



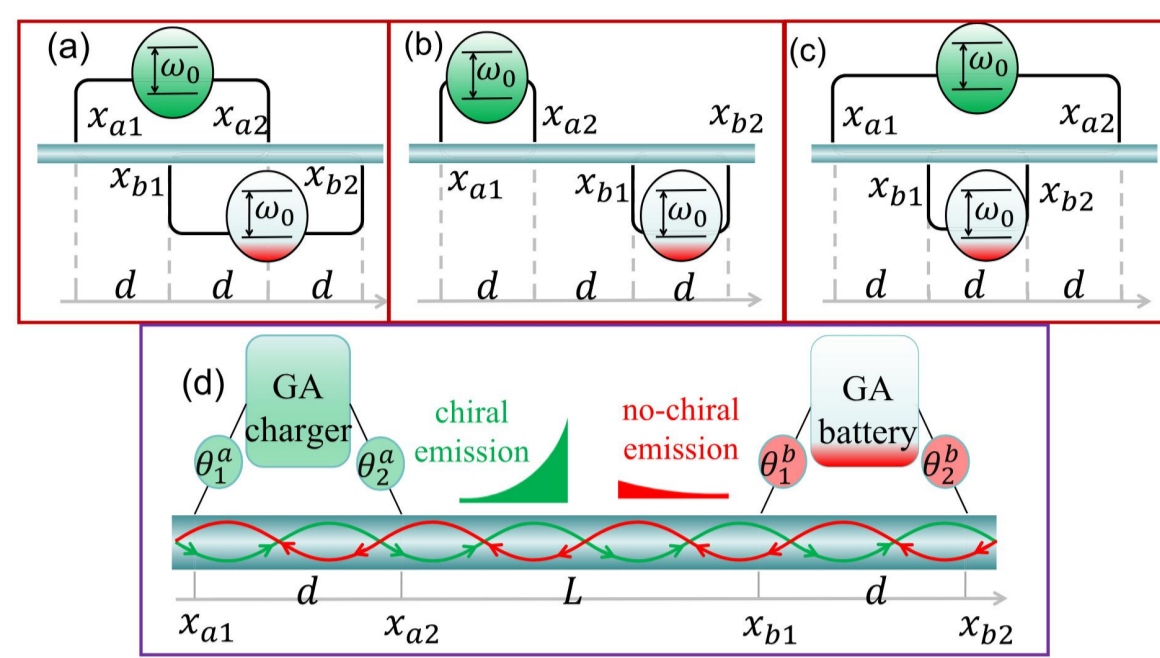
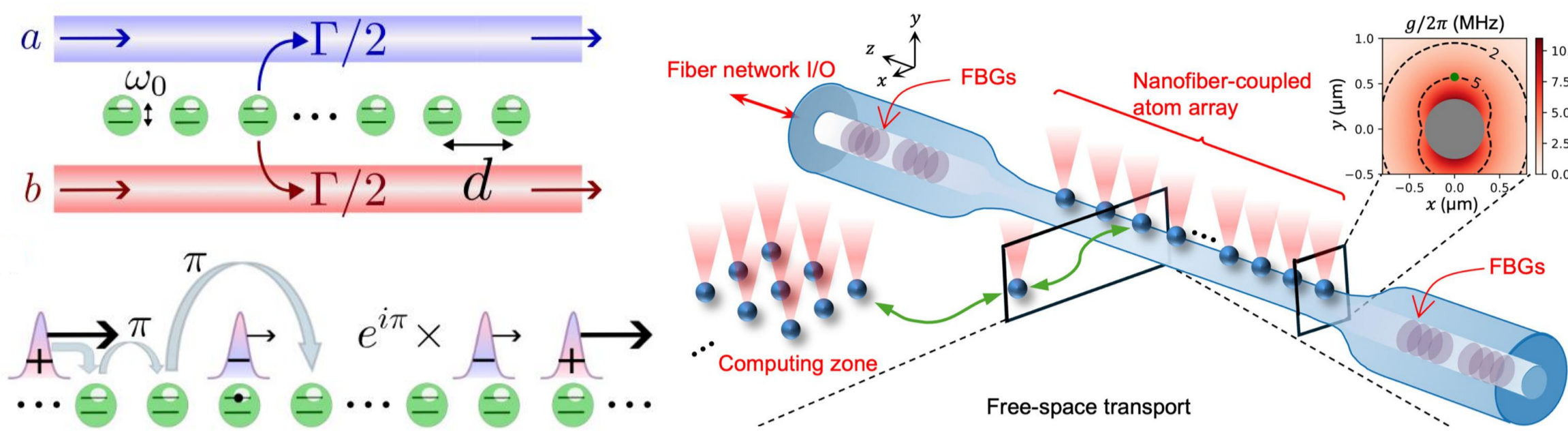
Most Subradiant Bound Photon Pairs from Chirality-Mediated Dispersion Softening

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Background: (Chiral) Waveguide QED



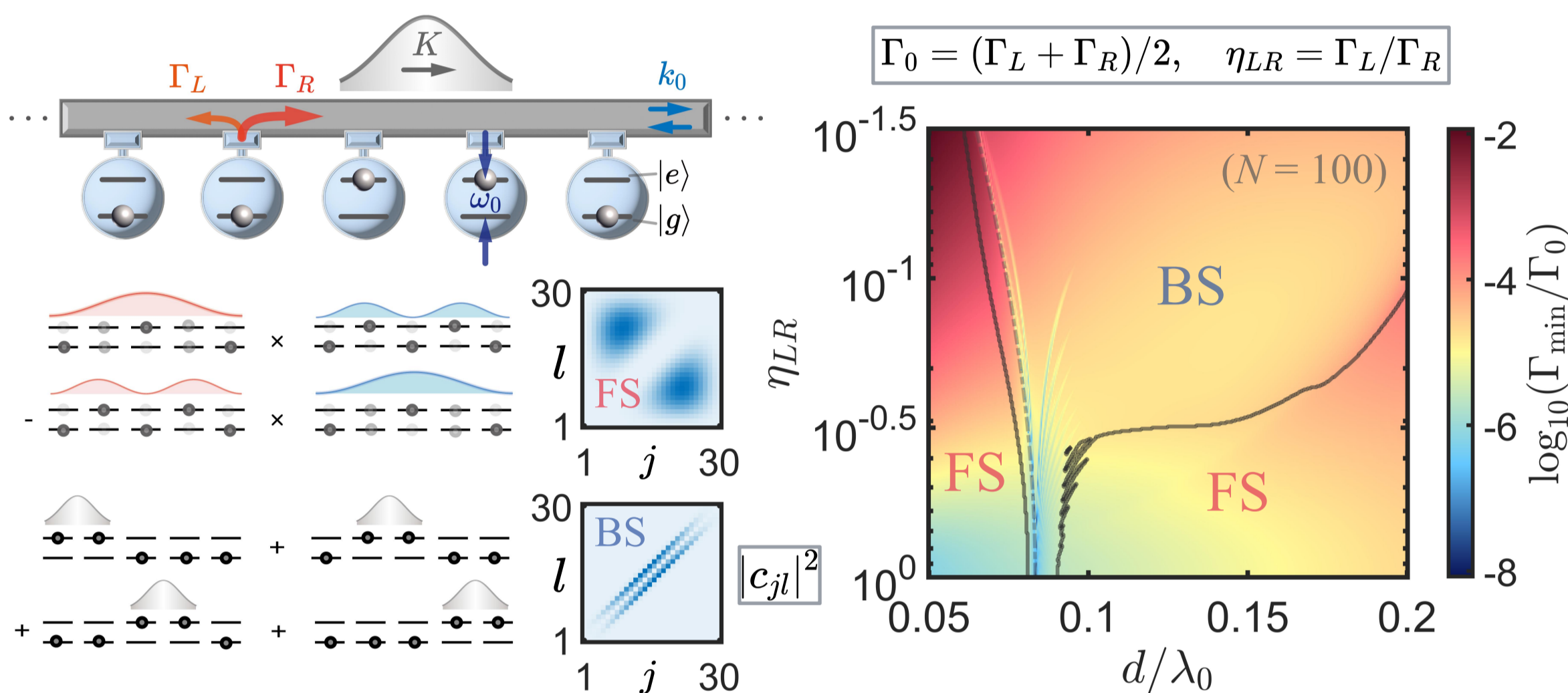
- Physical realization: Nanofibers, superconducting circuits...
- Infinite-range interaction + Photonic nonlinearity → Exotic many-body physics
- Applications: Photonic quantum gates, quantum networking, quantum batteries, photon storage, photon sources, ...

Passive photonic gate [1]

Quantum multiprocessor [2]

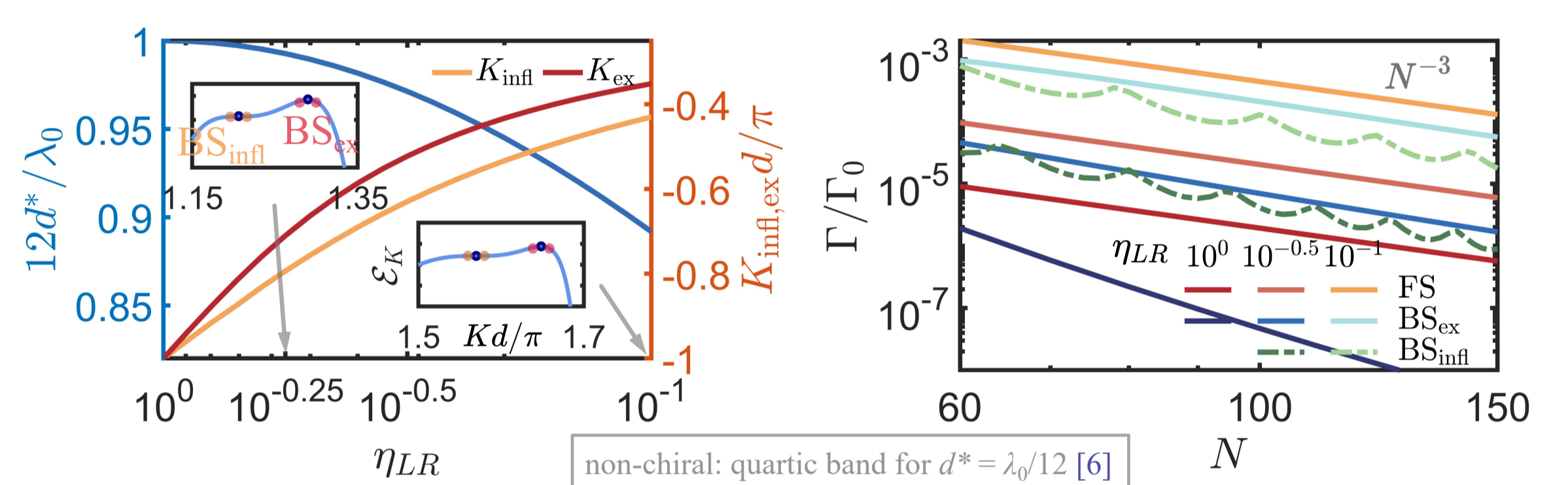
Quantum battery [3]

Most Subradiant Two-Excitation States: FS vs. BS



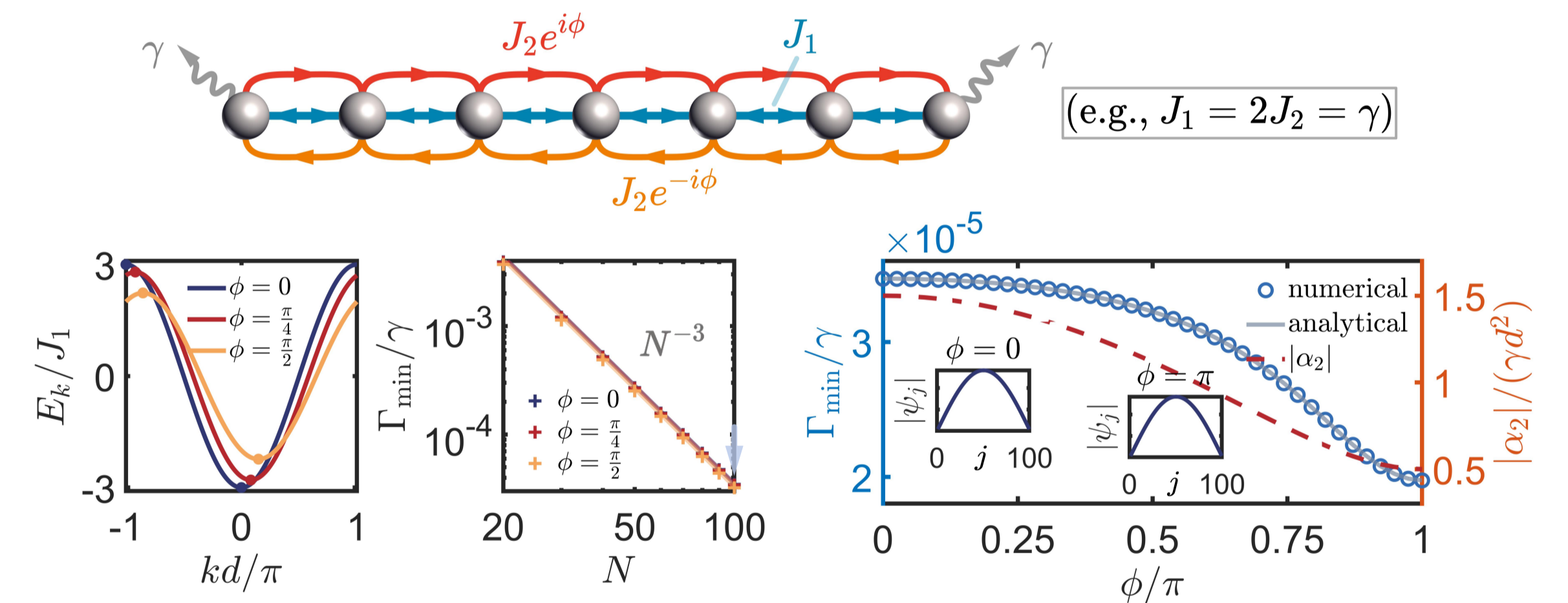
- Model: $H_{\text{eff}} = -\frac{i}{2} \sum_{j<l}^N e^{ik_0(x_l-x_j)} (\Gamma_L \sigma_j^\dagger \sigma_l + \Gamma_R \sigma_l^\dagger \sigma_j) - i \frac{\Gamma_0}{2} \sum_{j=1}^N \sigma_j^\dagger \sigma_j$
- Free-Fermion states (FSs): Spatially extended; decay rate $\Gamma \sim N^{-3}$ [4]
- Bound photon pairs (bound states, BSs): Spatially localized ← H^K [5]
- **Our discovery:** As chirality ↑, BS robustly becomes the most subradiant two-excitation state for different array spacing

Lifetime Oscillation & Cubic Band from Chirality



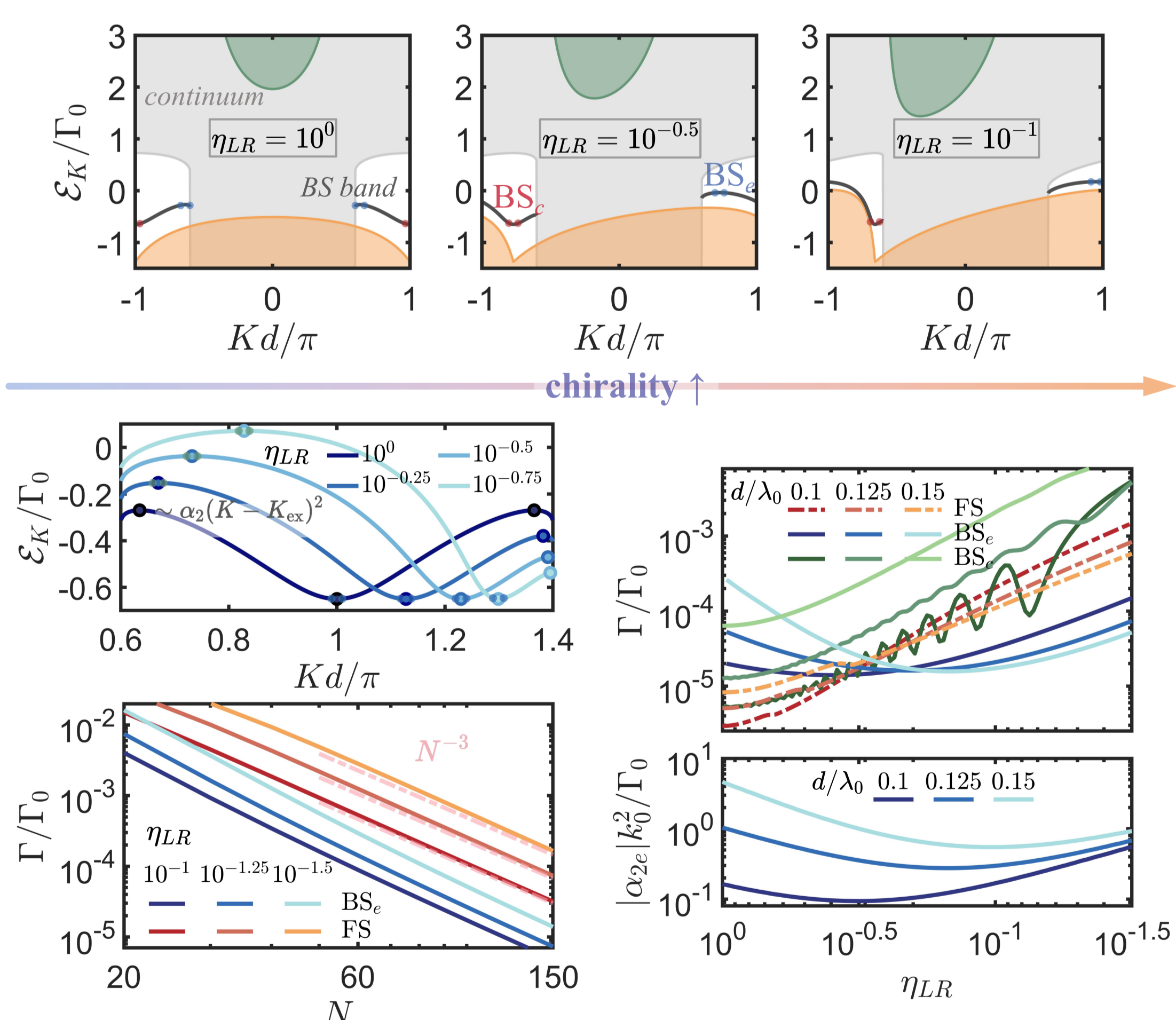
- Cubic band $\mathcal{E}_K \approx \alpha_3(K-K_{\text{ex}})^3$ emerges in the presence of chirality
- Most subradiant BS_{infl} with **oscillating lifetime** ← Cubic band: crossover between dispersions $(d > d^*, \sim N^{-3})$ & $(d < d^*, \sim N^{-1})$

Generalization: Modulating Subradiance with Chirality - A Simpler Toy Model



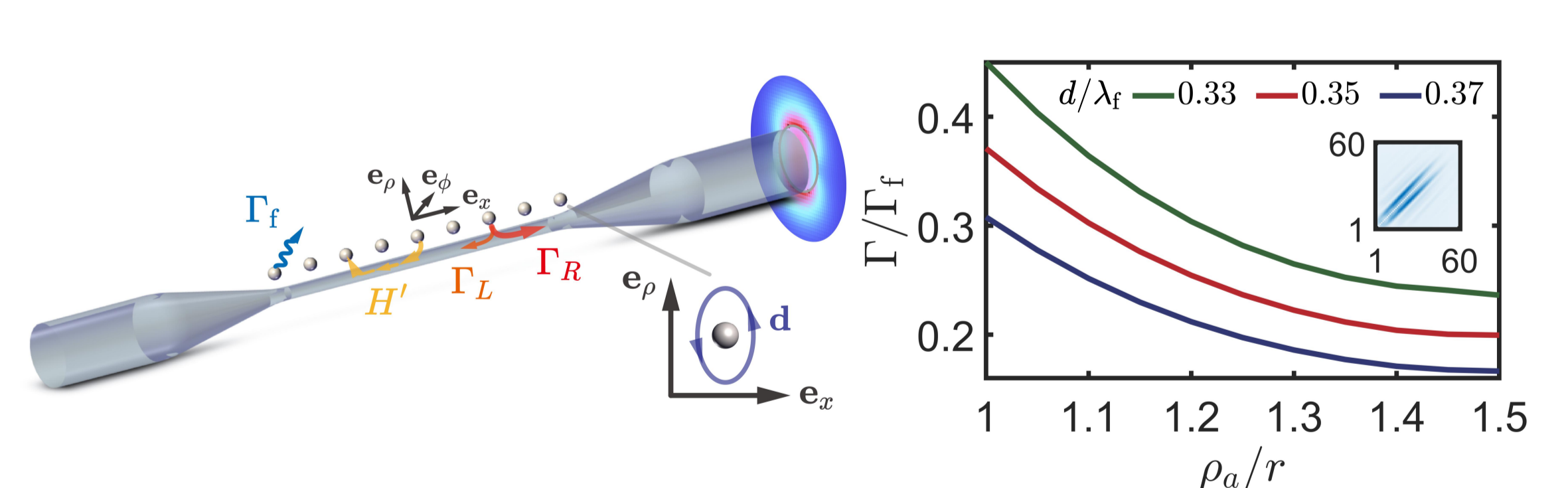
- Model: $H_a = -\sum_{j=1}^{N-1} [(J_1 + J_2 e^{i\phi}) a_{j+1}^\dagger a_j + \text{h.c.}] - i \frac{\gamma}{2} (a_1^\dagger a_1 + a_N^\dagger a_N)$
- Chirality-modulated subradiance: $\phi \uparrow \Rightarrow |\alpha_2| \downarrow \Rightarrow \Gamma \downarrow$

Mechanism: Chirality-Mediated Dispersion Softening



- **We analytically prove that the BS decay rate follows $\Gamma \sim |\alpha_2|/N^3$**
- For $\eta_{LR} \lesssim 1$: Chirality ↑ ⇒ $|\alpha_{2e}| \downarrow \Rightarrow |v_g| \downarrow \Rightarrow \Gamma \downarrow \Rightarrow$ Most subradiant BSs
- BS: ← & → propagating K modes interfere destructively at edges

Experimental Realization: Nanofiber Interface



- **Realistic nanofiber platform:** ^{87}Rb atoms (D_2) + Single-mode nanofiber
- BS emerges from chiral interaction besides strong near-field interaction
- Experimental detection: **Excited state dressing + Solitonic pulse** [7]...

Conclusions and Outlook

- Chiral interaction suppresses BS radiation at array edges via *dispersion softening* mechanism, realizing the longest-lived BSs across a wide spacing range
- Chirality acts as a general degree of freedom for shaping polaritonic dispersion relations toward subradiance → engineering exotic photon-photon correlations

References

- [1] T. Levy-Yeyati et al., PRXQ 6, 010342 (2025).
 [2] S. Sunami et al., PRXQ 6, 010101 (2025).
 [3] K.-X. Yan et al., PRL 136, 180401 (2026).
 [4] Y.-X. Zhang and K. Mølmer, PRL 128, 093602 (2022).
 [5] B. Bakkensen et al., arXiv:2110.06093.
 [6] A. Poddubny, PRA 101, 043845 (2020).
 [7] G. Calajó and D. Chang, PRR 4, 023026 (2022).