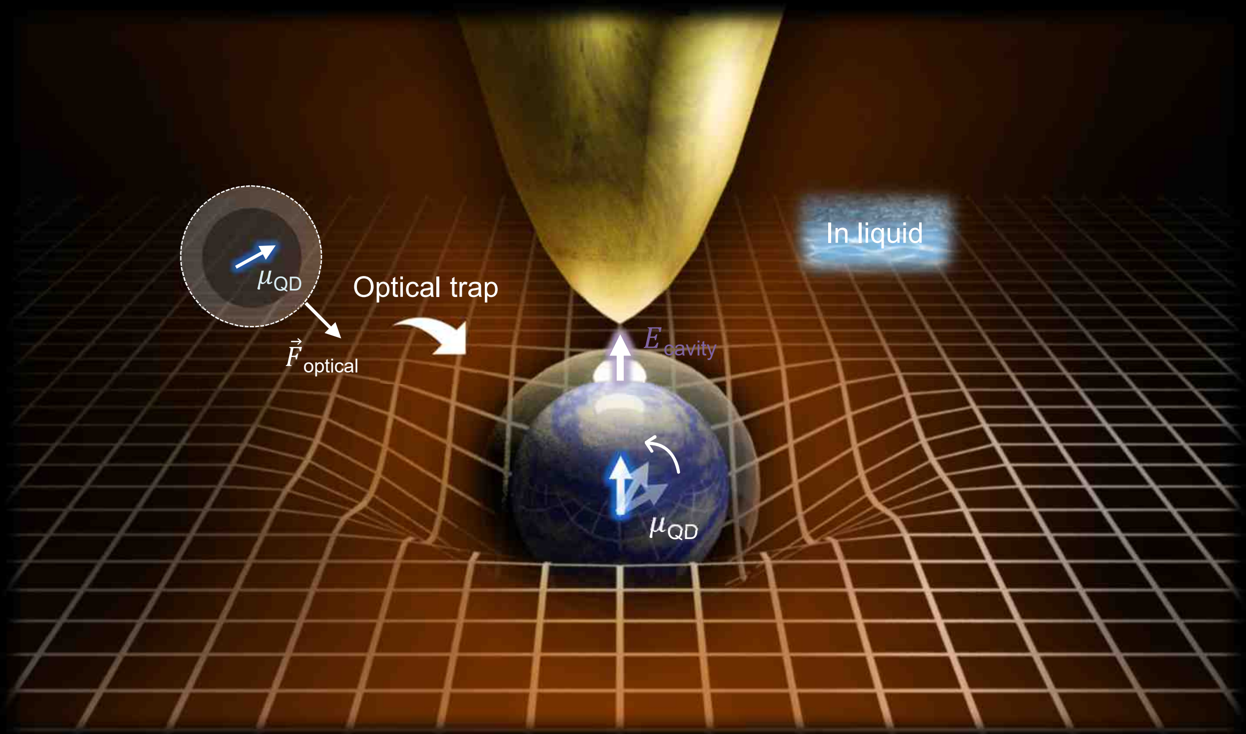
POSTECH
POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY

When near-field plasmonic tip meets quantum technologies



Kyoung-Duck Park

Department of Physics

Pohang University of Science and Technology (POSTECH)

The 20th U.S.-Korea Forum on Nanotechnology
Sep 14, 2026

Acknowledgements

Current active collaborators

Quantum materials

Vasily Kravtsov (ITMO U), Ki-Kang Kim (SKKU), Mun Seok Jeong (Hanyang Univ.), Sangmin Ahn (JBNU), Heejun Yang (KAIST), Deep Jariwala (PENN) Hong Seok Lee (JBNU), Hyun-Seok Lee (CBNU), Jonghwan Kim (POSTECH), Sohee Jeong (SKKU), Moon-Ho Jo (POSTECH), Jaehoon Lim (SKKU) Reuven Gordon (UVIC), Jim Schuck (Columbia U), Kaihui Liu (Peking U)

Quantum physics

Igor Aharonovich (UTS), Milos Toth (UTS), Matthew Pelton (UMBC), Markus Raschke (CU Boulder), Tao Jiang (Tongji Univ.), Junghoon Jahng (KRISS)

Plasmonic devices

Junsuk Rho (POSTECH), Hyeong-Ryeol Park (UNIST), Daisik Kim (UNIST), In Su Lee (POSTECH)

Molecular physics

Yung Doug Suh (UNIST/IBS)

Ultrafast/Nonlinear/Cryogenic spectroscopy

Fabian Rotermund (KAIST), Fengqiu Wang (Nanjing Univ.)

Current group members (~20)

Dr. H. Hwang, Dr. T. Lee, H. Lee, M. Kang, Y. Koo, T. Moon, S. Kim, J. W. Yu, H. Joo, Y. B. Kim, T. Baek, H. Oh, S. Jeong, W. Jung, I. Choi, K. Park, Y. Lee, S. Kang

Research area

Near-Field Optics

Dynamical control of nanoscale light-matter interactions

Near-field phenomena in nano-photonic devices

HL, …, and KDP, *Nature Materials* Published online (2026)

TM, …, and KDP, *Science Advances* 12, eady2186 (2026)

YK, …, and KDP, *Light: Science & Applications* 14, 218 (2025)

SK, …, and KDP, *Science Advances* 10, eadr0492 (2024)

YK, …, and KDP, *Light: Science & Applications* 13, 30 (2024)

HL, …, and KDP, *Nature Communications* 14, 1891 (2023)

YK, …, and KDP, *ACS Nano* 17, 4584 (2023)

YK, …, and KDP, *Light: Science & Applications* 12, 59 (2023)

HL, …, and KDP, *Science Advances* 8, eabm5236 (2022)

KDP et al., *Nano Letters* 18, 2912 (2018)

KDP et al., *Nature Nanotechnology* 13, 59 (2018)

KDP et al., *Nano Letters* 16, 2621 (2016)

Quantum Optical Technologies

Tip-enhanced quantum sensing

Single-photon emission in solid quantum materials

YK, …, and KDP, *Nature Communications* Published online (2026)

HL, …, and KDP, *Nano Letters* In press (2026)

HL, …, and KDP, Under revision in *Nano Letters* (2026)

HL, …, and KDP, *Physical Review Letters* 132, 133001 (2024)

HL, …, and KDP, *Advanced Functional Materials* 31, 2102893 (2021)

KDP et al., *Science Advances* 5, eaav5931 (2019)

Optical Instrumentations

Tip-enhanced nano-spectroscopy and -imaging (UV-VIS-IR)

Nano-optical characterizations of quantum materials

SK, …, and KDP, *Light: Adv & Manufact.* In press (2026)

JH, …, and KDP, *Advanced Photonics* Published online (2026)

HL, …, and KDP, *ACS Nano* 19, 42489 (2025)

HL, …, and KDP, *Nature Communications* 15, 8725 (2024)

TM, …, and KDP, *Nano Letters* 24, 3777 (2024)

MGK, …, and KDP, *Nano Letters* 24, 279 (2024)

HL, …, and KDP, *Nano Convergence* 10, 57 (2023)

MGK, …, and KDP, *Nature Communications* 13, 4133 (2022)

HL, …, and KDP, *ACS Nano* 15, 9057 (2021)

DL, …, and KDP, *Nature Communications* 12, 3465 (2021)

YK, …, and KDP, *Advanced Materials* 33, 2008234 (2021)

KDP et al., *Advanced Materials* 29, 1603601 (2017)

KDP et al., *Nano Letters* 16, 479 (2016)

Synchrotron Beamline Technologies

Development of synchrotron infrared nanospectroscopy (SINS) in IR beamline

Nano-characterizations of IR photonic devices

YK, …, and KDP, In preparation *(2026)*

SJ, …, and KDP, In preparation *(2026)*

Metrology and Inspection (Semiconductor Industry)

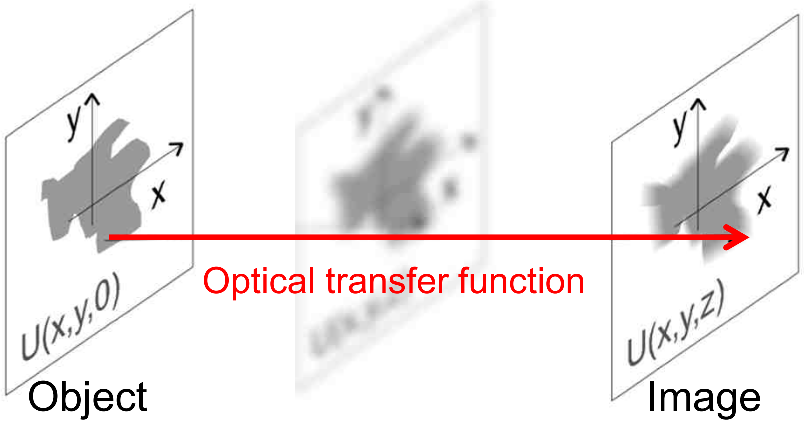
Development of MI instruments

Solving industrial problems in MI process

TB, …, and KDP, Several on-going projects

Spatial resolution limit in far-field imaging

Propagation of the light in imaging system



$$\alpha = \frac{k_x}{\lambda}, \beta = \frac{k_y}{\lambda}$$

From Helmholtz eq.

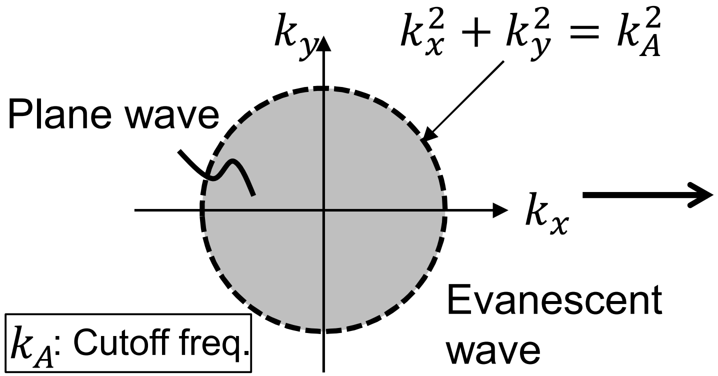
$$U(x,y,z) = \iint u(k_x, k_y, 0)\underbrace{\boxed{e^{2\pi i\sqrt{1-\alpha^2-\beta^2}z}}}_{\text{OTF}}dk_x dk_y$$

$\alpha^2+\beta^2<1$ → Propagation with limited bandwidth
: Plane wave

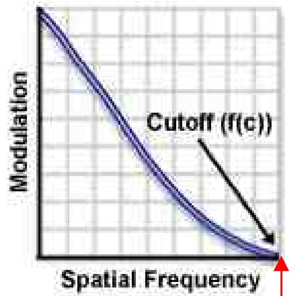
$\alpha^2+\beta^2>1$ → Signal decay exponentially
: Evanescent wave

Spatial resolution in imaging system

Frequency domain | Space domain



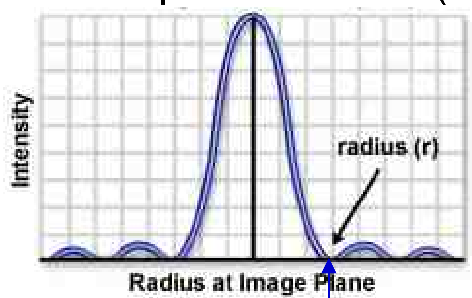
Transfer function



$$\frac{2\text{NA}}{\lambda} = k_A$$

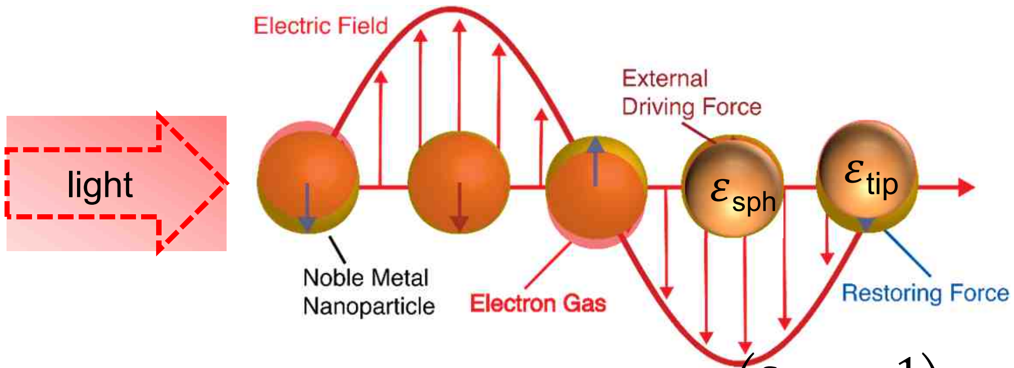
Fourier Transform

Point spread function (PSF)



Spatial resolution $r = \frac{\lambda}{2\text{NA}}$

Localized surface plasmon resonance (LSPR)



Resonance oscillation: $\alpha = 4\varepsilon_0 \pi r^3 \left(\frac{\varepsilon_{sph} - 1}{\varepsilon_{sph} + 2} \right)$

Nano-optical antenna: $\sigma_{sca} \propto |\alpha|^2$

i) Highly enhanced optical signal

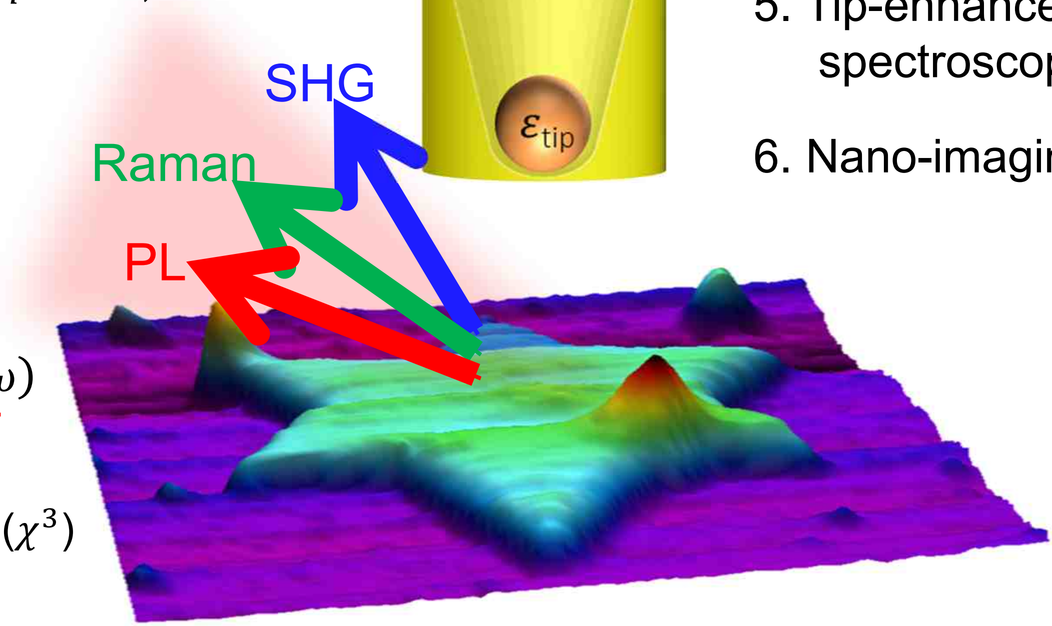
ii) Spatial resolution < 10 nm

$$k_{FF} = \frac{2\pi}{\lambda} \Rightarrow k_{NF} \sim \frac{\pi}{r} \gg k_{FF}$$

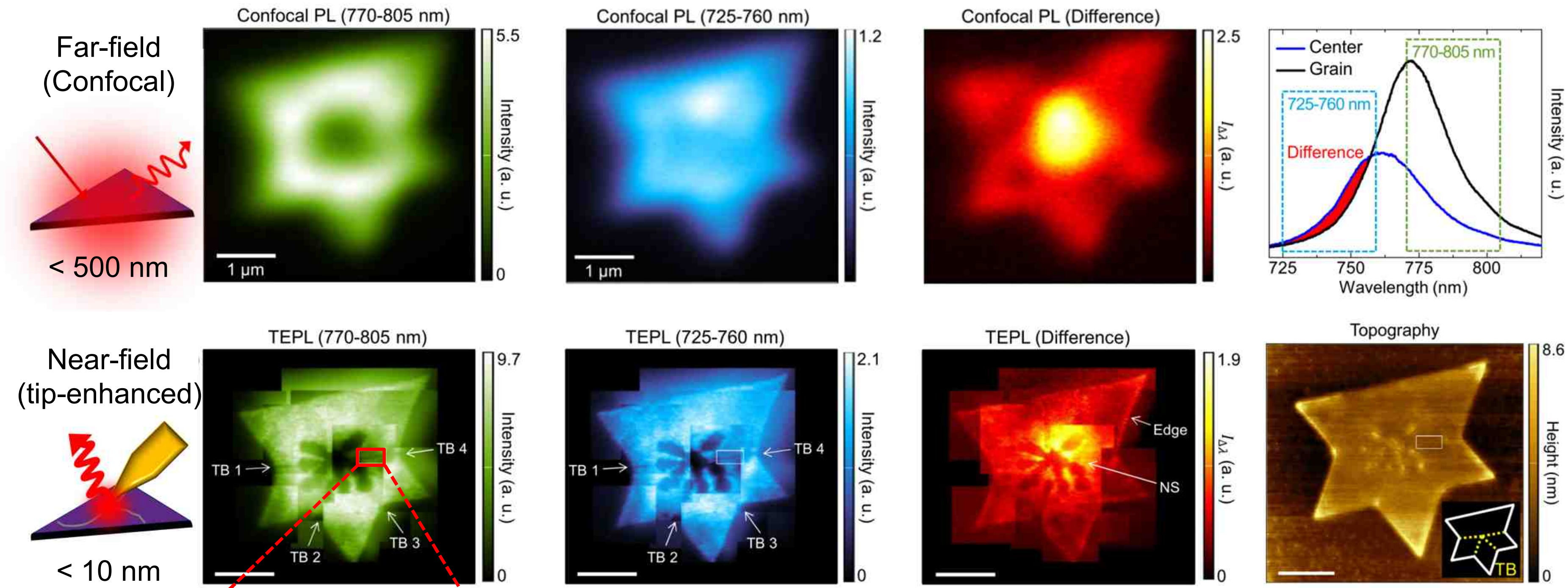
$$P(\omega) = \underline{\varepsilon_0 \chi^{(1)} \omega E(\omega)} + \underline{\varepsilon_0 \chi^{(2)} \omega_{(2)} E(\omega) E(\omega)}$$

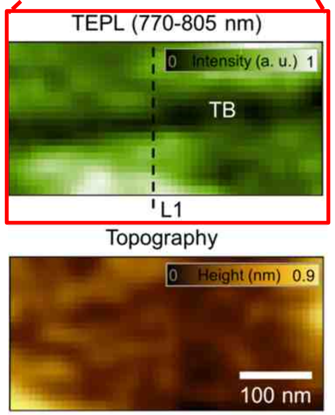
Tip-enhanced Raman	Tip-enhanced SHG
Tip-enhanced PL	Tip-enhanced FWM (χ^3)
⋮	⋮

1. Au wire
2. Etching
3. Dipole antenna
4. Approach
5. Tip-enhanced spectroscopy
6. Nano-imaging

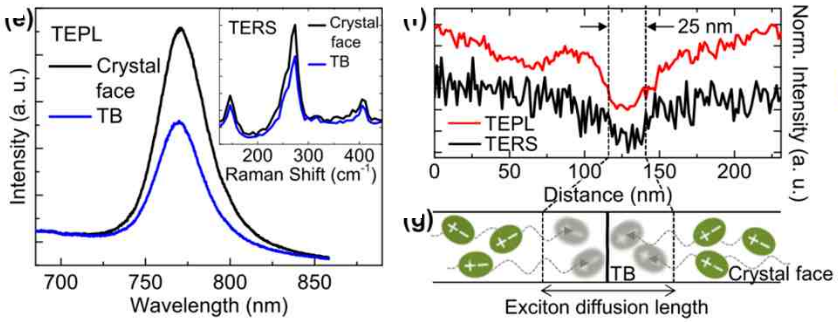


TEPL imaging of nanoscale defects of a WSe_2 ML





~25 nm width PL decrease without spectral shift:
exciton diffusion into non-radiative recombination center



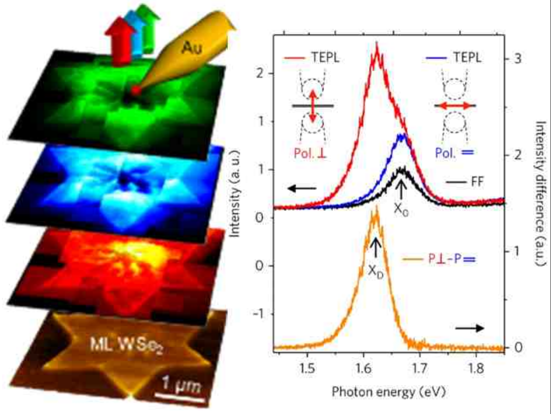
Expected exciton diffusion length in previous study:

$L = 2\sqrt{D_{exc}\tau}$ = ~24 nm

van der zande et al, *Nat. Mater.* **12,** 554 (2013)

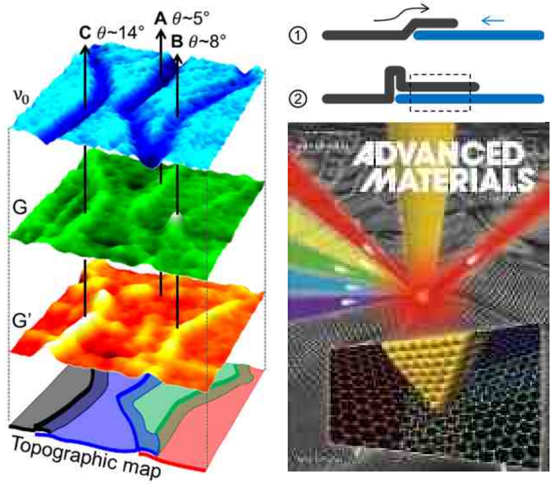
Tip-enhanced nano-spectroscopy and -imaging

TEPL of WSe_2 X_{dark}



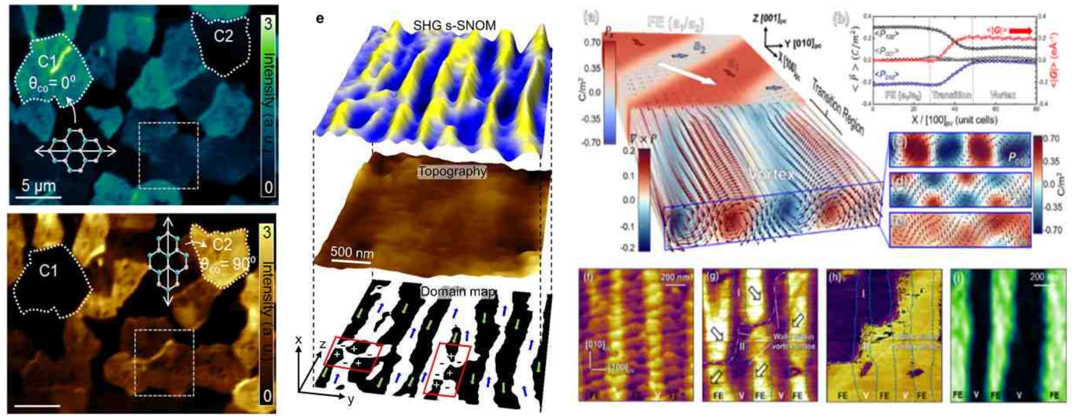
Park et al., ***Nat. Nano.*** (2019)
Park et al., ***Nano Lett.*** (2016)

TERS imaging of graphene



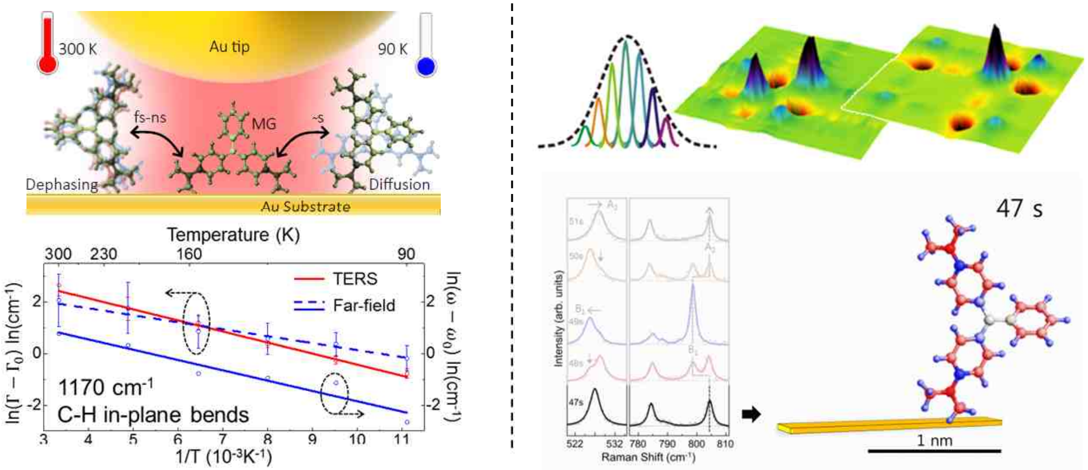
Park et al., ***Adv. Mater.*** (2017)

Nonlinear optical nano-crystallography



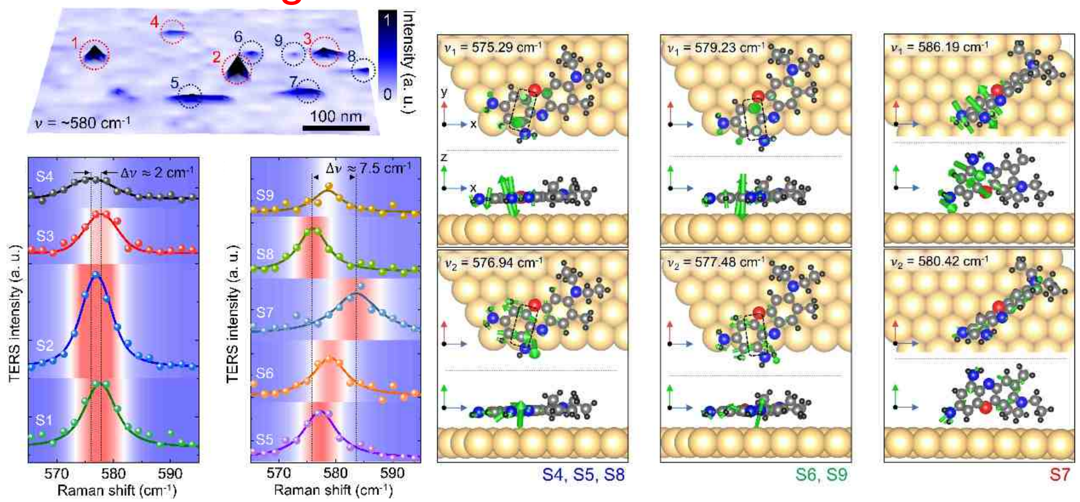
Park et al., ***Nano Lett.*** (2018)
Damodaran et al., ***Nature Mater.*** (2017)

Real-time motion of a single-molecule



Park et al., ***Nano Lett.*** (2016)

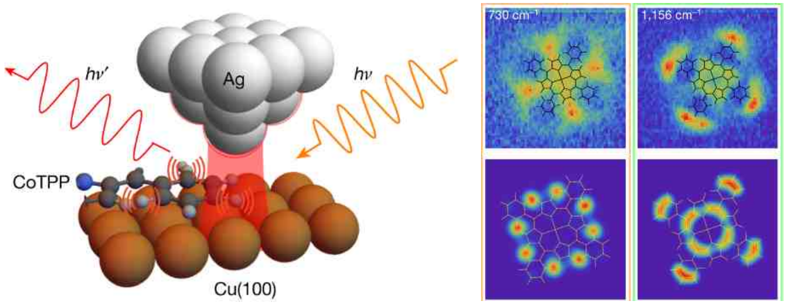
Room-T single-molecule TERS with freeze-frame



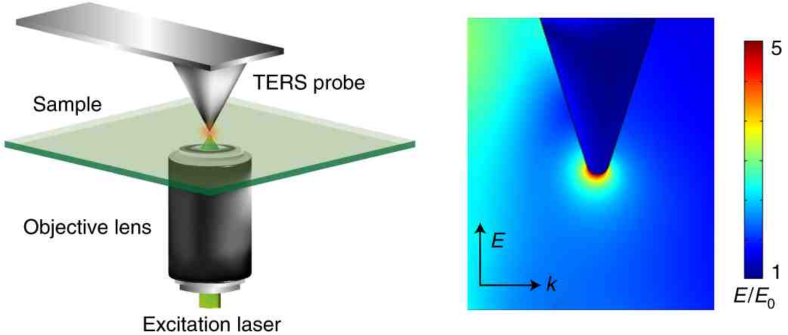
Kang et al., ***Nat. Commun.*** (2022)

Limitations of previous approaches for L-M interactions

Tip-enhanced nano-spectroscopy

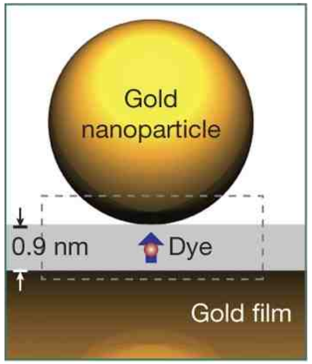


Lee et al., *Nature* **568**, 78 (2019)

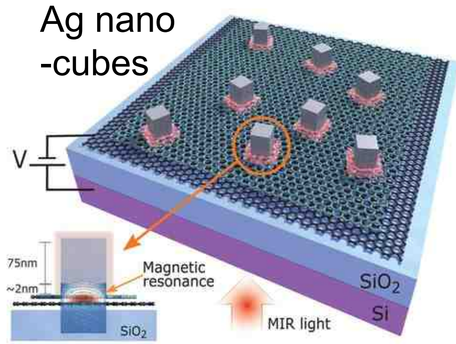


Kumar et al., *Nat. Protocols* **14**, 1169 (2019)

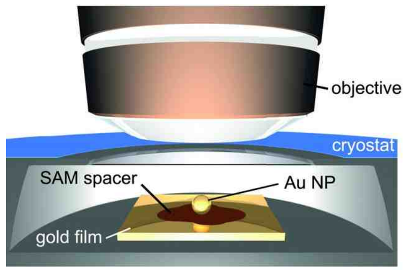
Plasmonic nano-cavity



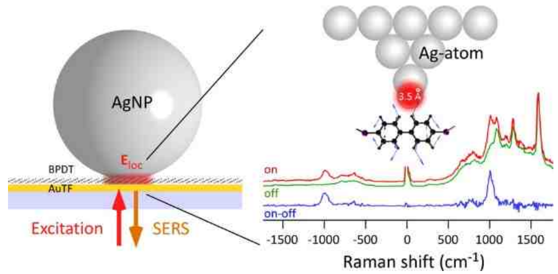
Chikkaraddy et al.,
Nature **535**, 127 (2016)



Epstein et al.,
Science **368**, 1219 (2020)



Benz et al., *Science* **354**, 726 (2016)



Shin et al., *Nano Lett.* **18**, 262 (2018)

But, each approach has several own limitations for light-matter interaction studies

- Field localization is smaller than nano-cavity
- Single tip geometry → hard to define mode volume
- Inducing strong light-matter interactions is difficult

- Dynamical control of L-M interactions is difficult
- Control experiment for different matters is difficult
- Diffraction-limited optical characterizations

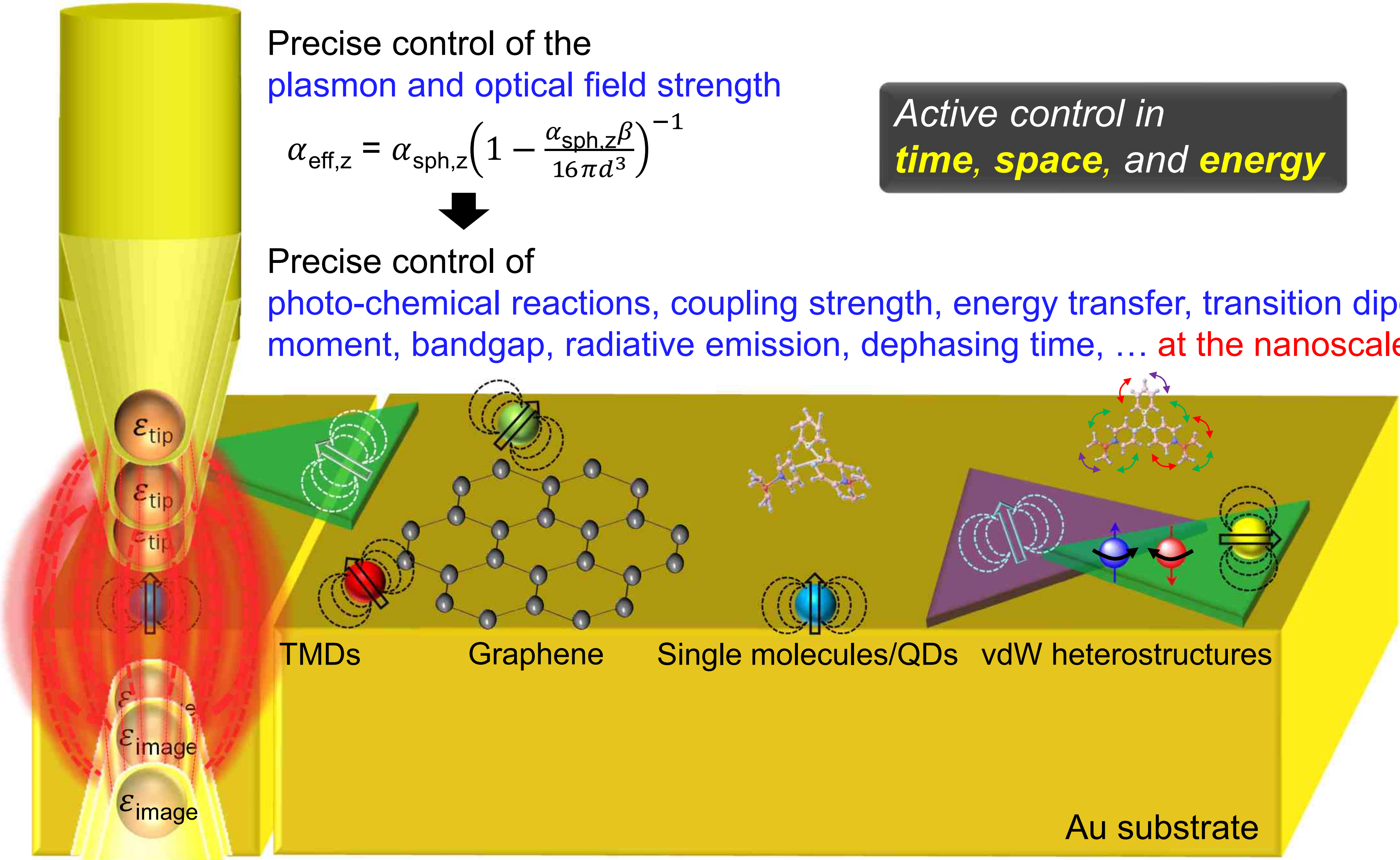
Tip-induced control of nanoscale light-matter interactions

Precise control of the
plasmon and optical field strength

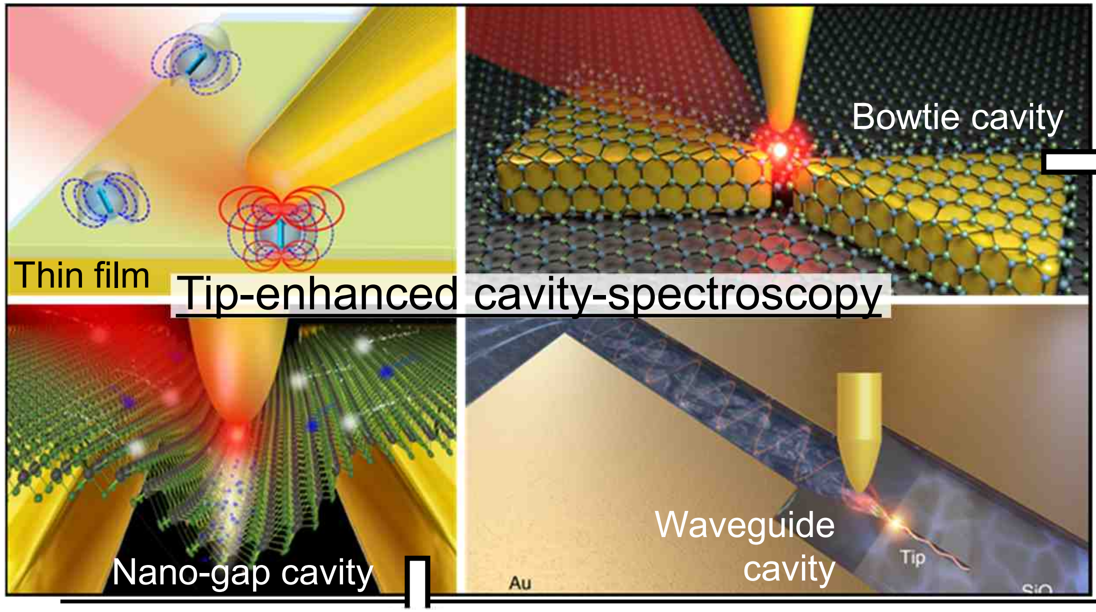
$$\alpha_{\mathrm{eff},z} = \alpha_{\mathrm{sph},z}\left(1 - \frac{\alpha_{\mathrm{sph},z}\beta}{16\pi d^3}\right)^{-1}$$

Precise control of
photo-chemical reactions, coupling strength, energy transfer, transition dipole moment, bandgap, radiative emission, dephasing time, … at the nanoscale

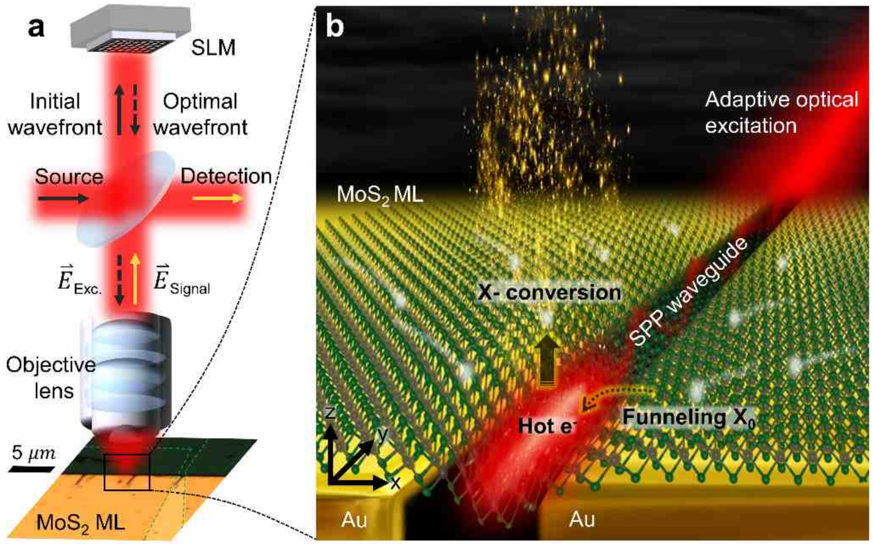
Active control in
time**,** ***space*****, and** ***energy***

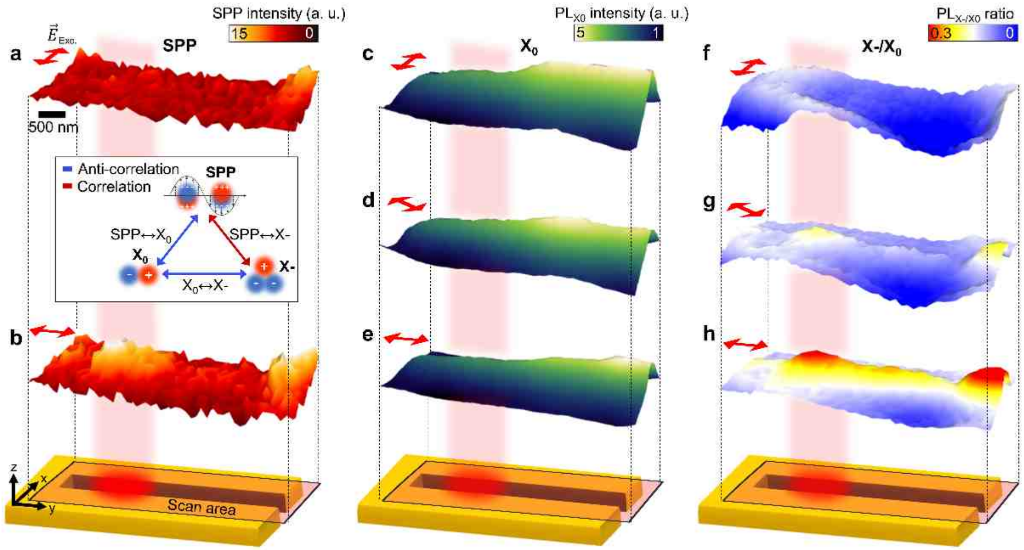


Tip-enhanced cavity-spectroscopy (TECS)



<u>Localized exciton control</u>: ***Adv. Funct. Mater.*** (2021)



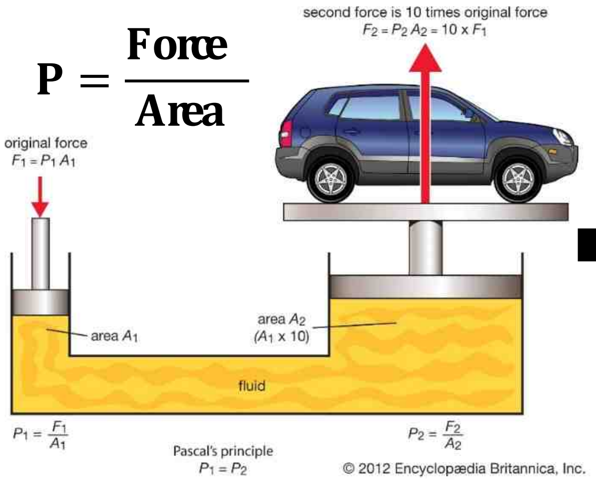


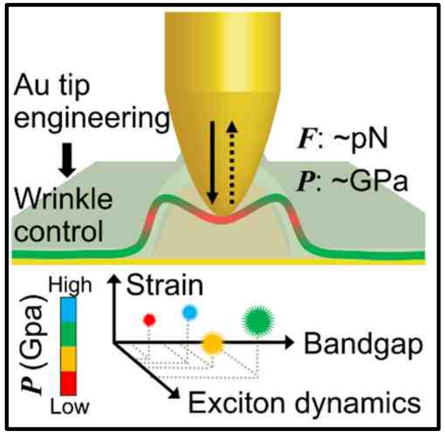
<u>All-optical control of ultrathin trionic waveguide</u>: ***Nat. Commun.*** (2023)

Nano-spectroscopy with GPa scale tip-pressure control

GPa scale tip-pressure control

$$P = \frac{\text{Force}}{\text{Area}}$$





Large pressure **~GPa**

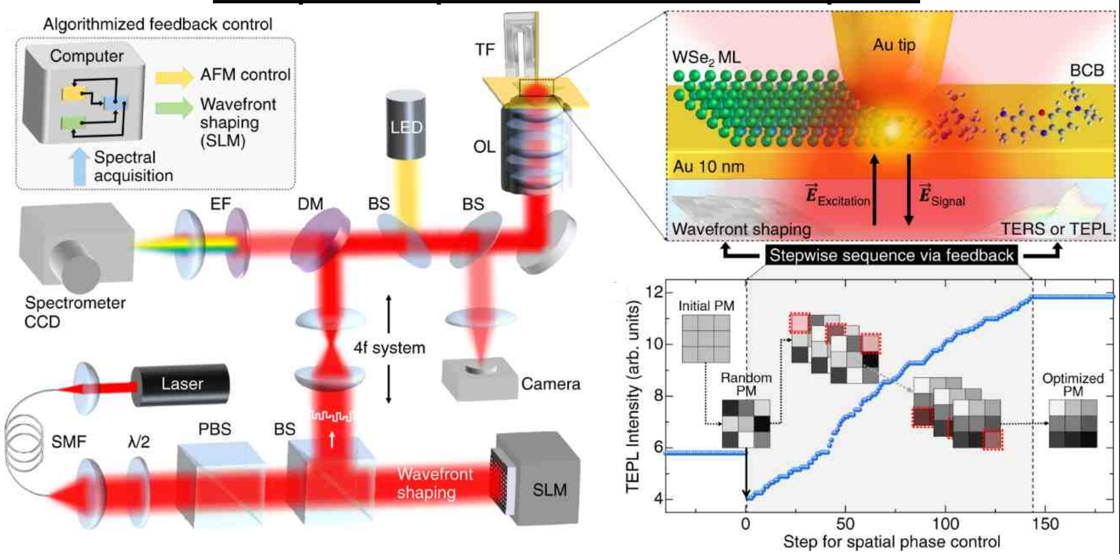
Exciton density & energy control: ***Adv. Mater.*** (2021)

Perov. single QD bandgap control: ***ACS Nano*** (2021)

Interlayer exciton/trion control: ***Light: Sci. & Appl.*** (2023)

Nano-spectroscopy with adaptive near-field polarization control

Adaptive optics + Near-field optics



Adaptive Raman/IR modes control: ***Nat. Commun.*** (2021)

Adaptive two-bits optical computing & communications

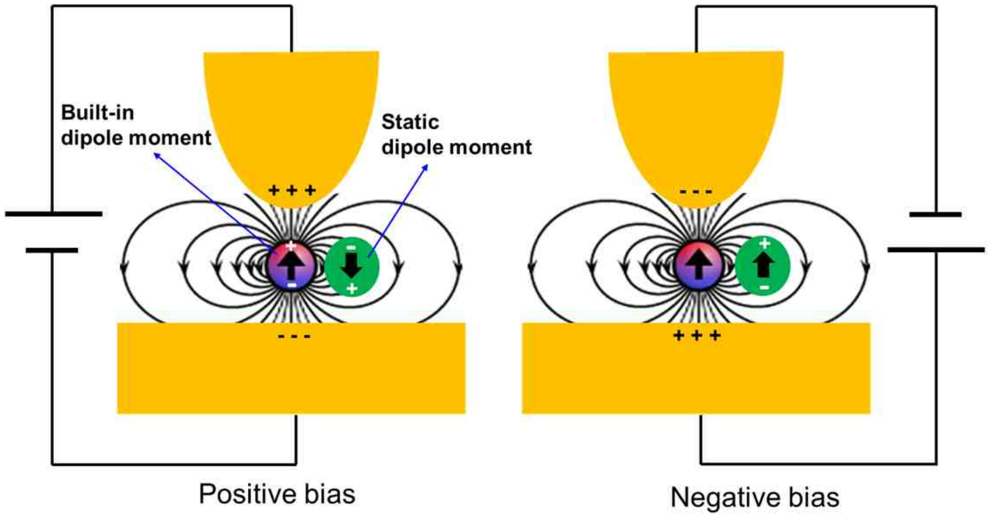
Interlayer exciton emission control: ***ACS Nano*** (2023)

Resonance & sensitivity tunable gap-enhanced Raman

Adaptive tunable GERS: ***Nano Letters*** (2024)

Nano-spectroscopy with quantum tunneling control

Tip-enhanced electric charge control

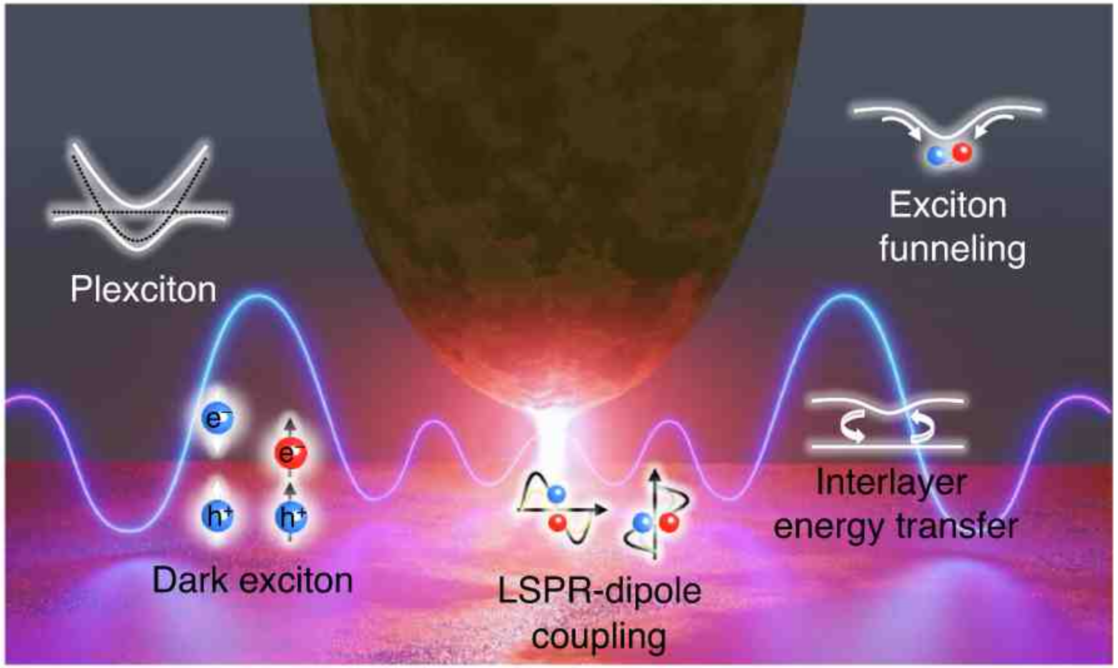


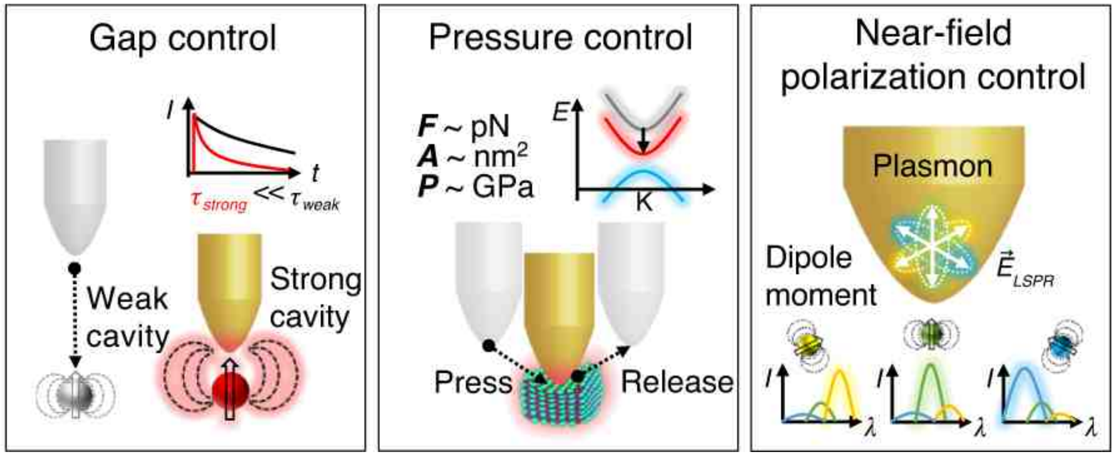
Nano-spectroscopic E pulse modulator: ***Sci Adv*** (2024)

Electrical control of strong coupling: ***Phys Rev Lett*** (2024)

8 MHz nano-excitonic modulator: ***Nat Comm*** (2024)

Tip-induced control of nanoscale light-matter interactions





<u>Conventional roles</u>
<u>of near-field microscopy:</u>

- **Seeing nanoscale structures** with the nano-optical probe
- **Observing optical properties** of materials at the nanoscale

⋮

Method for
imaging & spectroscopy

<u>Expanded roles</u> <u>of near-field microscopy:</u>

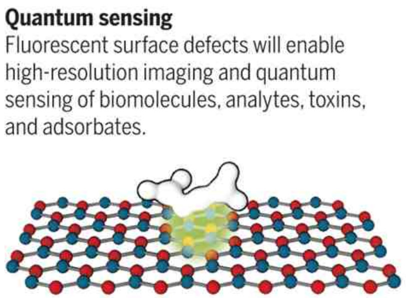
Dynamic control of **quantum light-matter interactions** at the nanoscale

See more:
Koo et al., *Light: Science & Applications* **13,** 30 (2024)

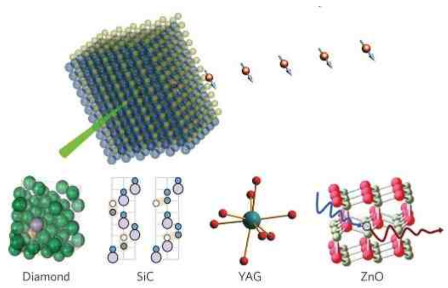
What is quantum sensing?

1) Sensing of quantum sources

Quantum emitters from atom/photonic/solid systems

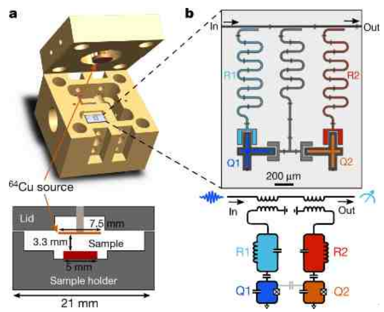


Science **358**, 170 (2017)



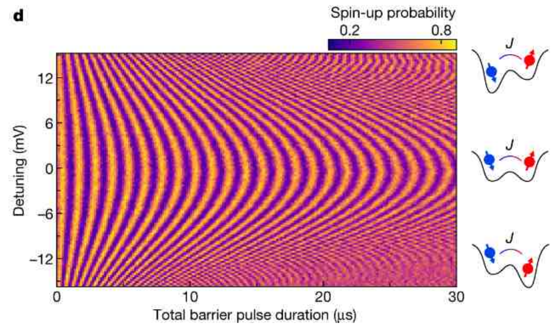
Nat. Photon. **10**, 631 (2016)

Superconducting qubits



Nature **584**, 551 (2020)

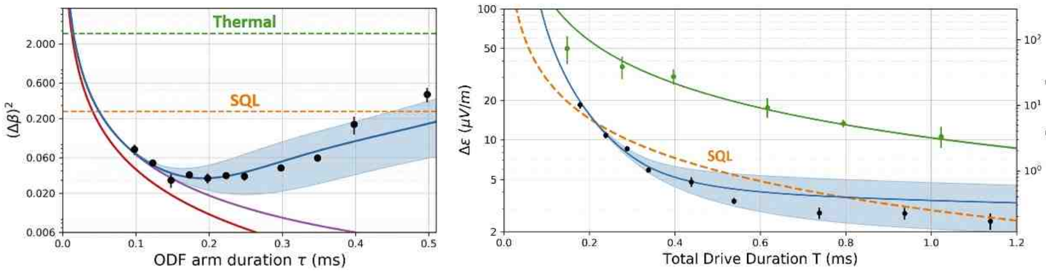
Spin qubits



Nature **601**, 343 (2022)

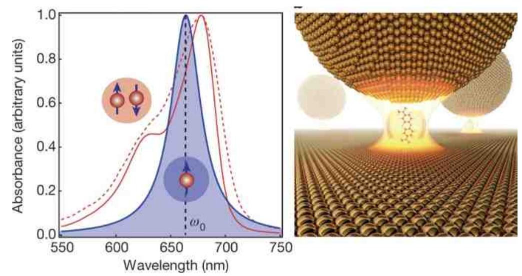
2) Quantum-enhanced sensing for physical quantities

Displacement, temperature, force, electric-field …
with spin, orbit, phonon …



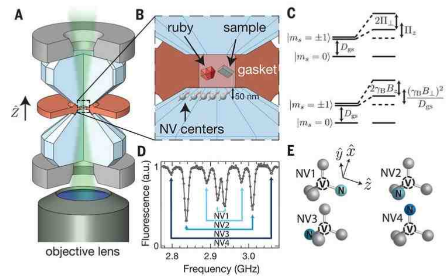
Science **373**, 673 (2021)

Optical field, photon …
with Rabi, Rashba …



Nature **535**, 127 (2016)

Magnetic field …
with Zeeman …



Science **366**, 1349 (2019)