# Quantum Sensing of strong coupling with free electrons

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Strong coupling in light-matter systems is a central concept in cavity quantum electrodynamics, and is essential for many quantum technologies. Especially in the optical range, full control of highly-connected multi-qubit systems necessitates quantum coherent probes with nanometric spatial resolution, which are currently inaccessible. Here [1], we propose the use of free electrons as high-resolution quantum sensors for strongly-coupled light-matter systems. Shaping the free-electron wavepacket enables the measurement of the quantum state of the entire hybrid systems. We specifically show how quantum interference of the free-electron wavepacket gives rise to a quantum-enhanced sensing protocol for the position and dipole orientation of a sub-nm emitter inside a cavity. Our results showcase the great versatility and applicability of quantum interactions between free-electrons and strongly-coupled cavities, relying on the unique properties of free-electrons as strongly interacting flying qubits with miniscule dimensions.

## Current methods for measuring strongly coupled systems are limited

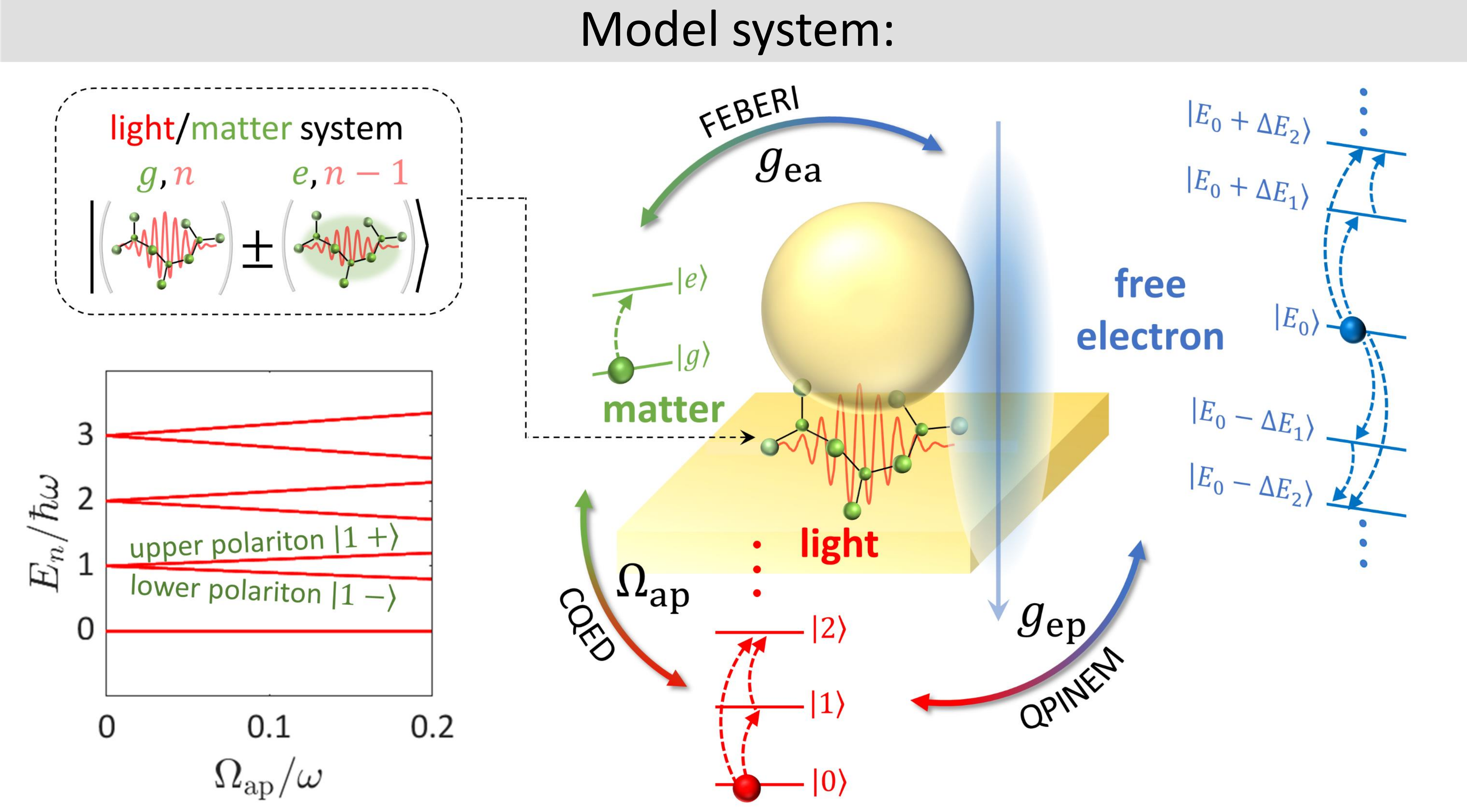
Optics (reflection, PL)[2]: measure Rabi splitting
Diffraction-limited

Quantum probes (photons/atoms) [3]: measure quantum state
Limited to a subsystem (light **or** matter)

Electron energy loss spectroscopy [4]
High resolution, can measure Rabi splitting
usually insensitive to quantum coherence

## Proposal for quantum sensing of strong coupling with free electrons

Model system:

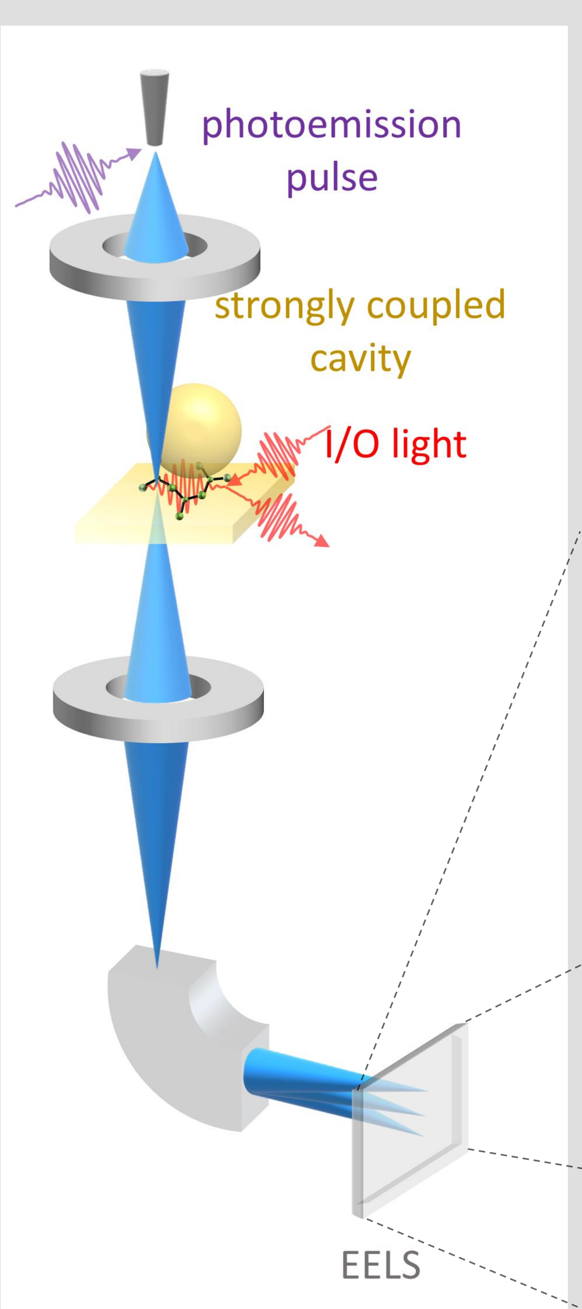



**Photonic cavity with a single emitter:**

- Jaynes-Cummings model [5] with hybrid polaritons
- Rabi splitting with Rabi frequency $\Omega_{ap}$

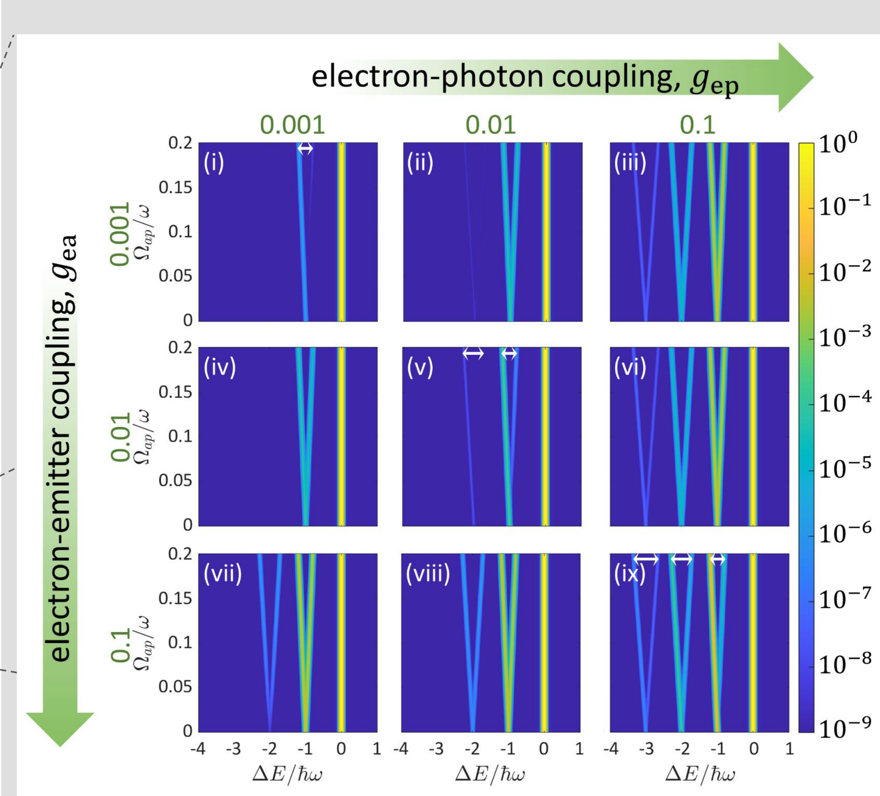
**Free electron probe:**

- Continuous energy ladder, gains or loses quanta of energy
- Electron-matter coupling [6]: $g_{ea}$, typical values $<10^{-4}$
- Electron-light coupling [7]: $g_{ep}$, typical values of $10^{-2}$ to $10^{-3}$



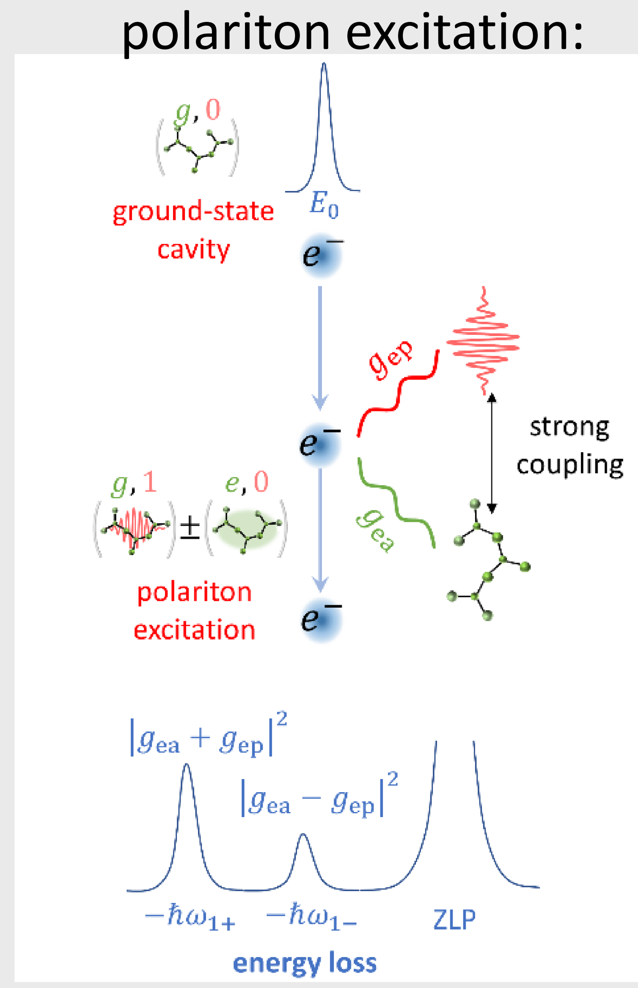

A free-electron probes a strongly-coupled system (can be excited by external light)

Electron energy loss spectra reveal Rabi splitting and quantum interference features:

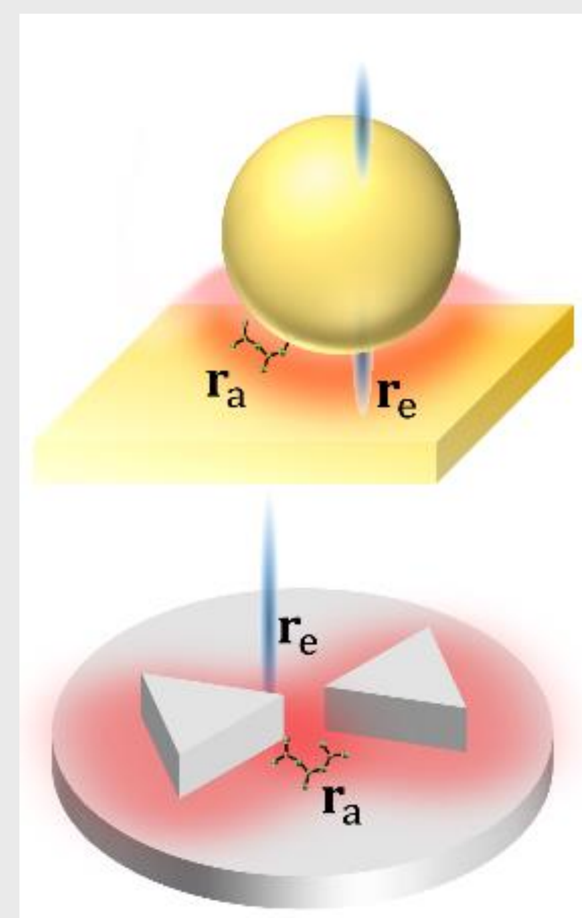


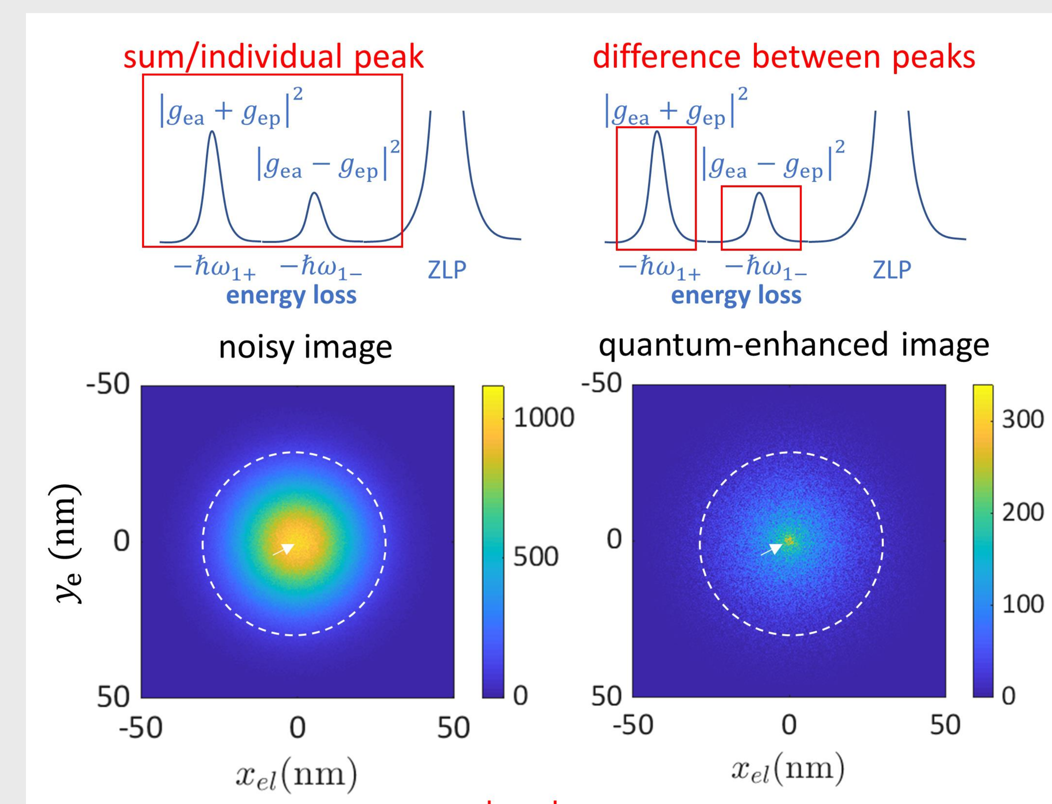

## Quantum interference between electron-matter and electron-light coupling allows enhanced sensitivity

Quantum interference in polariton excitation:



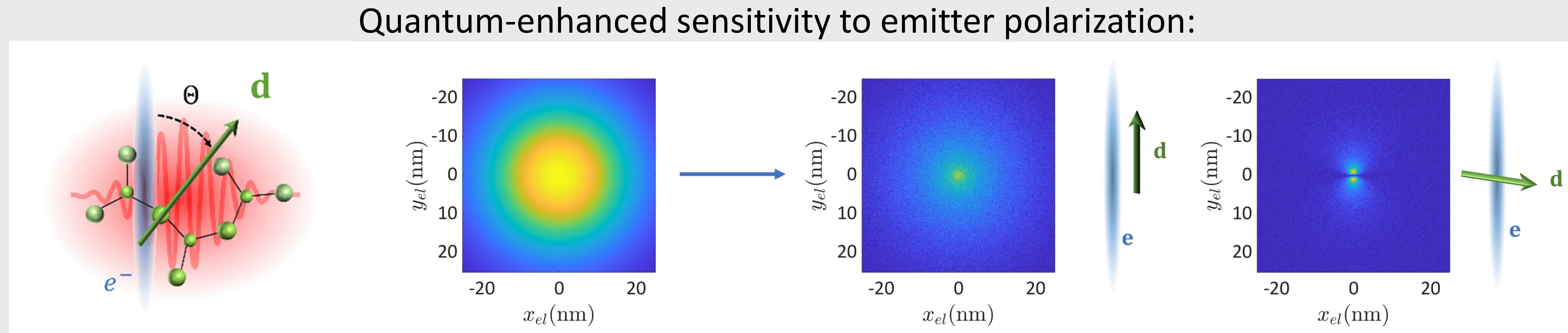

Quantum-enhanced imaging of emitter position:



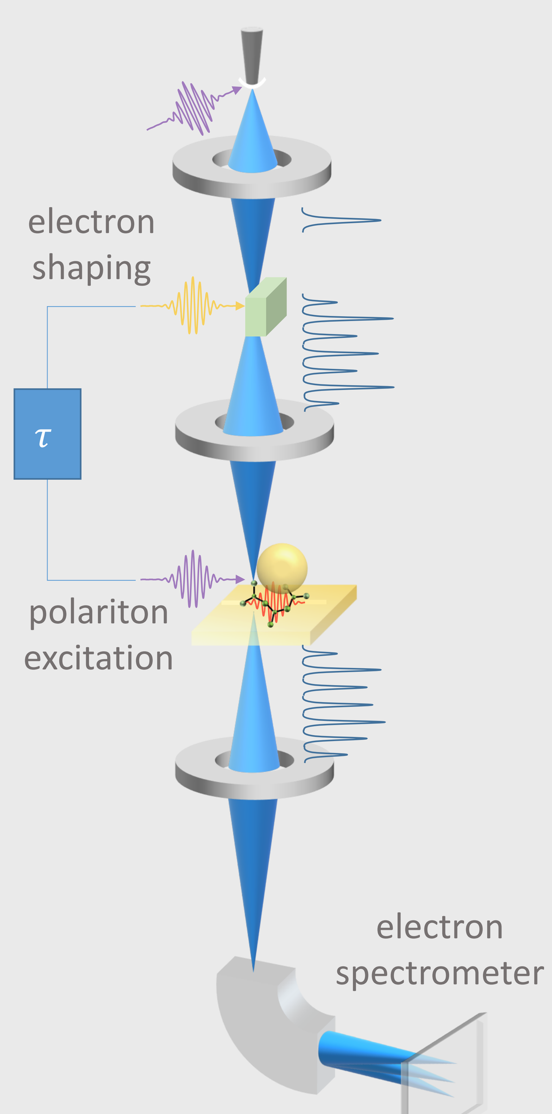


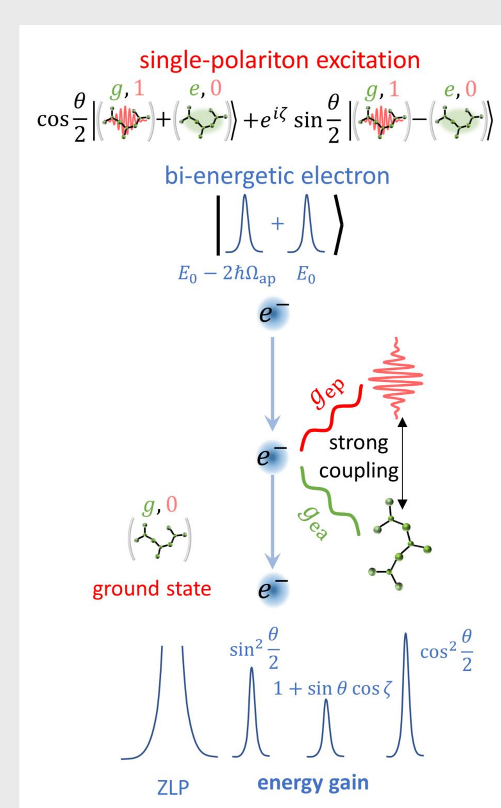

$$\text{quantum enhancement} = \frac{|g_{ep}|}{|g_{ea}|}\,\mathrm{erf}\left(\frac{\hbar\Omega_{ap}}{\sqrt{2}\Delta\epsilon}\right)\left|\cos(\arg g_{ep}g_{ea}^{*})\right|$$

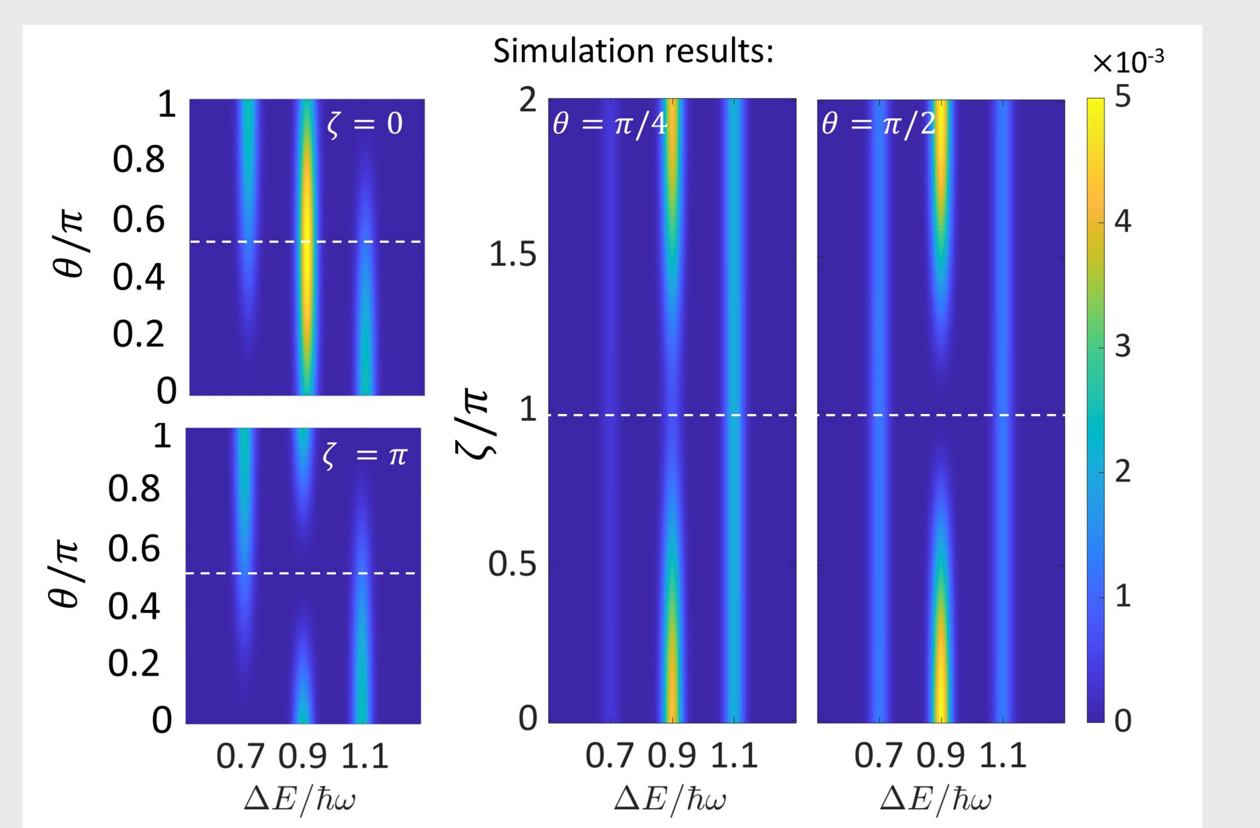
Quantum-enhanced sensitivity to emitter polarization:



## Polariton quantum state sensing with pre-shaped free-electron wavefunctions

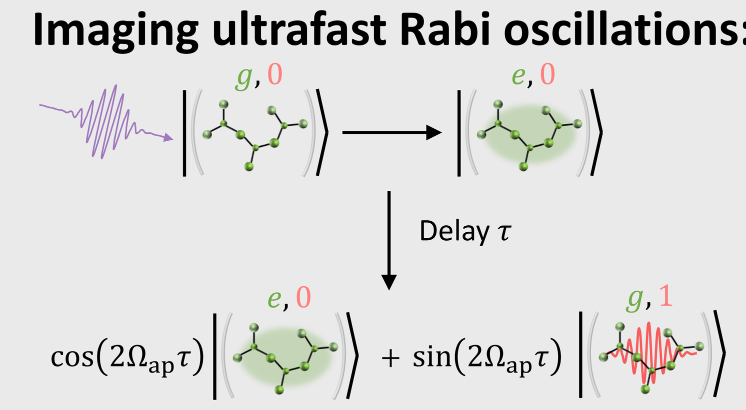



1. Electron shaped to a superposition of energies
2. System excited to an arbitrary single-polariton superposition
3. Electron absorbs polariton after delay $\tau$
4. Electron energy gain peaks hold full information about the excited state

**Imaging ultrafast Rabi oscillations:**




## CONCLUSIONS and OUTLOOK

- We propose a quantum sensing protocol for strongly-coupled light–matter systems using free-electron probes, based on quantum interference.
- Besides showing promise as quantum probes, free-electrons can be used as carriers of quantum information, reading the quantum state encoded in a strongly-coupled cavity.
- Free-electrons can be used for temporally-resolved imaging of ultrafast Rabi oscillations.

## References

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