Geometric control of optical dipoles at a cold atom--nanofiber interface

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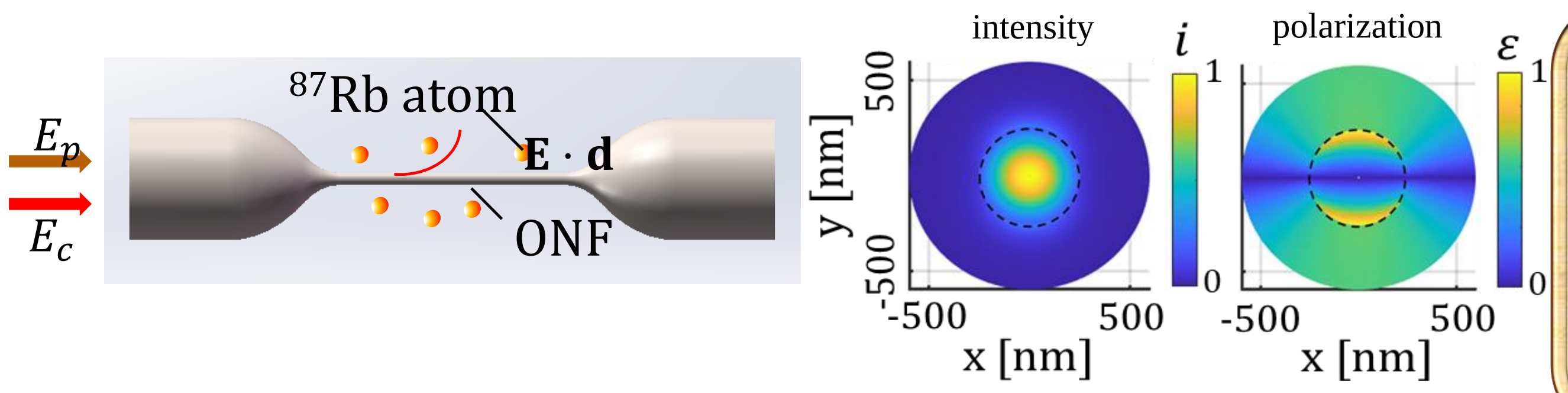
Introduction:

- Novel quantum optics research requires precise, arbitrary control of optical dipoles.
- Nanophotonic interfaces: Strong interaction between confined photons and atoms.
- Challenge: How to perfect optical control in the near field, despite the field inhomogeneity?
- This work: We demonstrate geometric phase control of optical dipoles at a nanoscale atom-fiber interface with a high efficiency agreeing with theoretical prediction. The robust technique can be perfected to support near-field-lattice based 1D quantum optical researches.

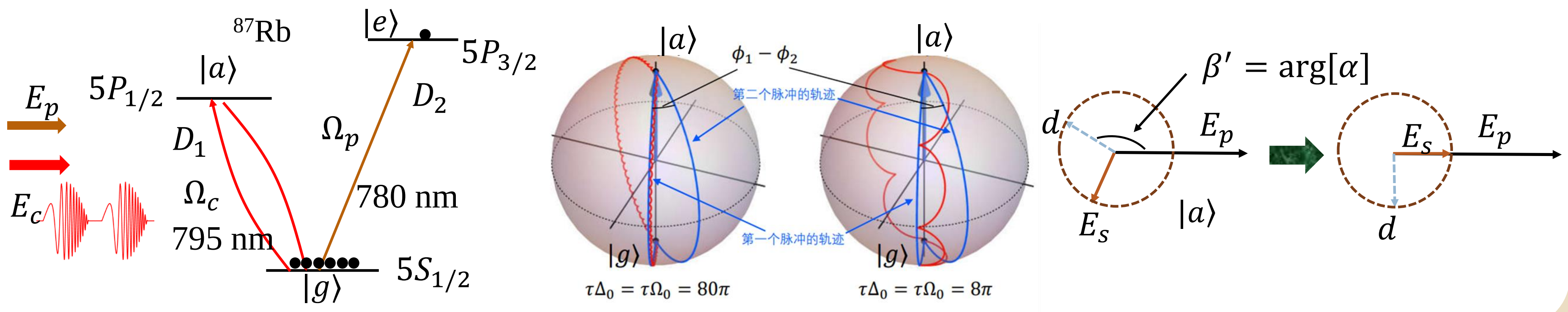
➢ Evanescent coupling and control at the cold atom-nanofiber interface



- Depending on the fiber diameter, $d < \lambda$, ~20% of guided light propagates evanescently in vacuum to interact with cold atoms (The HE11 mode).
- Strong and efficient coupling, "infinite range" interaction.

➢ Geometric phase control of optical dipoles

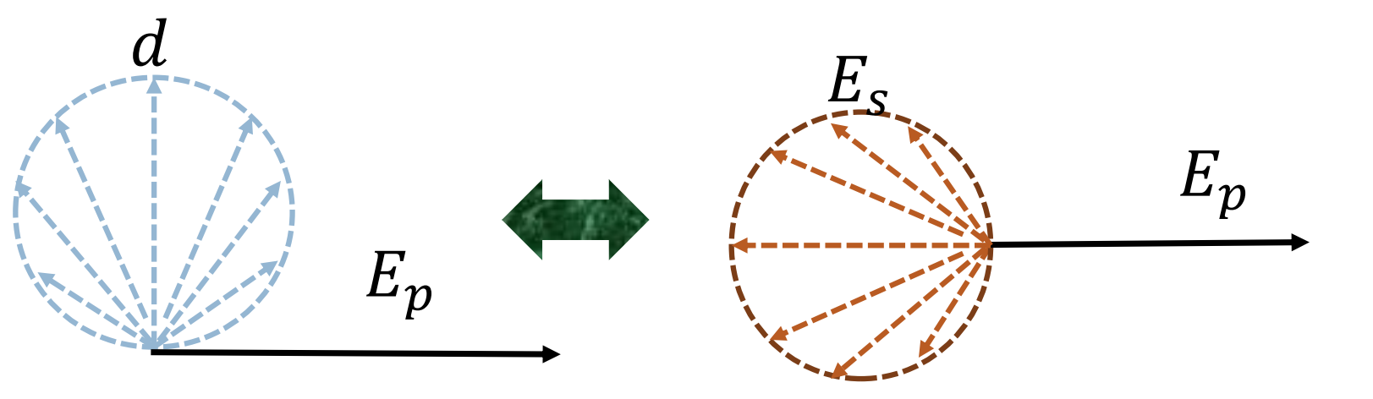
- Electric dipole moment for 2-level atom: $\langle \mathbf{d}\rangle = \mathbf{d}_{eg}\rho_{ge} + c.c \Rightarrow \mathbf{d}_{eg}\rho_{ge}\boldsymbol{\eta_d}e^{-i\gamma} + c.c$
- The geometric phase γ can be written to the ground state $|g\rangle$ by cyclically driving the auxiliary $|g\rangle \longrightarrow |a\rangle$ transition. $\boldsymbol{\eta_d}$: dipole control complex coefficient.

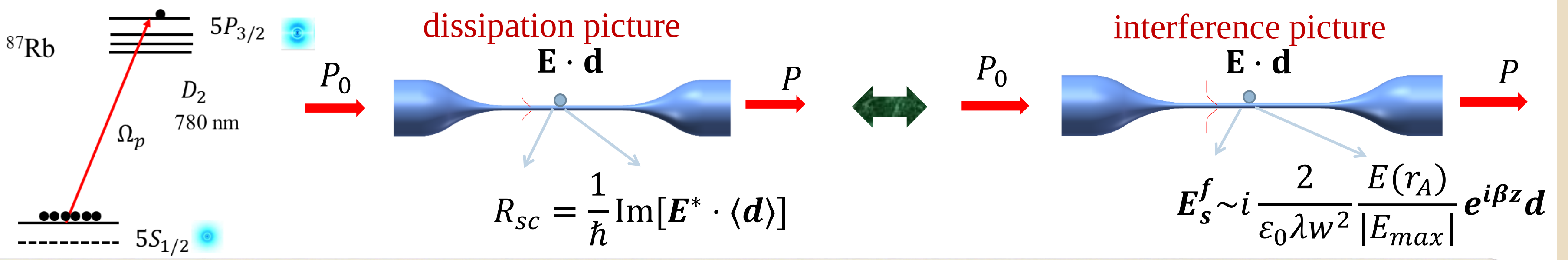


Measurement Principles:

➢ Evanescent attenuation of guided probe by cold atoms

Optical theorem: The scattering of the guided probe by the atoms is proportional to the imaginary part of the coherent forward scattering into the same mode.





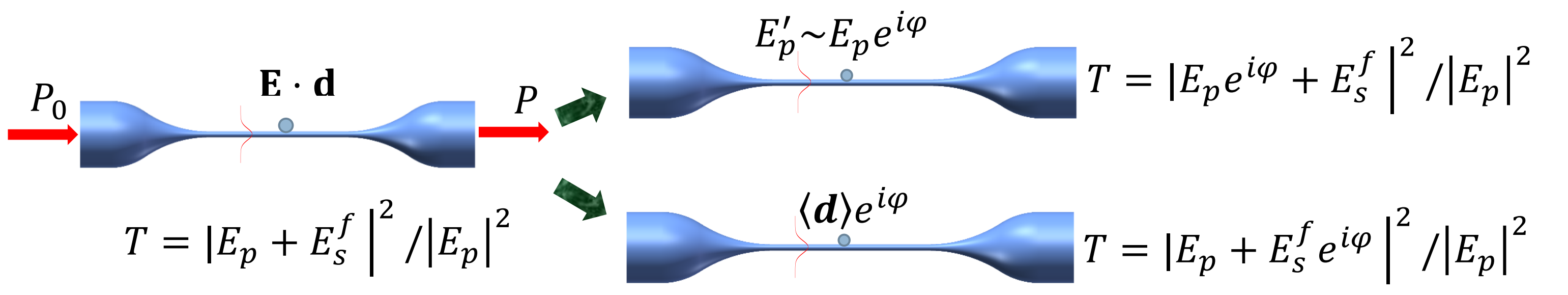
$$R_{sc} = \frac{1}{\hbar}\mathrm{Im}[\boldsymbol{E}^* \cdot \langle\boldsymbol{d}\rangle]$$

$$\boldsymbol{E_s^f} \sim i\frac{2}{\varepsilon_0 \lambda w^2}\frac{E(r_A)}{|E_{max}|}\boldsymbol{e^{i\beta z}d}$$

- Single atom optical depth: $OD_1 = \frac{\hbar\omega R_{sc}}{P_0} \sim \frac{2P_{sc}}{\epsilon_0 c w^2 |E_{max}|^2} \sim \frac{1}{\epsilon_0 \lambda w^2}\frac{2\mathrm{Im}\,[E^*(\boldsymbol{r}_A)\cdot\langle d\rangle]}{|E_{max}|^2} \longleftrightarrow \frac{E^* E_s^f + c.c.}{|E_{max}|^2}$

$$OD_1 = \frac{3\lambda^2}{4\pi^2 w^2}\frac{1}{1+s}\bar{I}(r_A)Im[\frac{\Gamma/2}{\Delta - i\Gamma/2}] \left(\bar{I}(r_A) = \left|\frac{E(r)}{E_{max}}\right|^2 : \text{normalized intensity at the atom location} \right)$$

➢ What happens if the relative phase between the dipole and probe suddenly jumps?



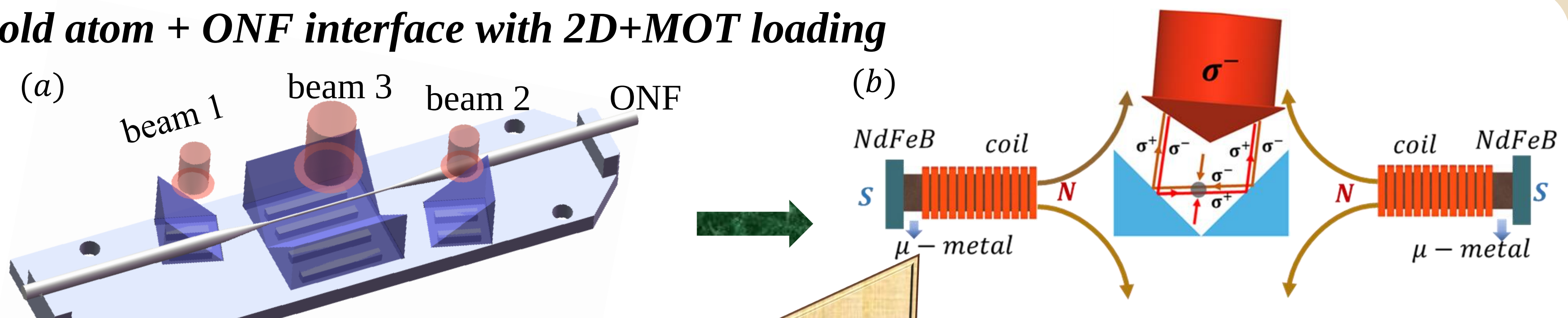
$$T = |E_p + E_s^f|^2/|E_p|^2$$

$$T = |E_p e^{i\varphi} + E_s^f|^2/|E_p|^2$$

$$T = |E_p + E_s^f e^{i\varphi}|^2/|E_p|^2$$

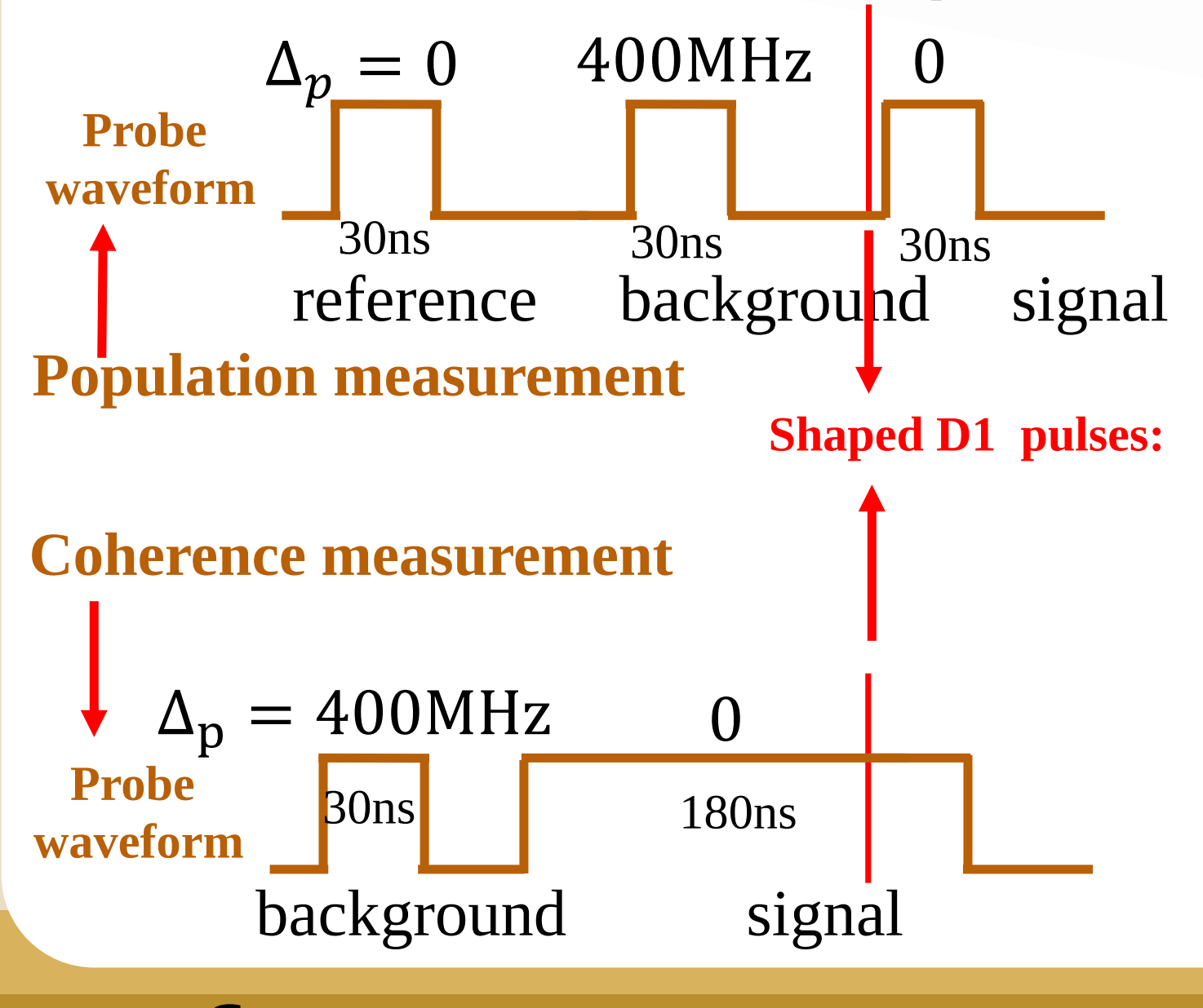
Experimental Setup:

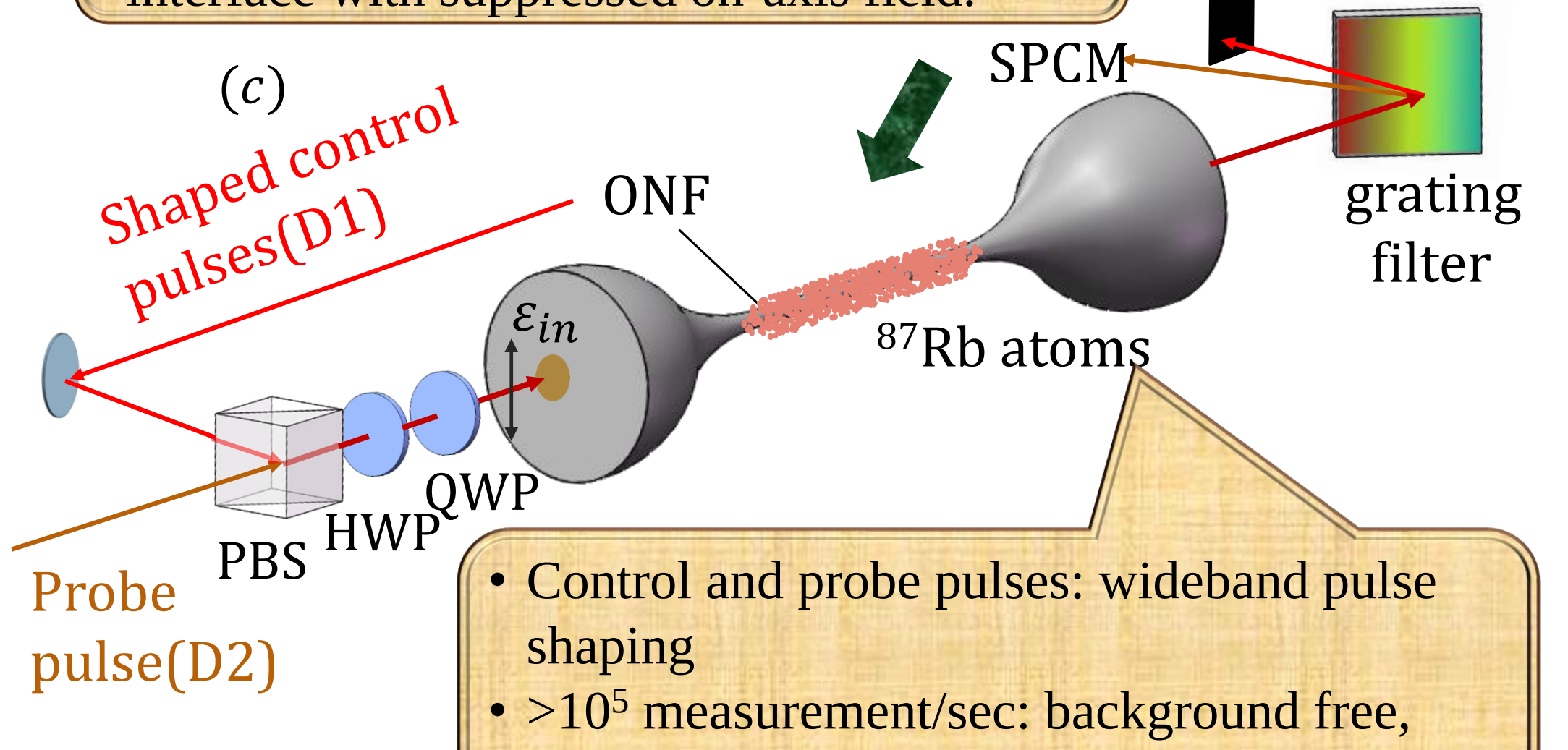
➢ Cold atom + ONF interface with 2D+MOT loading



- Compact setup with low power consumption
- 2D MOT geometry naturally support ONF interface with suppressed on-axis field.

➢ Probe and control waveforms





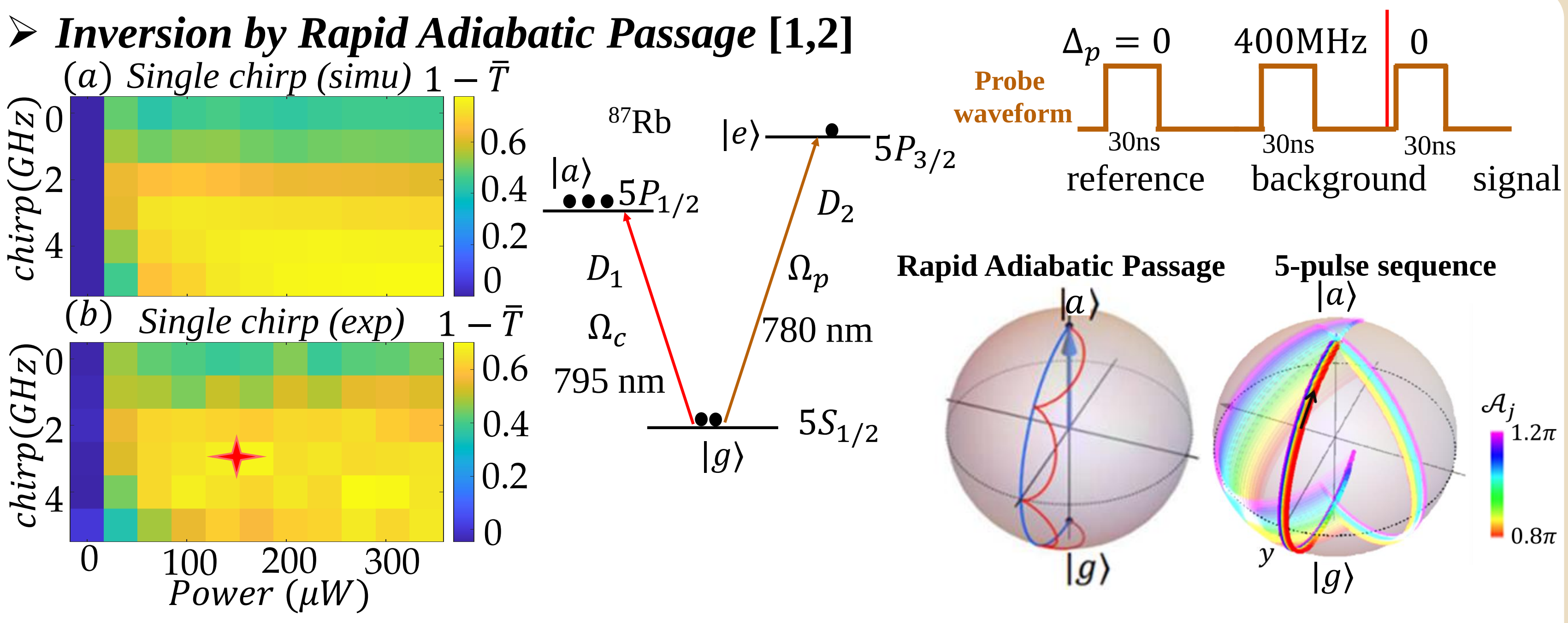
- Control and probe pulses: wideband pulse shaping
- >10⁵ measurement/sec: background free, accurate transmission measurements.

Reference

[1] Y. He et al, *"Geometric Control of Collective Spontaneous Emission", Phys. Rev. Lett. 125, 213602 (2020)*
[2] Y. Ma et al, *"Composite picosecond control of atomic state through a nanofiber interface", Phys. Rev. Applied 20, 024041 (2023)*

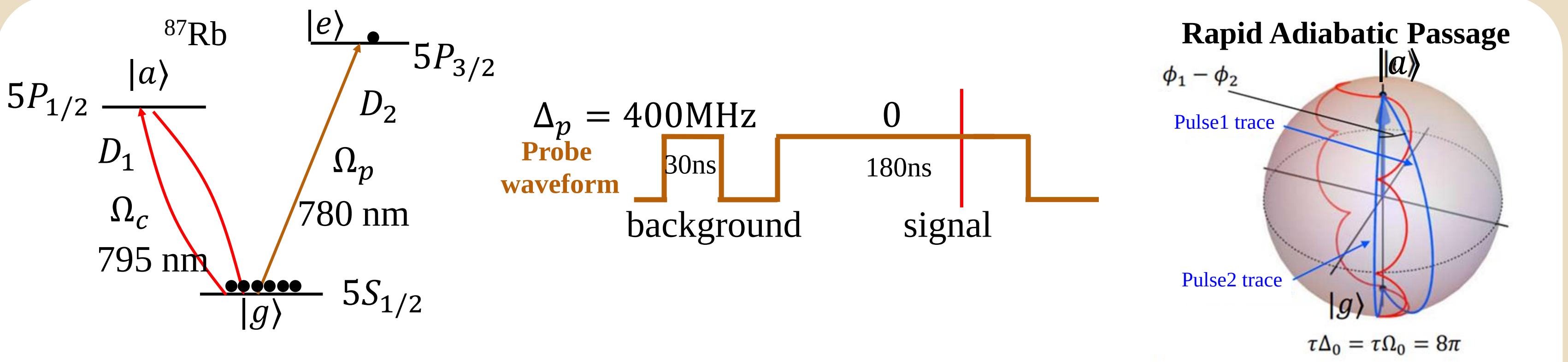
Robust population inversion:

➢ *Inversion by Rapid Adiabatic Passage* [1,2]



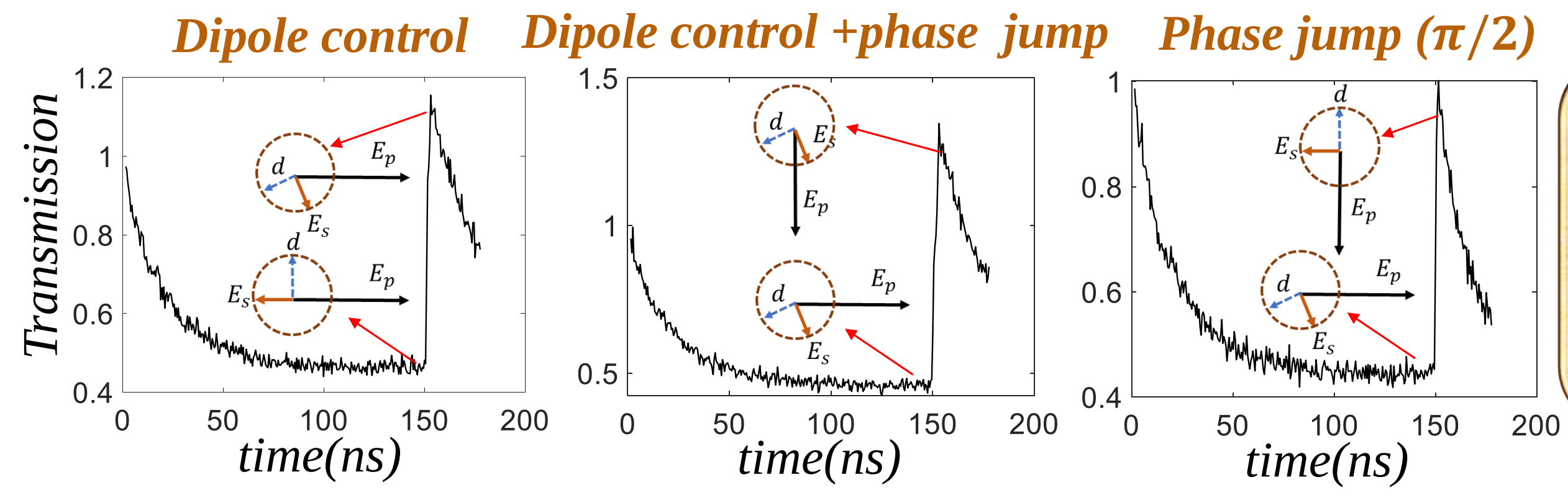
- Efficient D1 population inversion can be driven by either composite[2] or adiabatic[1] pulses within a nanosecond at ONF interface.
- The experimental observations agree excellently with full-level numerical simulation in the near field.

Geometric control of optical dipole:



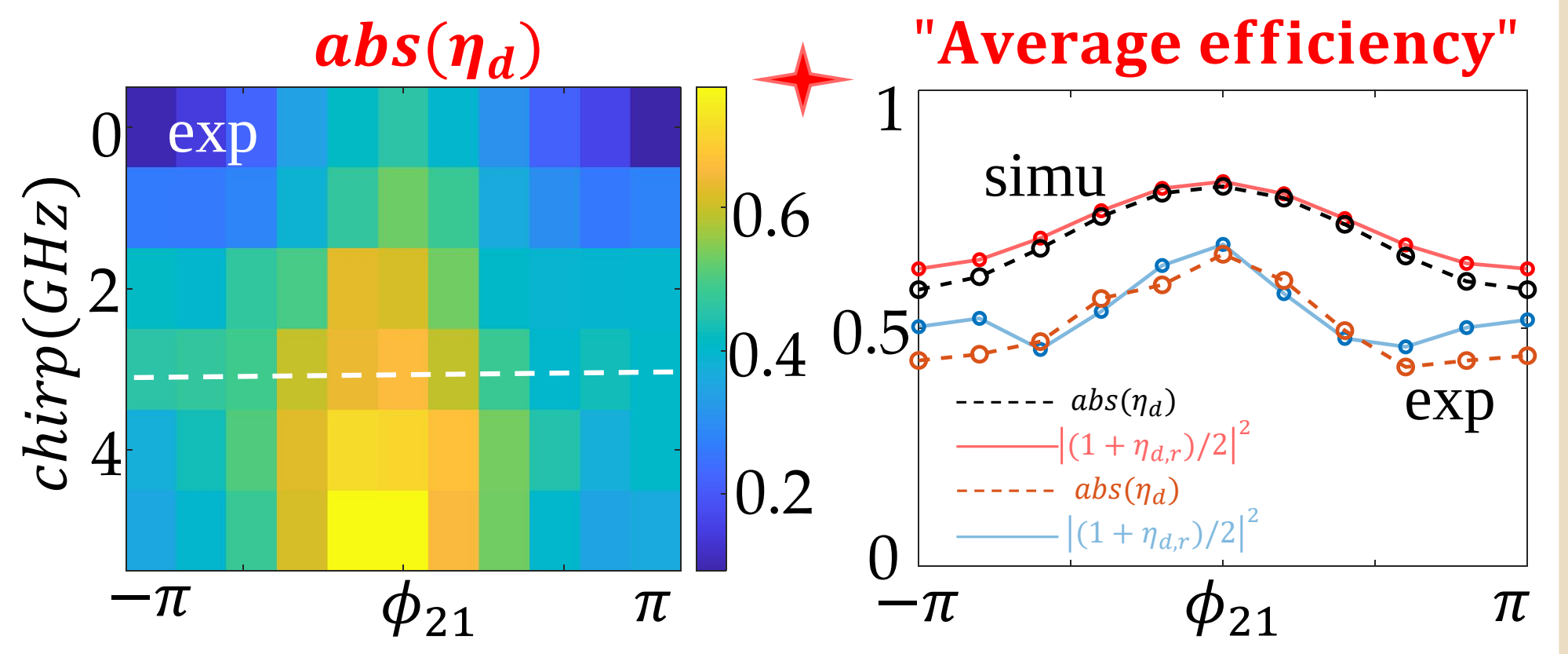
- By successively applying two optimally chirped pulses with ϕ_{21} phase difference, the optical phase is transferred to the near-field atomic dipoles, $\gamma = \phi_{12} + \pi$, reflected in the transient probe transmission.
- A probe phase-jump globally induces the same ϕ_{21} relative to $\mathbf{E_s^f}$, leading to similar transmission signal.
- According to $\mathbf{E}_s(r) \sim \sum \mathbf{G}(\mathrm{r}, r_j)\cdot\mathbf{d}_j$, we estimate the dipole control efficiency by observing the $\mathbf{E}_s$-transient within nanoseconds.

➢ *Experimental results*

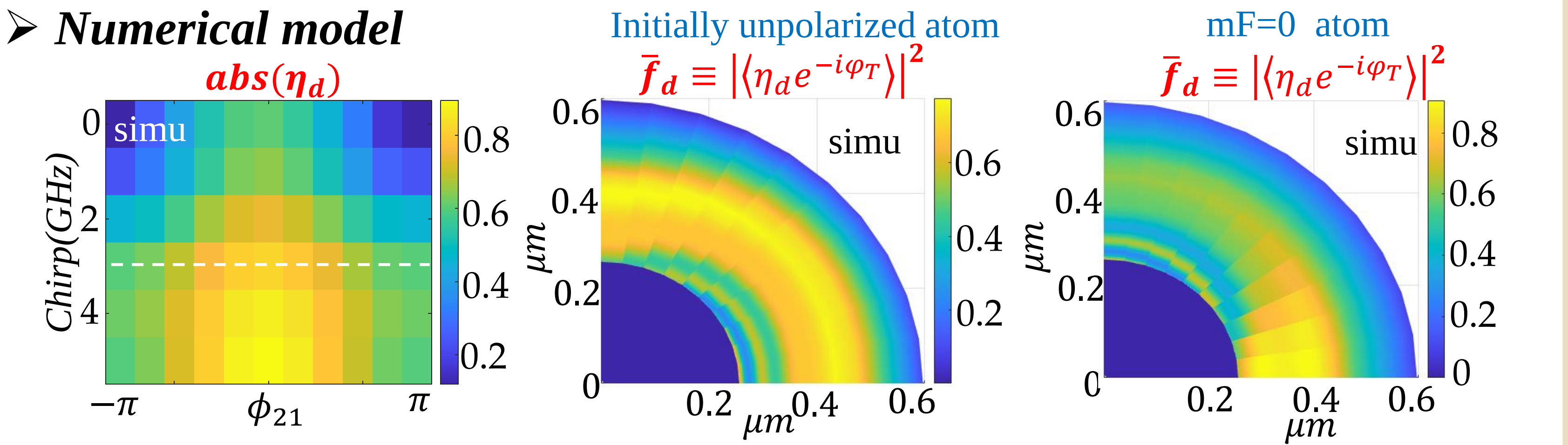


To characterize a dipole control sequence, three measurements are performed to fix the $\mathbf{E}_s$ phase relative to $\mathbf{E}_p$

- A weak resonant probe $\mathbf{E}_p$ for 150 ns to establish steady-state dipoles and $\mathbf{E}_s$.
- A pair of $\tau_c = 0.6$ ns chirped pulses to write in geometric phase with $\eta_d\mathbf{E}_s$.
- $T_1 = |\mathbf{E}_p + \eta_d\mathbf{E}_s|^2$, $T_2 = |i\mathbf{E}_p + \eta_d\mathbf{E}_s|^2$ $T_3 = |i\mathbf{E}_p + \mathbf{E}_s|^2$ ➔ η_d



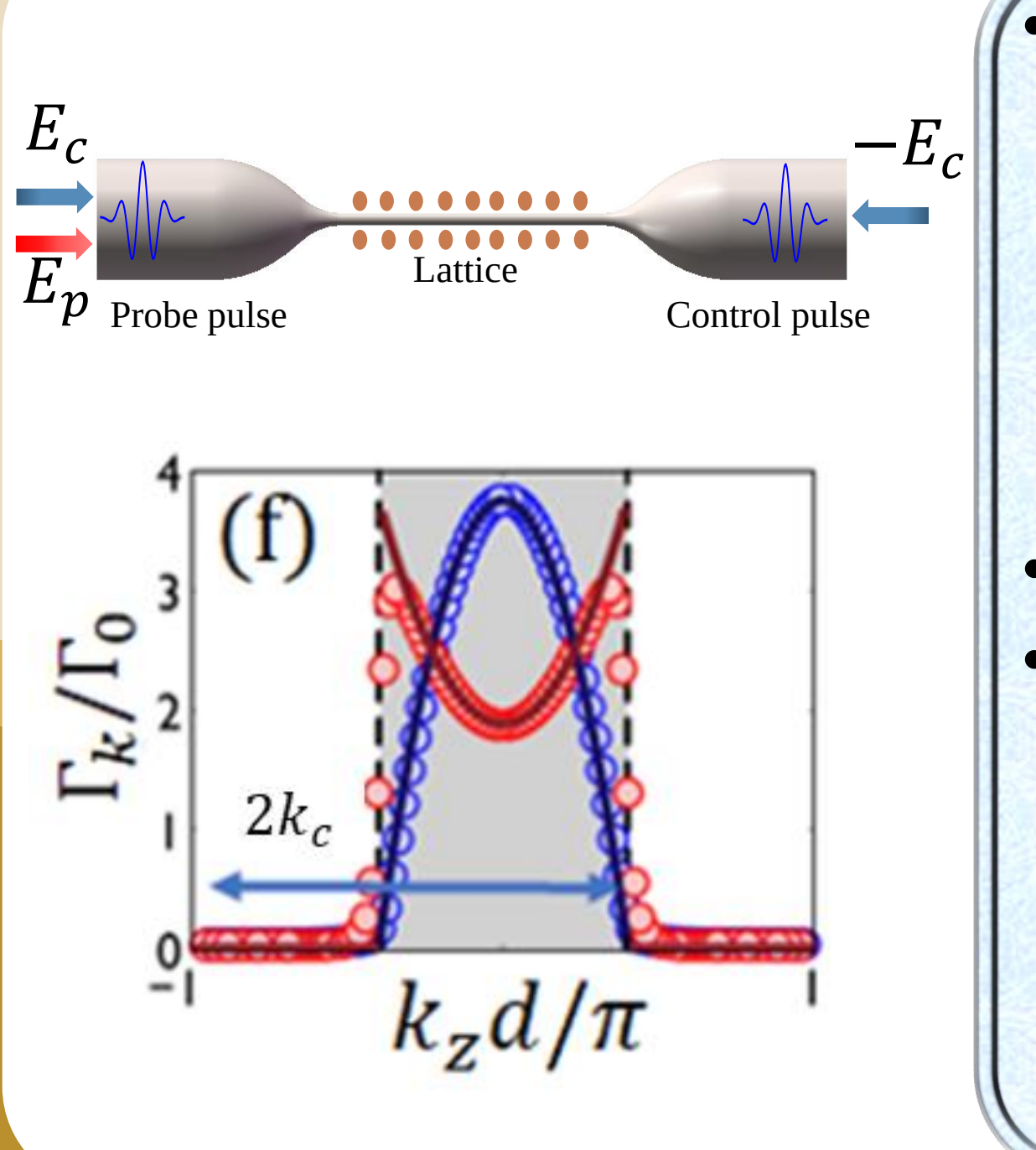
➢ *Numerical model*



- Keep it simple: uniform, non-interacting atoms in the near field.
- HE11 mode, evanescent full-level OBE.
- Parameters match the experiment.

- Exp geometric phase control via evanescent couplings with an efficiency averaged over the near field dipoles to be above 50%.
- Exp performance is about 20% lower than numerical expectation, likely related to inaccurate near-field modeling of distributions.
- Numerical model predicts atomic dipole control with **90%** fidelity at specific locations with linear local polarization and mF=0.

Summary & outlook



- We demonstrate geometric phase control of optical dipoles at a cold atom-nanofiber interface, for the first time. Ensemble-averaged efficiency $|\eta_d| \approx 50\%$ is retrieved with a phase-jump spectroscopy. The result is agreeable with theoretical expectations for the nano-scale quantum control.
- Novel 2DMOT-ONF interface with ~field-free line.
- In our next step, by loading atoms into a near-field lattice and by sending geometric-phase-writing ONF-guided pulses from opposite directions, the D2 collective dipole excitation can be coherently shifted into sub-radiant domain, potentially enabling highly nontrivial many-body quantum optical researches.

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