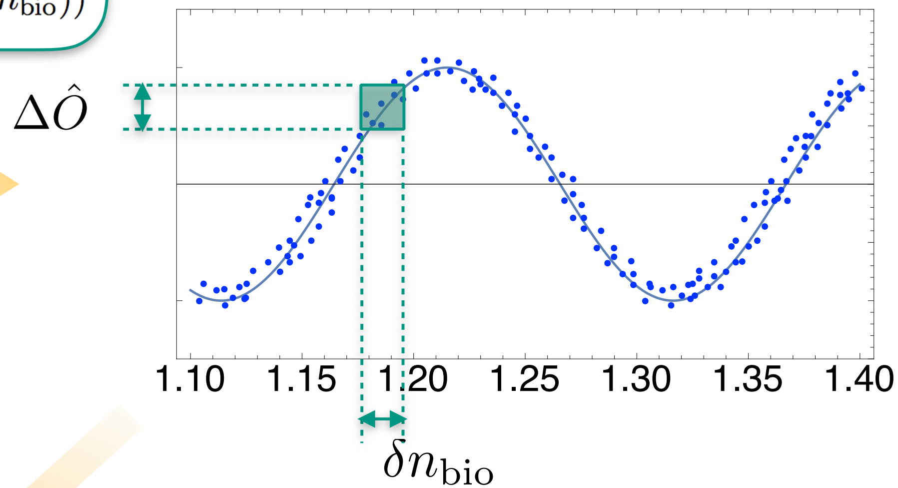
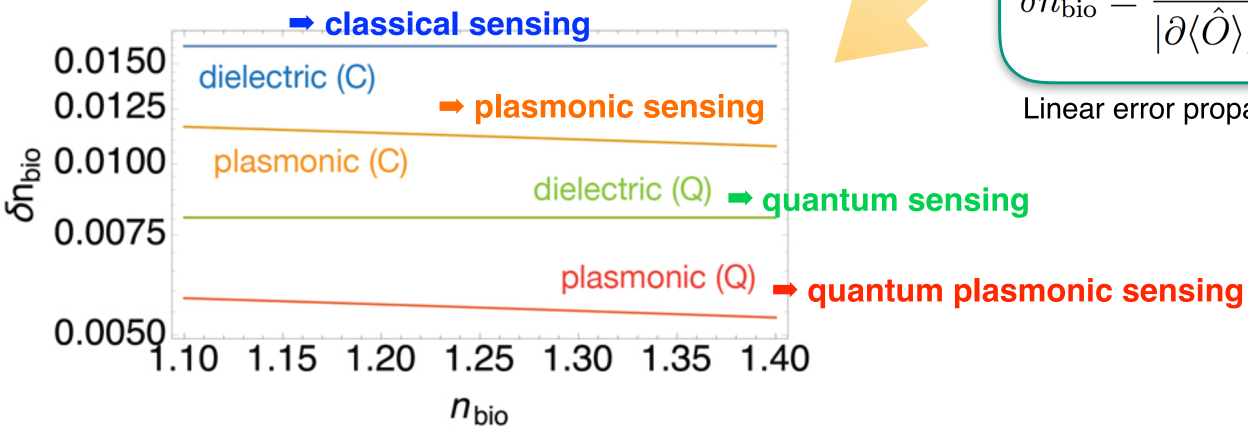



- Maximum detectable precision or minimum resolution

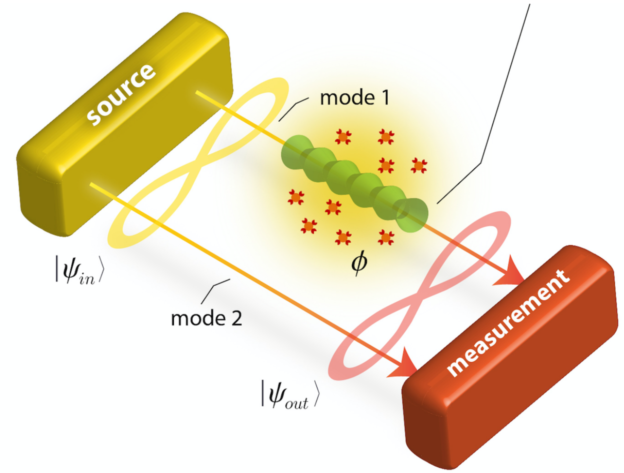



$$\delta n_{\text{bio}} = \frac{\Delta \hat{O}}{|\partial \langle \hat{O} \rangle / \partial n_{\text{bio}}|}$$

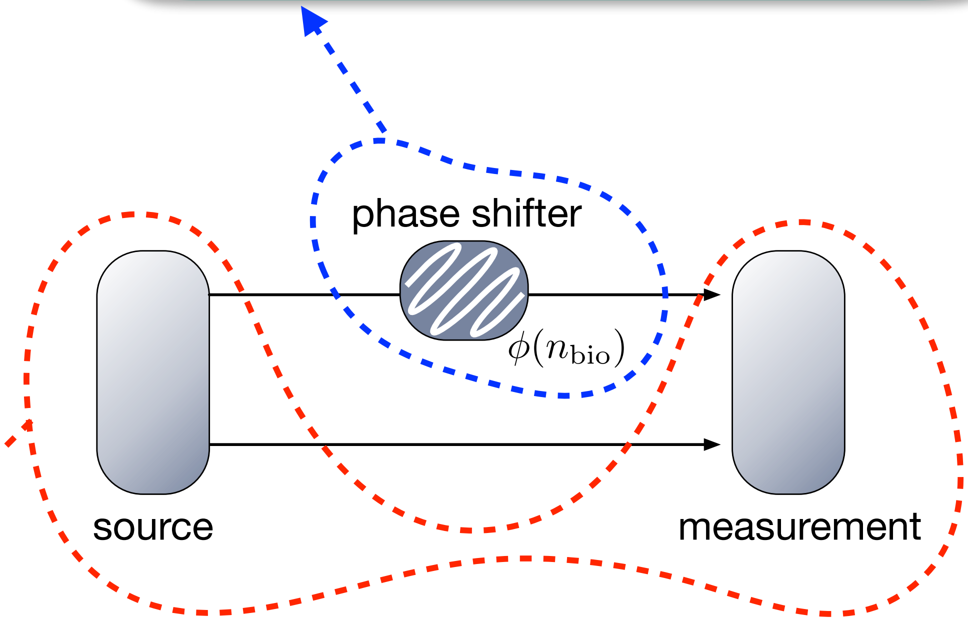
Linear error propagation method

C. Lee et. al., ACS Photonics, 3, 992 (2016)

# Roles of ‘quantum’ and ‘plasmonic’ sensing




- Plasmonic sensing
  : *how sensitively the transducer can induce the change in optical phase when an environment is altered.*




- Quantum sensing
  : *how sensitively the source and measurement can identify the change of optical phase when it occurs.*

C. Lee et. al., ACS Photonics, 3, 992 (2016)

# Roles of ‘quantum’ and ‘plasmonic’ sensing

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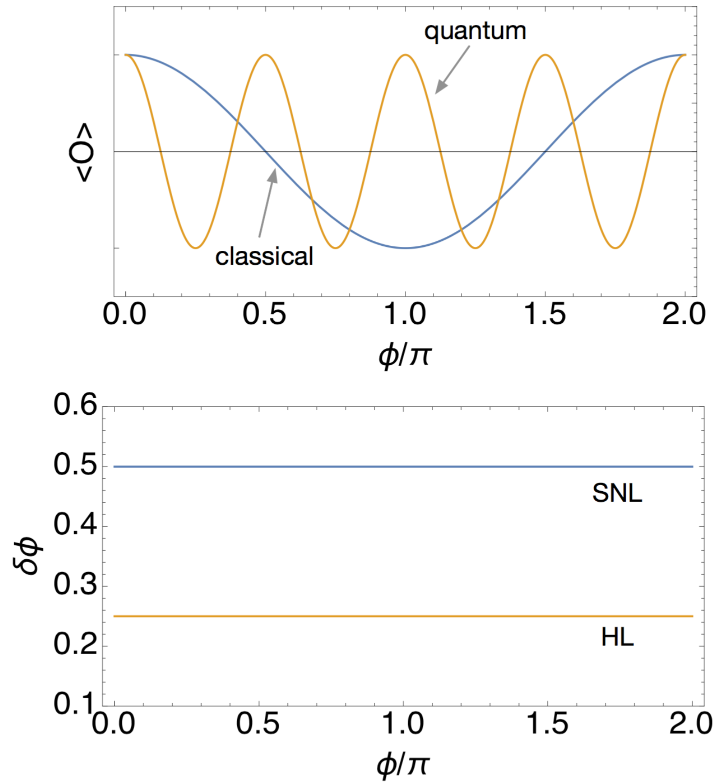


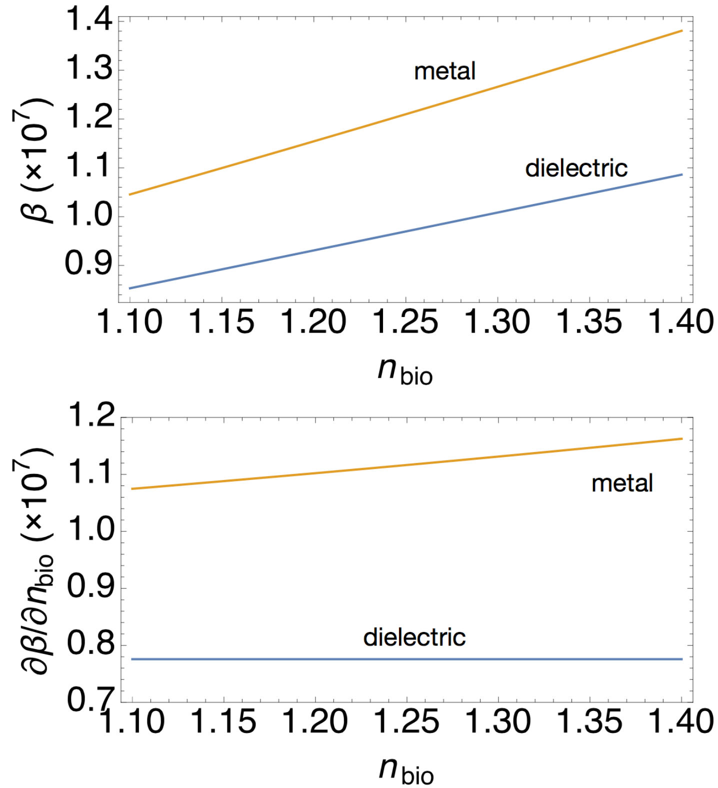


C. Lee et. al., ACS Photonics, 3, 992 (2016)

# Roles of 'quantum' and 'plasmonic' sensing

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- **Quantum sensing**
  : *how sensitively the source and measurement can identify the change of optical phase when it occurs.*

- **Plasmonic sensing**
  : *how sensitively the transducer can induce the change in optical phase when an environment is altered.*

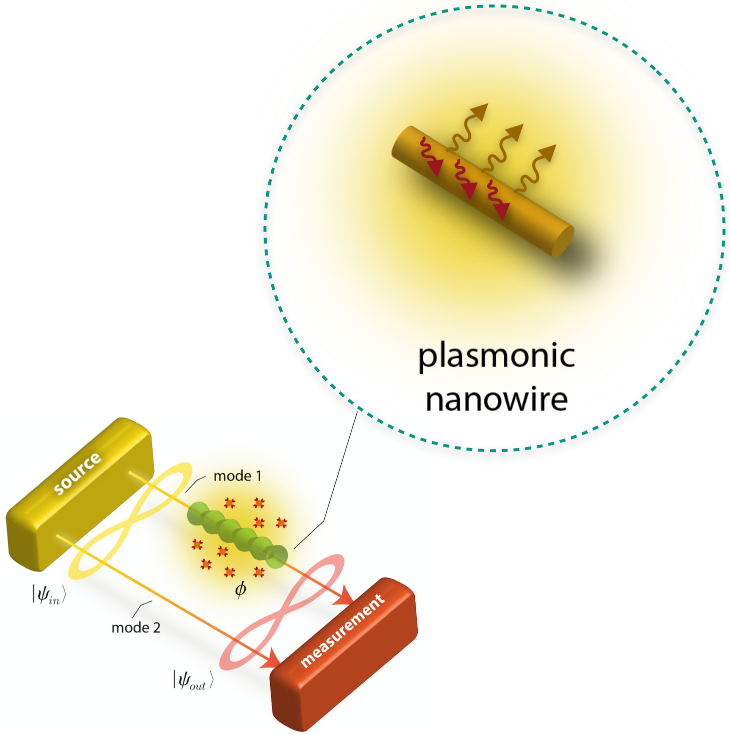
- **Quantum plasmonic sensing**

$$\delta n_{\text{bio}} = \frac{\Delta \hat{O}}{|\partial \langle \hat{O} \rangle / \partial n_{\text{bio}}|}$$

$$\delta n_{\text{bio}} = \delta\phi \left| \frac{\partial \phi}{\partial n_{\text{bio}}} \right|^{-1}$$

C. Lee et. al., ACS Photonics, 3, 992 (2016)

# Lossy sensing




- Quantum example (Heisenberg limited)

$$|\psi_{\text{in}}\rangle = \left(|N0\rangle_{12} + |0N\rangle_{12}\right)/\sqrt{2}$$

- General N-photon state

$$|\psi_{\text{in}}\rangle = \sum_{n=0}^{N} c_n |n, N-n\rangle$$

- Minimum resolution via Cramer-Rao bound

$$\delta n_{\text{bio}} = \delta\phi \left|\frac{\partial\phi}{\partial n_{\text{bio}}}\right|^{-1}$$

$$\delta\phi = F_Q^{-1/2}$$

U. Dorner, et al., PRL, 102, 040403 (2009)

C. Lee et. al., ACS Photonics, 3, 992 (2016)

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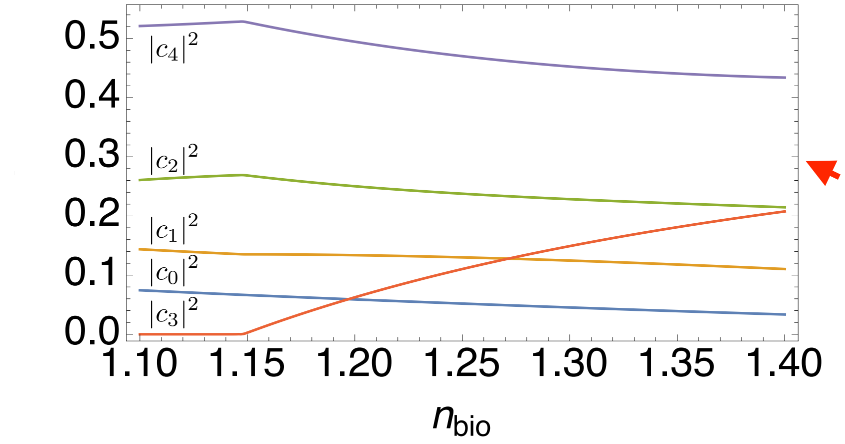


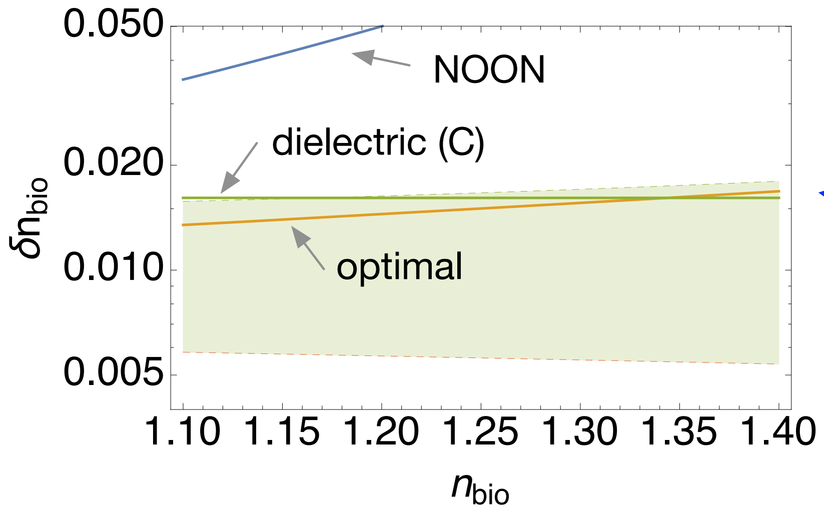


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# Single-mode intensity-sensitive ATR sensing

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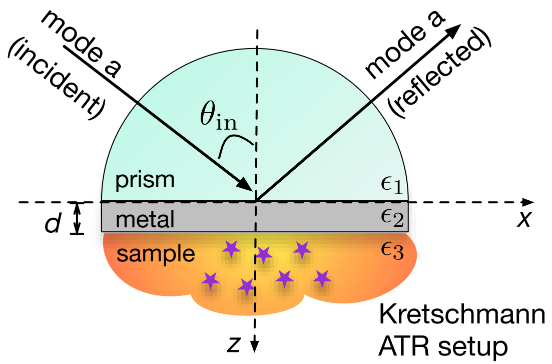
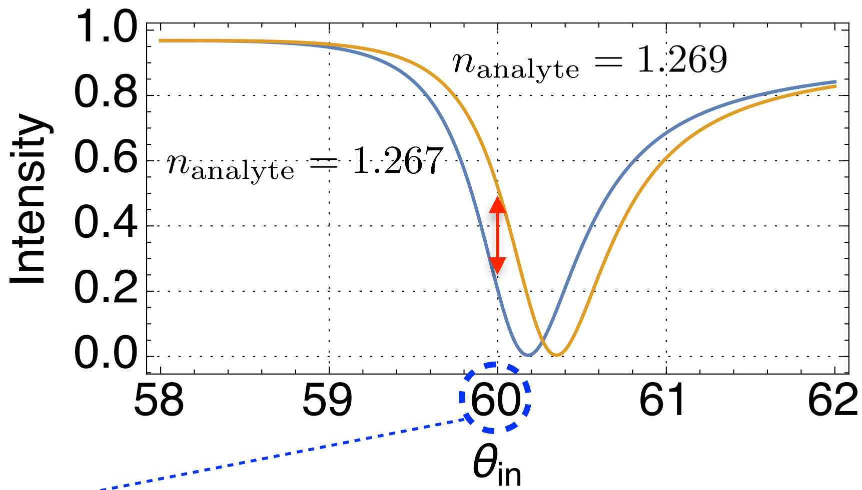
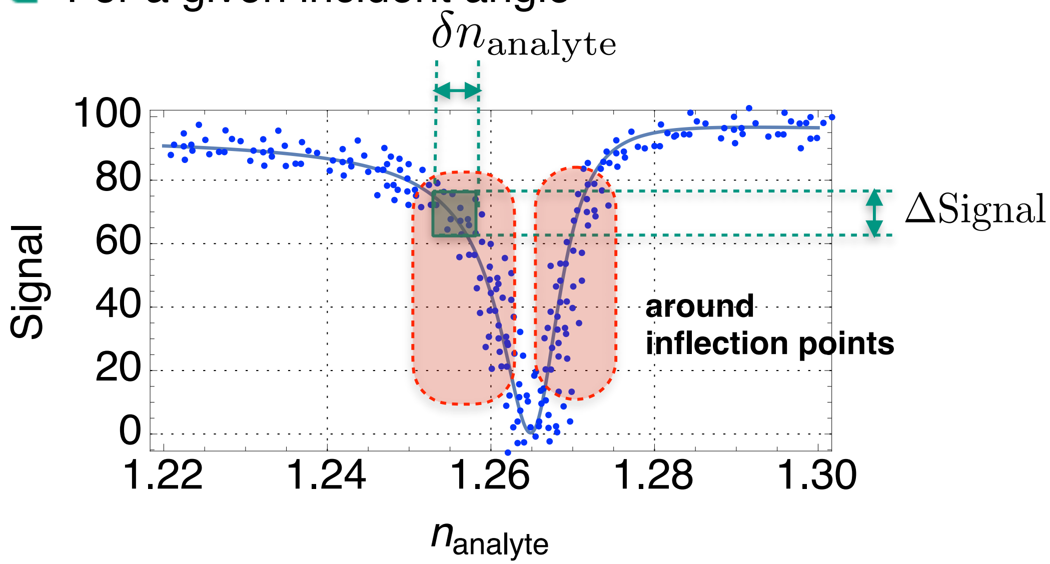
- Intensity-sensitive ATR sensing




- For a given incident angle




The average photon number of initial probe beam, as an example,

$$\text{Signal} = |r_{\text{spp}}|^2 N$$

$$\Delta\text{Signal} = \sqrt{|r_{\text{spp}}|^2 N}$$

- Parameter estimation

$$\delta n_{\text{analyte}} = \frac{\Delta\text{Signal}}{\left|\frac{\partial\text{Signal}}{\partial n_{\text{analyte}}}\right|}$$

# Two-mode intensity-sensitive ATR sensing

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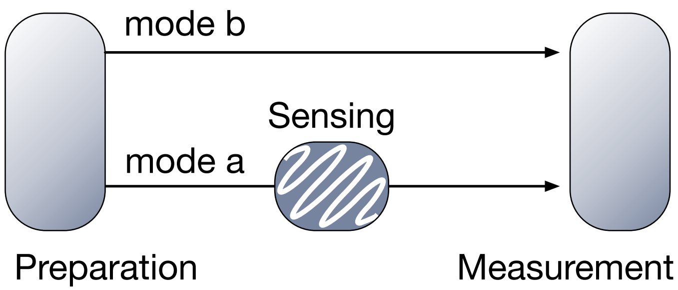
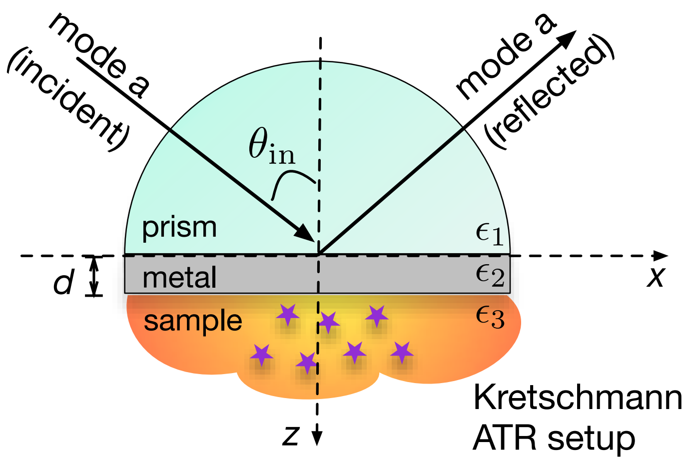
- Two-mode SPR sensing with differential intensity measurement




- Example states: twin modes

$$N_a = N_b$$
$$\Delta N_a = \Delta N_b$$

* Classical state $|\alpha\rangle|\alpha\rangle$

* Two-mode squeezed vacuum state (SPDC)

$$|\text{TMSV}\rangle = \frac{1}{\cosh(r)} \sum_{n=0}^{\infty} (-1)^n e^{in\phi} \tanh^n(r) |n, n\rangle$$

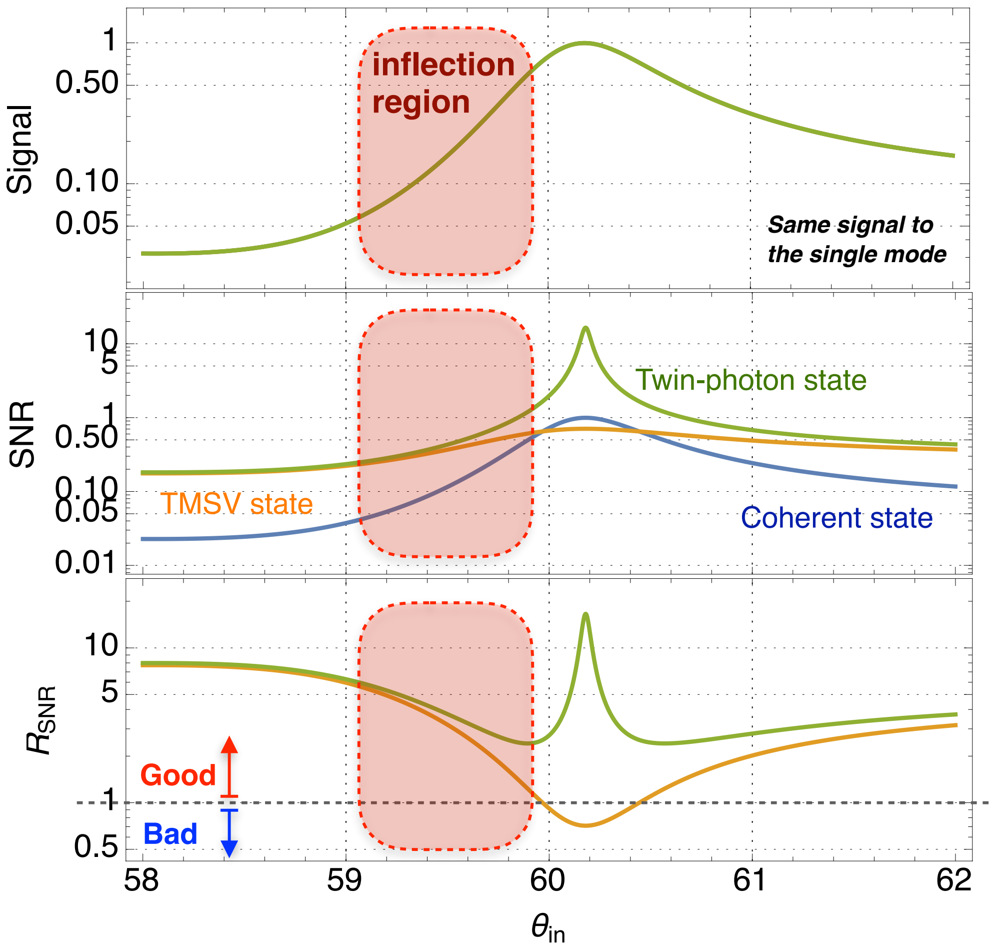
* Twin photons $|n_a\rangle|n_b\rangle$

- Measurement: intensity difference

$$\hat{M} = \hat{b}^\dagger \hat{b} - \hat{a}^\dagger \hat{a}$$

* two-mode correlation can be used.
* the excess noise can be eliminated.

# Two-mode intensity-sensitive ATR sensing

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| | |
|---|---|
| Average input power | $N_a = N_b = 1$ |
| No channel losses at both modes | $\eta_a = \eta_b = 1$ |
| Refractive index of sample | $n_{\mathrm{analyte}} = 1.267$ |

# Two-mode intensity-sensitive ATR sensing

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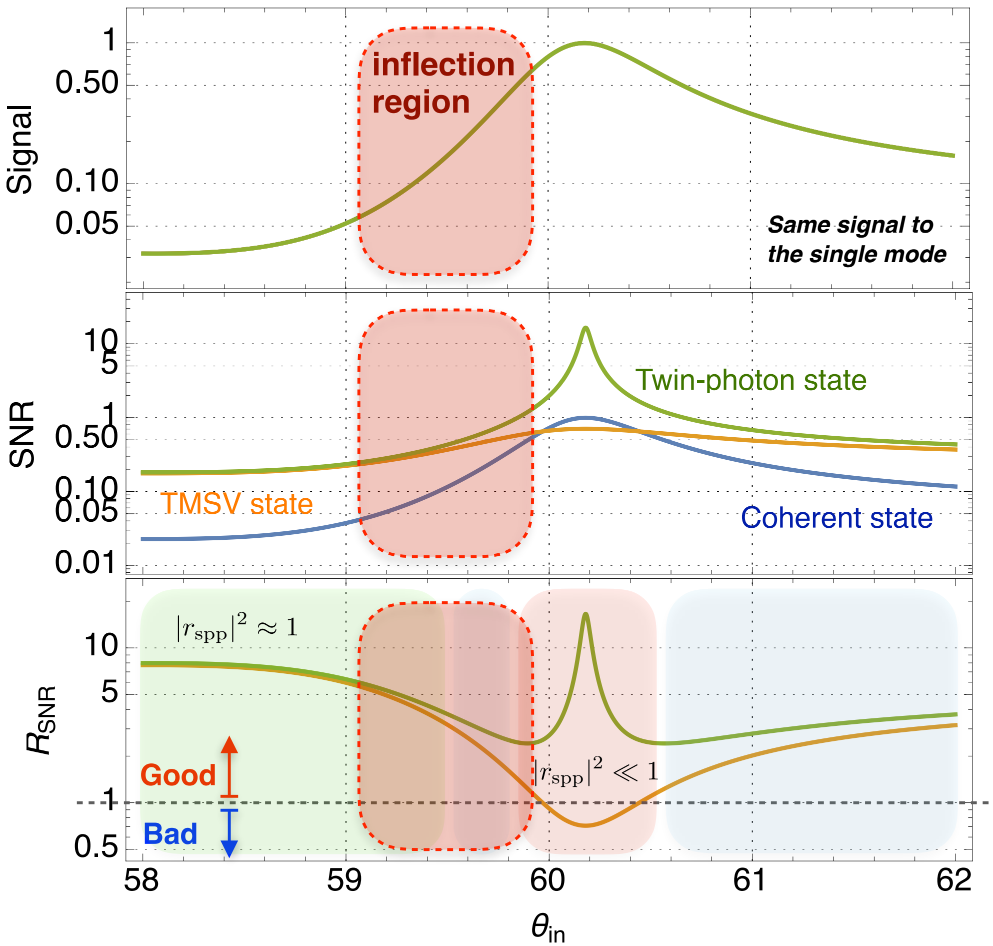



$$R_{\mathrm{SNR}} = \frac{SNR}{SNR_c} = \sqrt{\frac{1+|r_{\mathrm{spp}}|^2}{(1-|r_{\mathrm{spp}}|^2)^2 Q_{\mathrm{M}} + 2\sigma|r_{\mathrm{spp}}|^2 + (1-|r_{\mathrm{spp}}|^2)}}$$

Mandel Q-factor $Q_{\mathrm{M}} = \frac{\langle \Delta N_a^2 \rangle}{\langle N_a \rangle} - 1$

Degree of correlation $\sigma = \frac{\langle \Delta (N_a - N_b)^2 \rangle}{\langle N_a \rangle + \langle N_b \rangle}$

| | $Q_{\mathrm{M}}$ | $\sigma$ | $R$ |
|---|---|---|---|
| ***Coherent state*** | 0 | 1 | 1 |
| ***TMSV state*** | >0 | 0 | $\sqrt{\frac{1+|r_{\mathrm{spp}}|^2}{(1-|r_{\mathrm{spp}}|^2)^2 Q_{\mathrm{M}} + (1-|r_{\mathrm{spp}}|^2)}}$ |
| ***Twin-photon state*** | -1 | 0 | $\sqrt{\frac{1+|r_{\mathrm{spp}}|^2}{(1-|r_{\mathrm{spp}}|^2)|r_{\mathrm{spp}}|^2}}$ |

# Two-mode intensity-sensitive ATR sensing

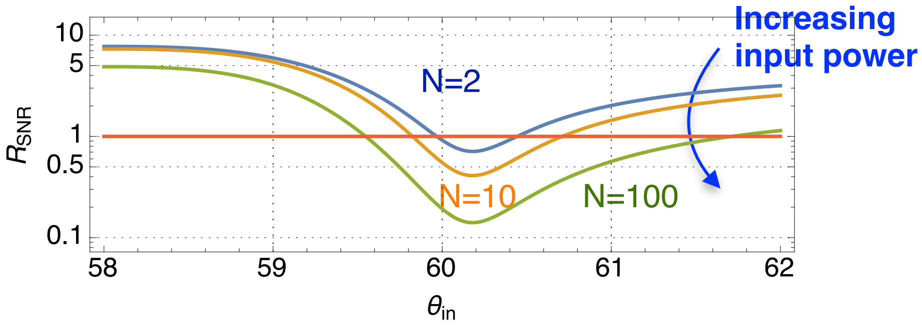
- Two-mode squeezed state (SPDC)

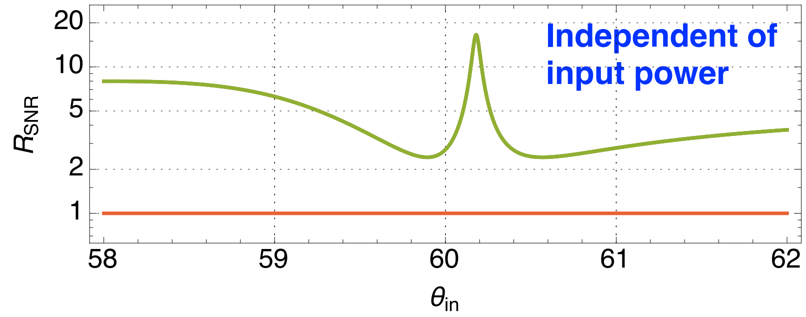
$$|\mathrm{TMSV}\rangle = \frac{1}{\cosh(r)} \sum_{n=0}^{\infty} (-1)^n e^{in\phi} \tanh^n(r) |n, n\rangle$$

- Twin photons

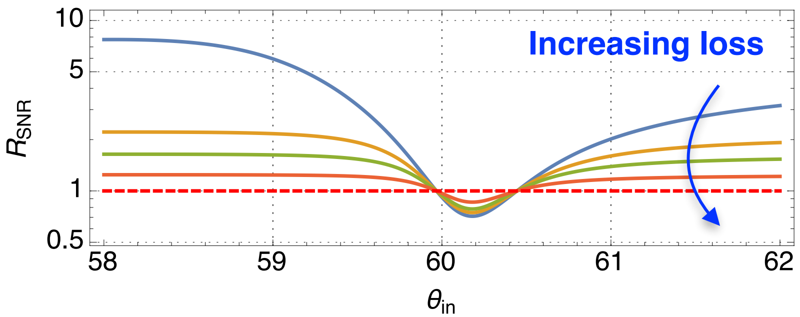
$$|n_a\rangle |n_b\rangle$$

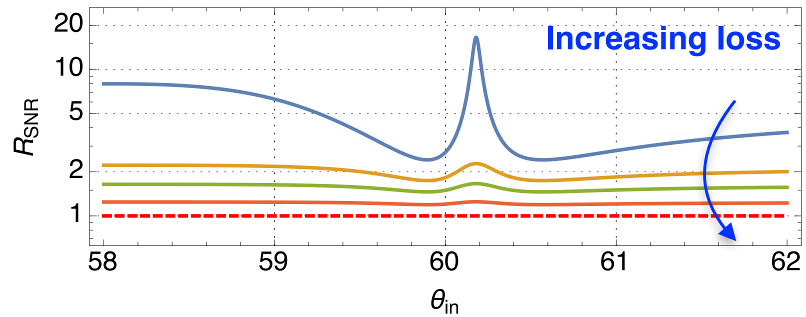
- Effect of increasing the input photon number




- Effect of increasing the channel losses



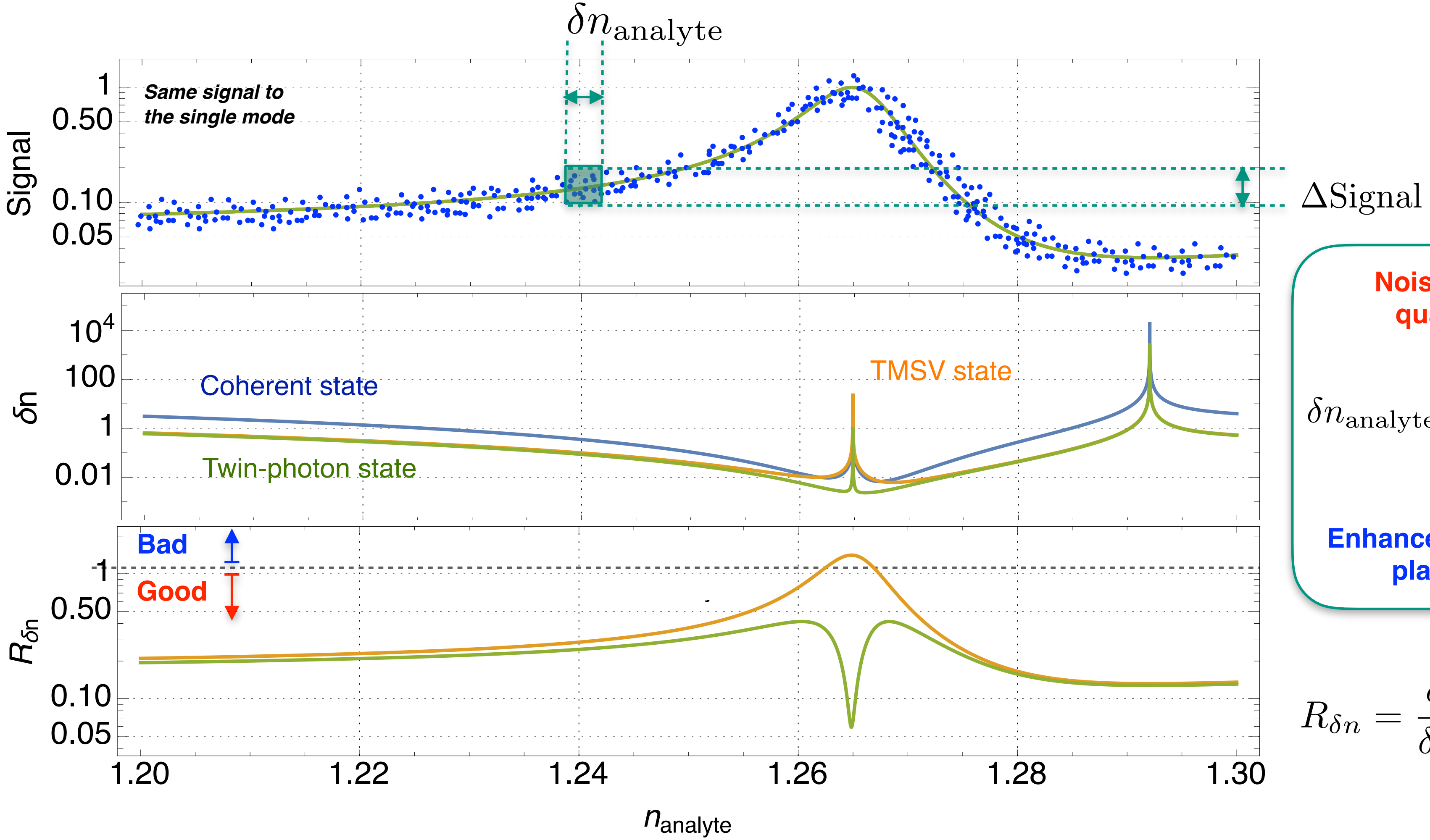



# Estimation of the refractive index

- for a given incident angle $\theta_{\text{in}} = 60$

$N_a = N_b = 1$

$\eta_a = \eta_b = 1$




**Noise-reduction by quantum sensing**

$$\delta n_{\text{analyte}} = \frac{\Delta\text{Signal}}{\left|\frac{\partial\text{Signal}}{\partial n_{\text{analyte}}}\right|}$$

**Enhanced sensitivity by plasmonic sensing**

$$R_{\delta n} = \frac{\delta n}{\delta n_c}$$

# Conclusion

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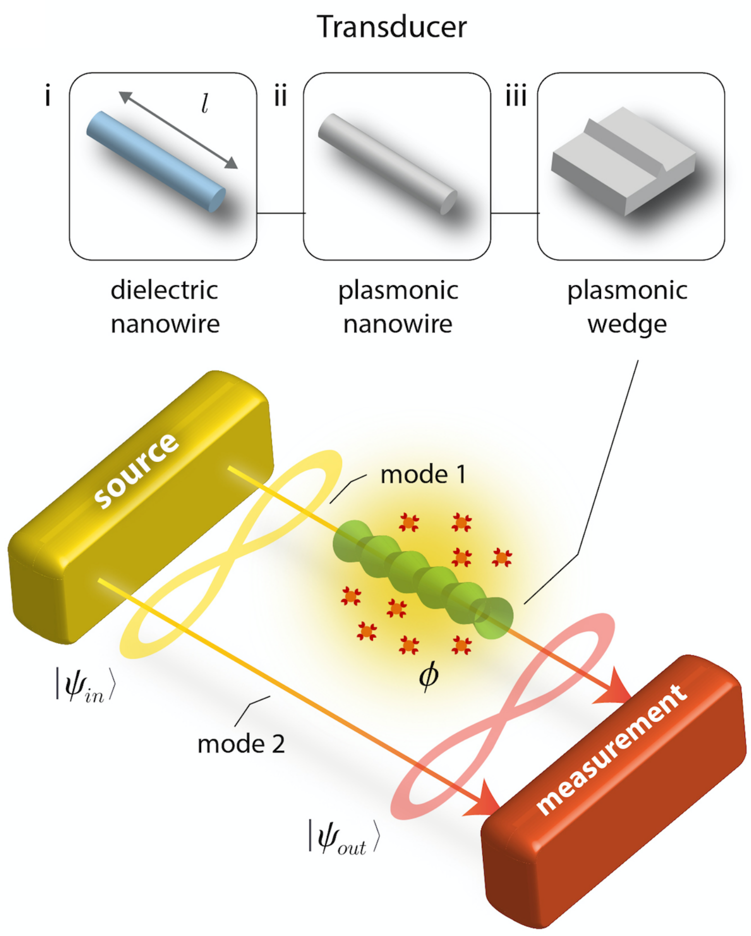
## Phase-sensitive nanowire sensing

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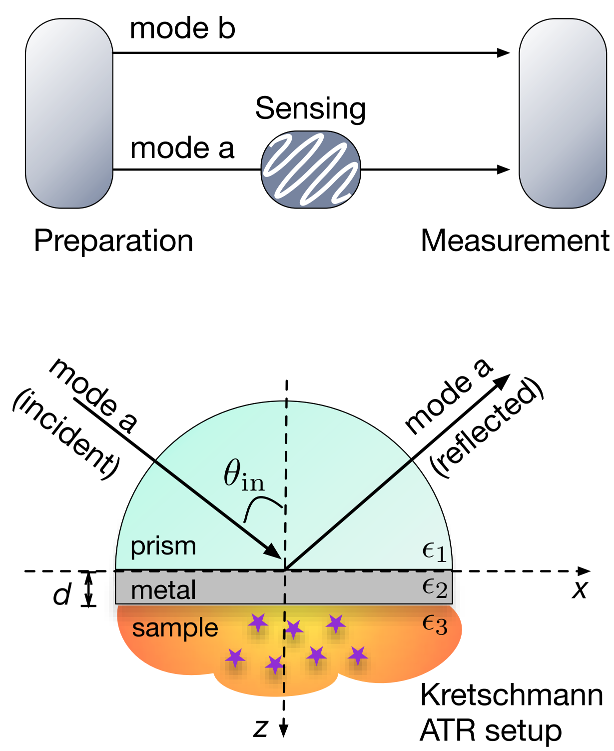
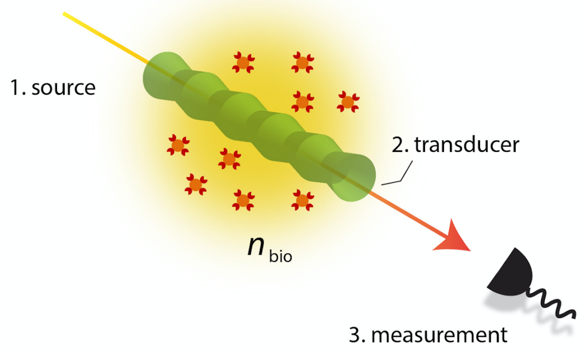
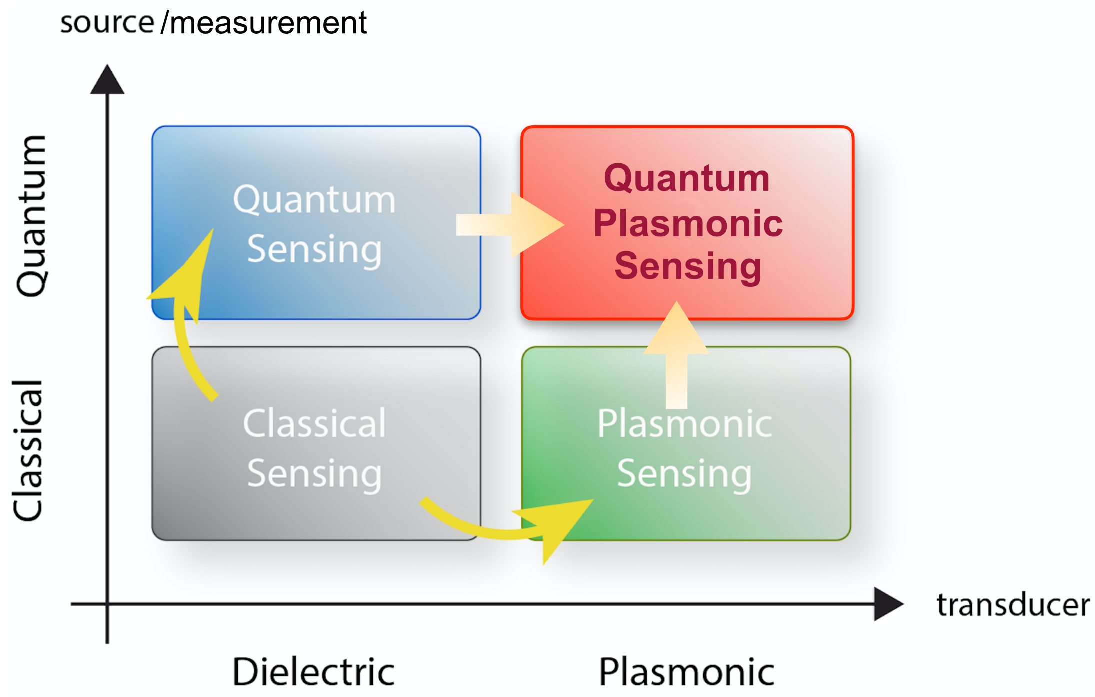
## Intensity-sensitive prism sensing




(in preparation)

# Conclusion

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# Thank you!

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