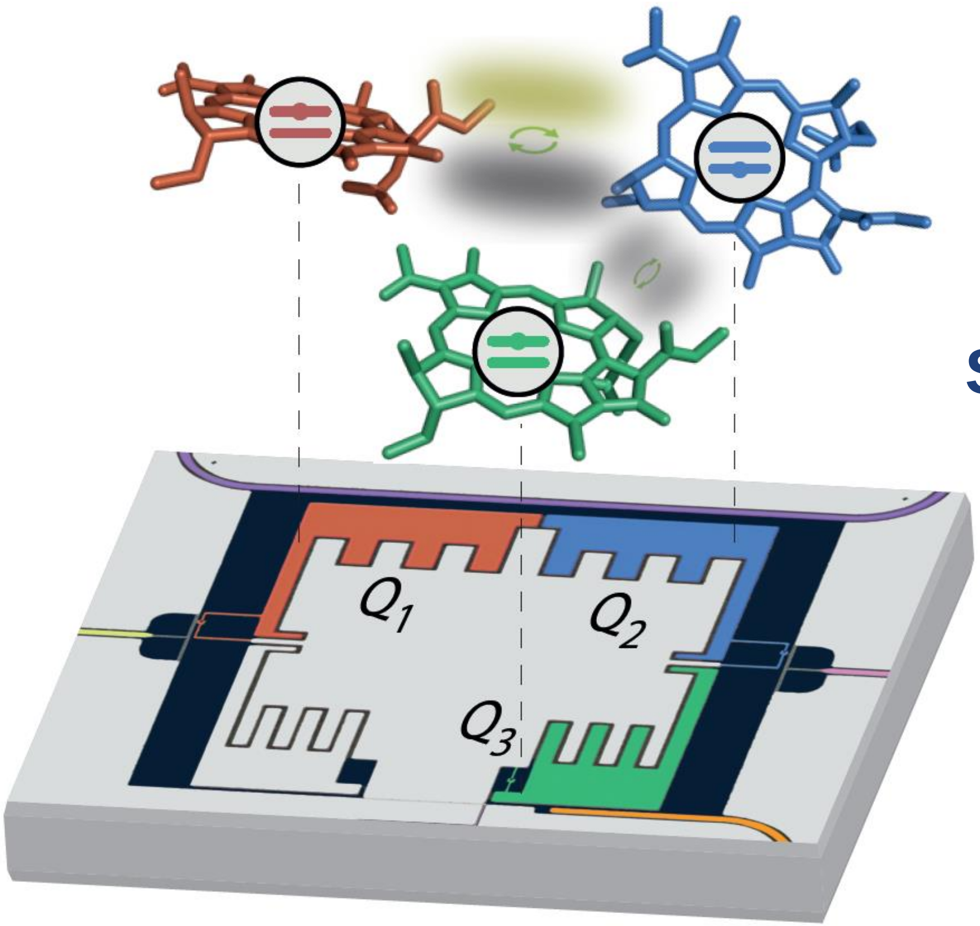


# Studying the Functional Quantum Biology of Light-Harvesting Processes with Superconducting Circuits

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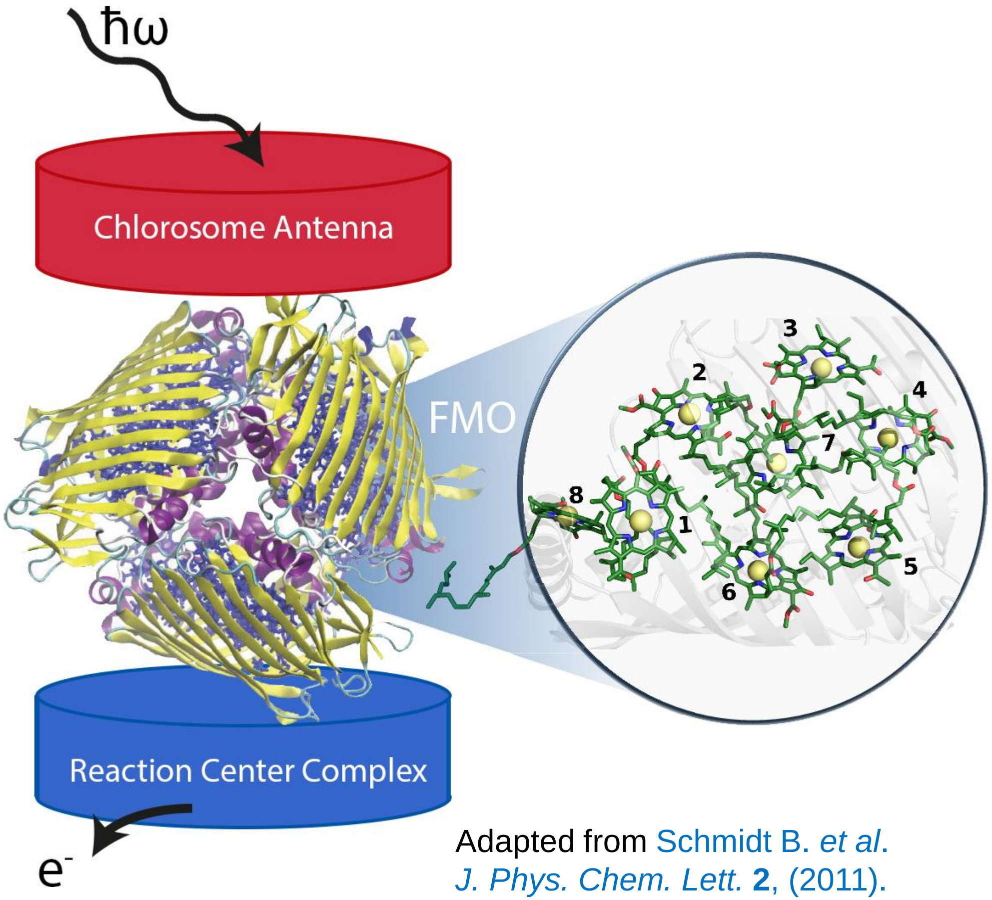
# Quantum Effects in Light Harvesting

- Do quantum phenomena play an important **functional** role in biological systems?

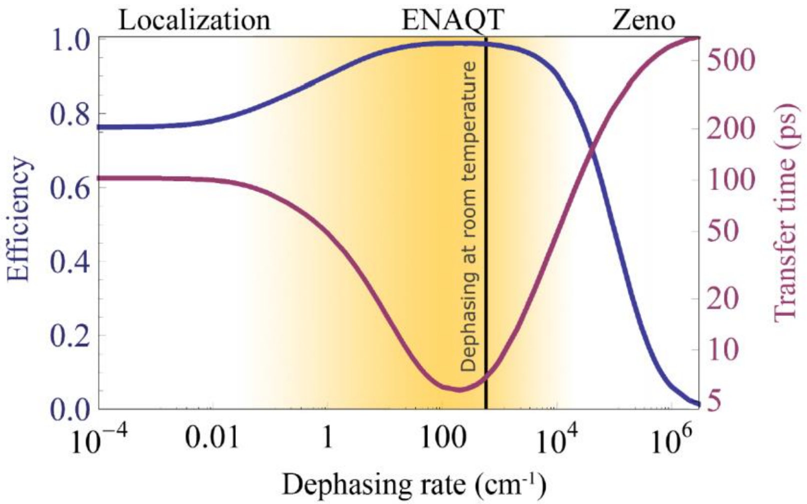
- Photosynthetic complexes could harvest the available light with high efficiency (95%).
  Caruso, F. et al. *J. Chem. Phys.* **131**, 10 (2009).

- Experimental observations of long lasting coherences in Fenna-Matthews-Olson (FMO) pigment protein complex
  Review: Scholes, et al., *Nat. Chem.* **3**, 763 (2011).

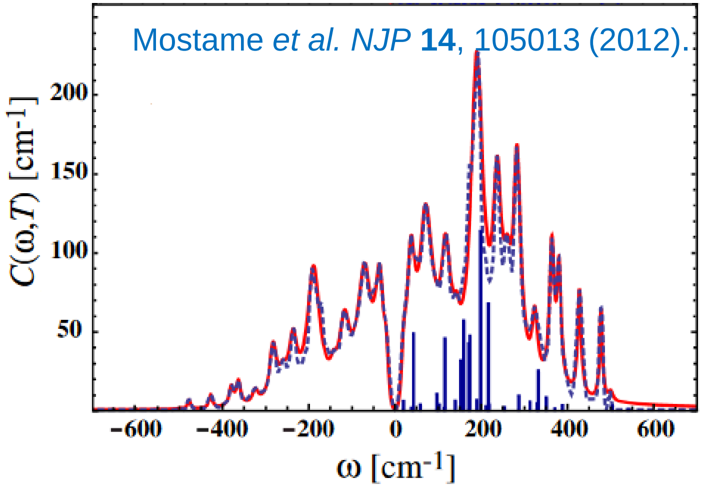
# Noise Assisted Transport




Adapted from Schmidt B. *et al*. *J. Phys. Chem. Lett.* **2**, (2011).



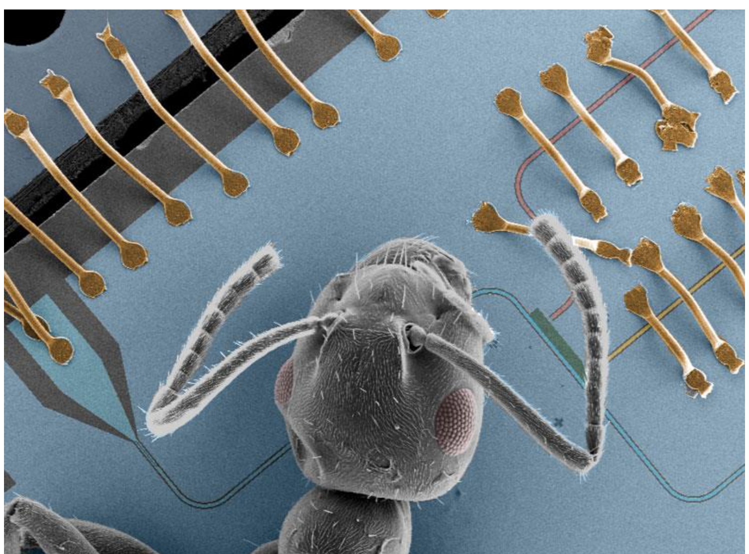

Rebentrost *et al. NJP* **11**, 033003 (2009).




Mostame *et al. NJP* **14**, 105013 (2012).

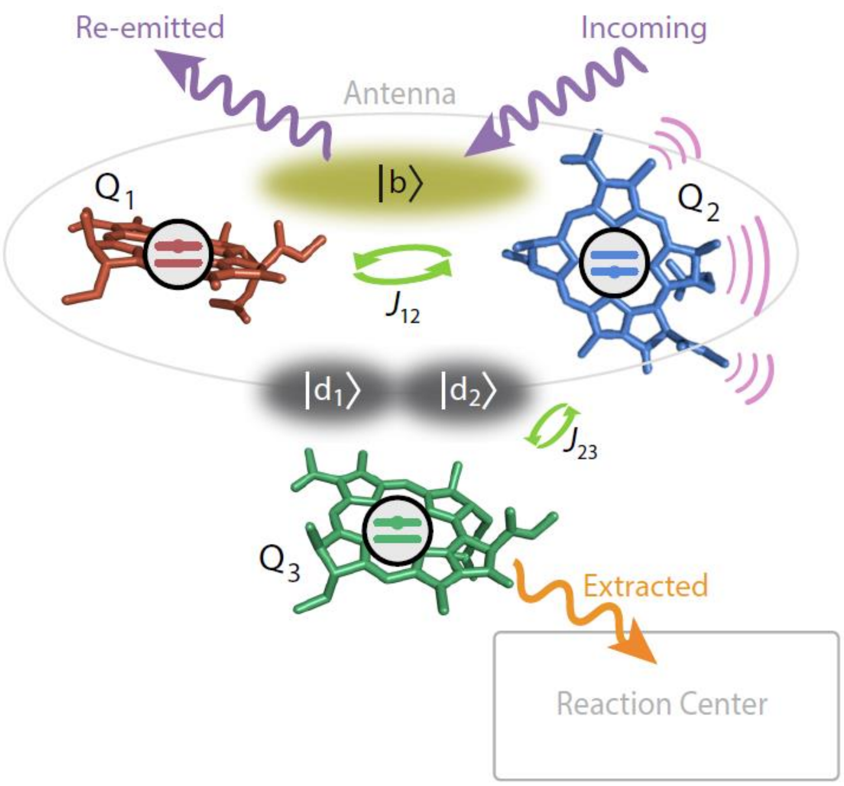
# Experimental Implementation

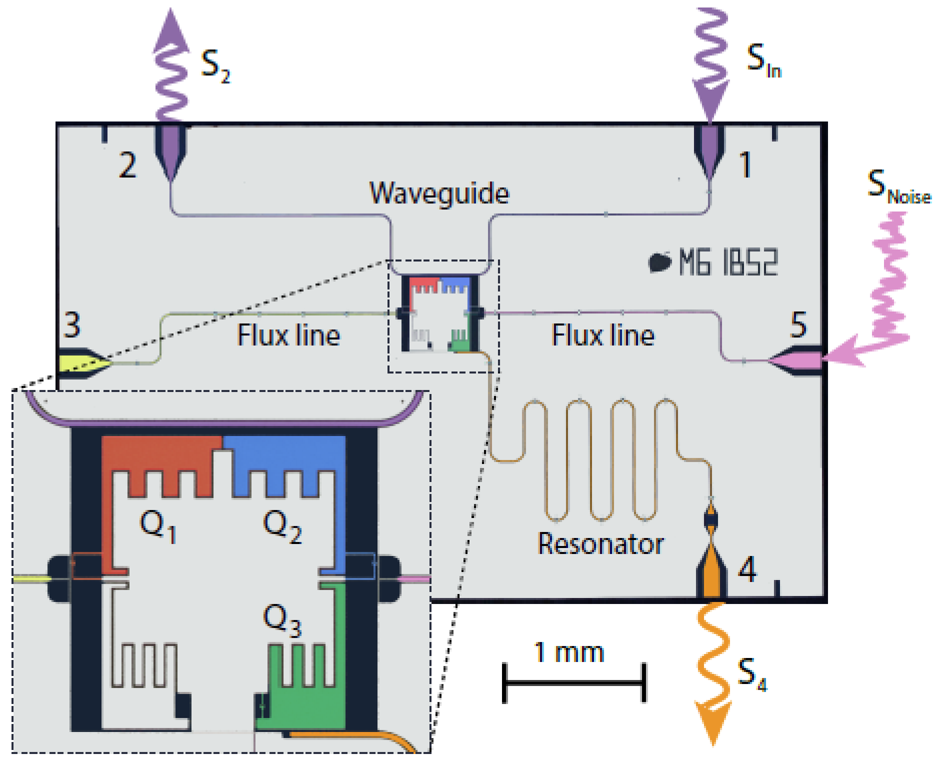
- Quantum two-level systems
- Delocalized excited states
- Bright/Dark states
- Control of energy level configuration
- Control over the environment



**Superconducting circuits**

# Experimental Implementation




**Haken-Strobl-Reineker model:**[1]

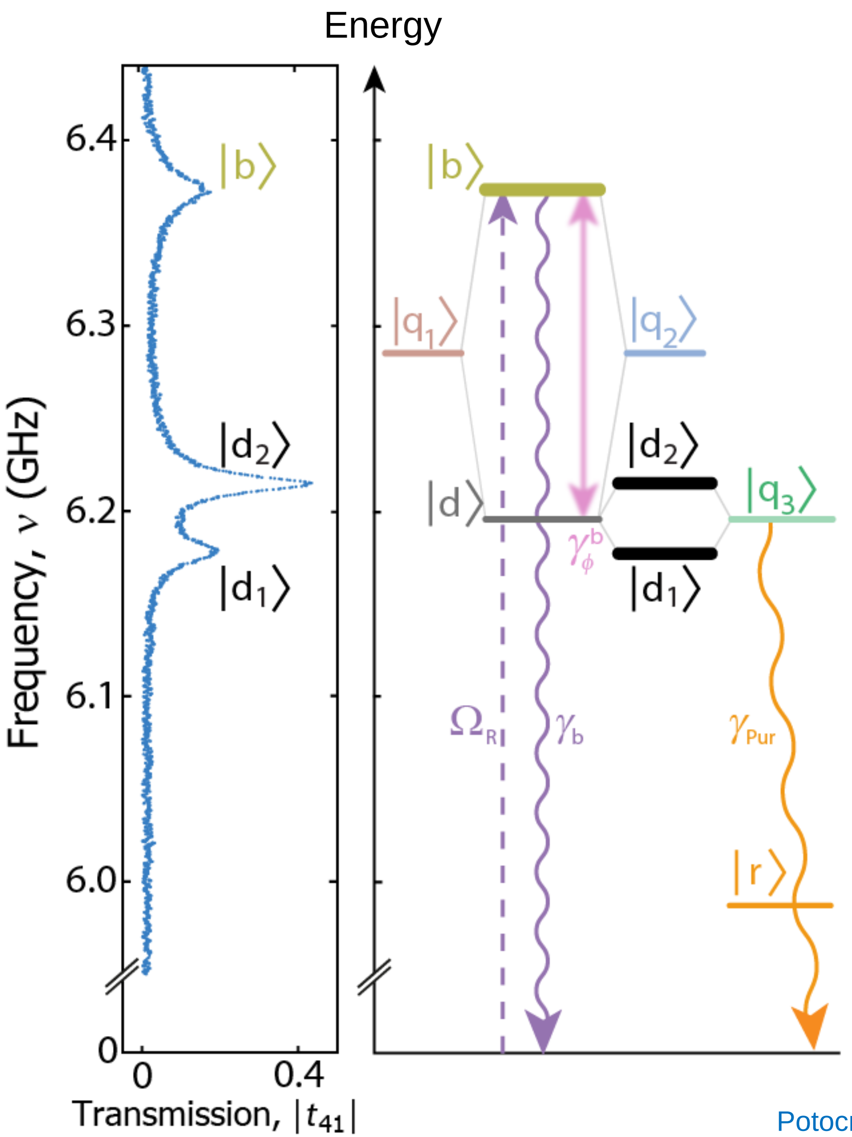
Potocnik *et al.* arxiv:1710.07466.

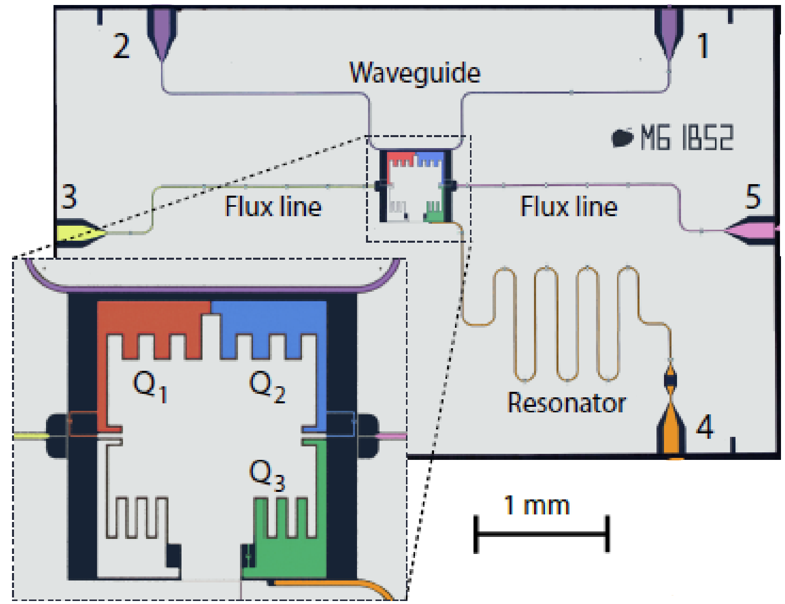
$$\mathcal{H} = \frac{1}{2}\sum_{j=1}^{N}[\epsilon_j + \delta\epsilon_j(t)]\sigma_j^z + \frac{1}{2}\sum_{i<j}^{N} J_{ij}\left(\sigma_i^x\sigma_j^x + \sigma_i^y\sigma_j^y\right)$$



[1]Haken, H. and Reineker, P. *Z. Phys* **249**, 253 (1972). Haken, H. and Strobl, G. *Z. Phys* **262**, 135 (1973).

# Spectroscopy and Energy Level Diagram



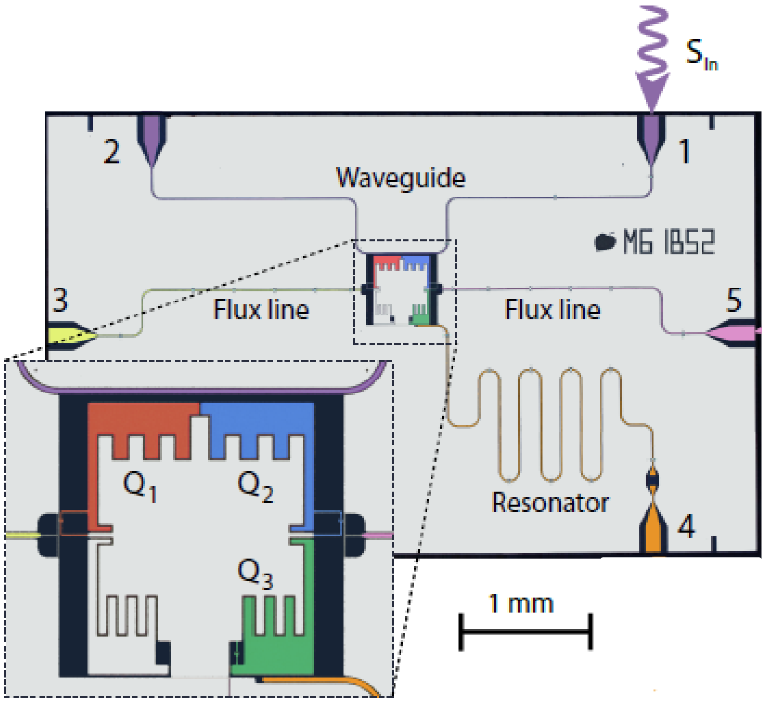

Coupling Rates:
- $J_{12}/2\pi$ = 86.7 MHz
- $J_{d3}/2\pi$ = 18.5 MHz

Relaxation Rates:
- $\gamma_b/2\pi$ = 12.4 MHz
- $\gamma_d/2\pi$ = 0.3 MHz
- $\gamma_{Pur}/2\pi \approx$ 23 MHz

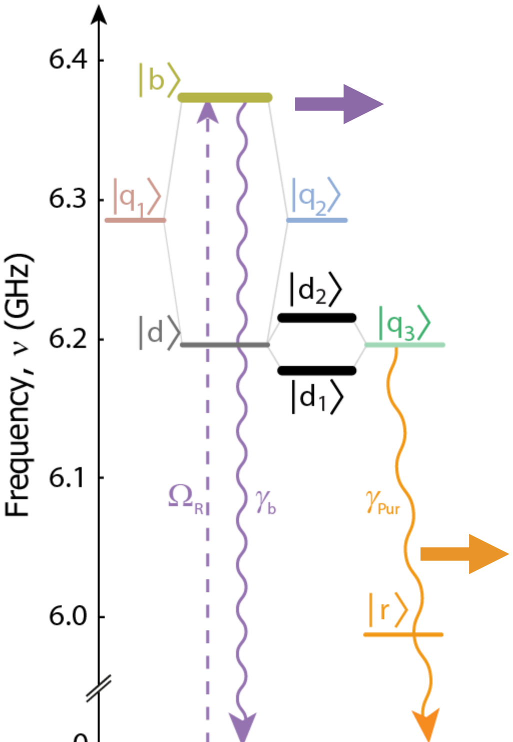
Potocnik *et al.* arxiv:1710.07466.

# Experimental Scheme

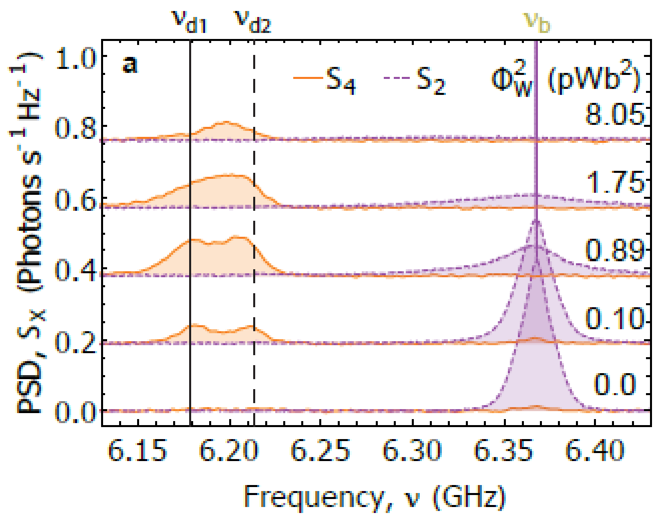
- Drive $Q_{1,2}$ through wave guide coherently/incoherently with adjustable BW/power
- Apply low frequency noise to $Q_2$ with adjustable BW/power through flux line
- Detect emission power spectrum at resonator and transmission line



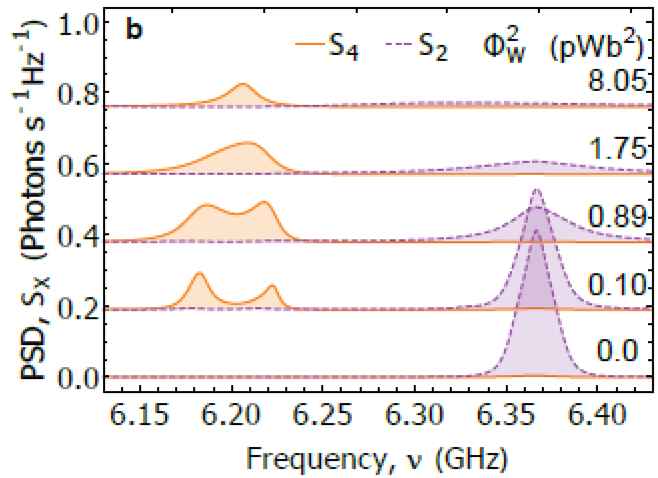
# Coherent Excitation and White Noise Environment




Experimental data:




Lindblad Master equation simulation:

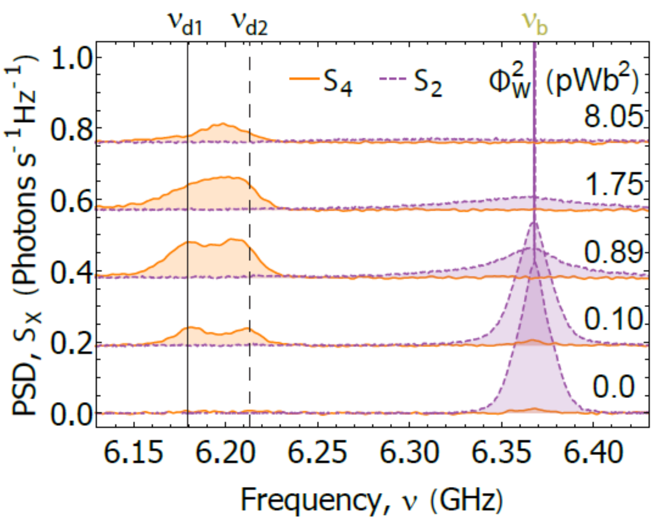


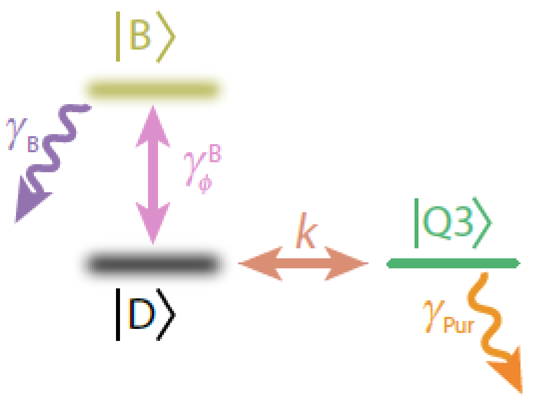

- Noise assisted energy conversion and excitation transfer
- Bright and dark states are broaden due to added noise
- Crossover from strong coupling to weak coupling regime
- Only $Q_3$ mode visible in the weak coupling regime
- Excellent agreement with master equation simulations

Potocnik *et al.* arxiv:1710.07466.

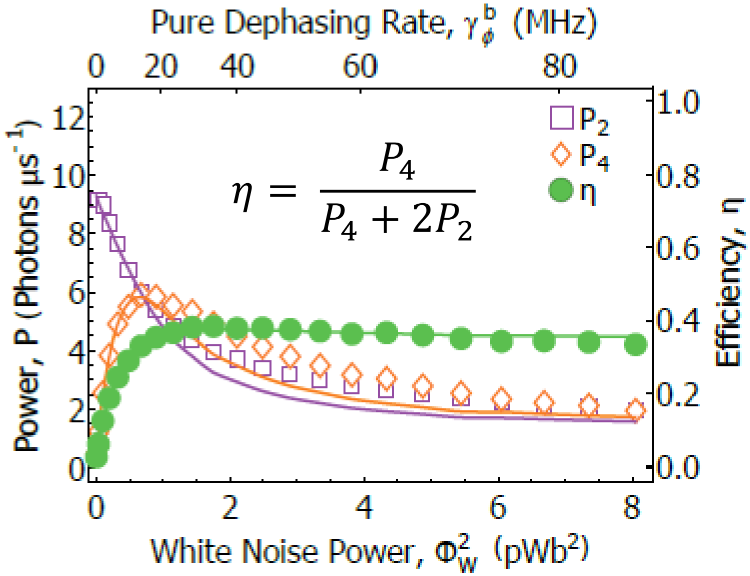
# Efficiency: Coherent Excitation/White Noise

Spectra:



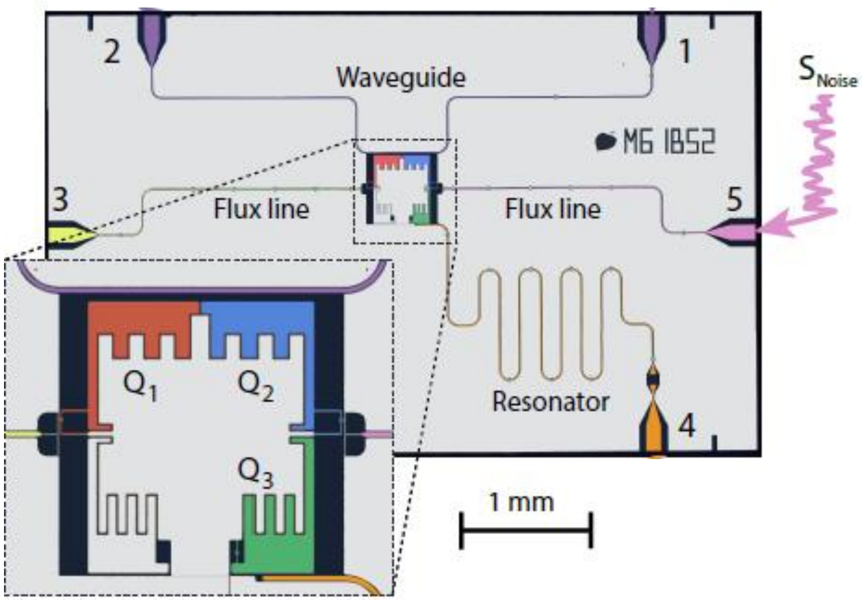

Integrated powers:

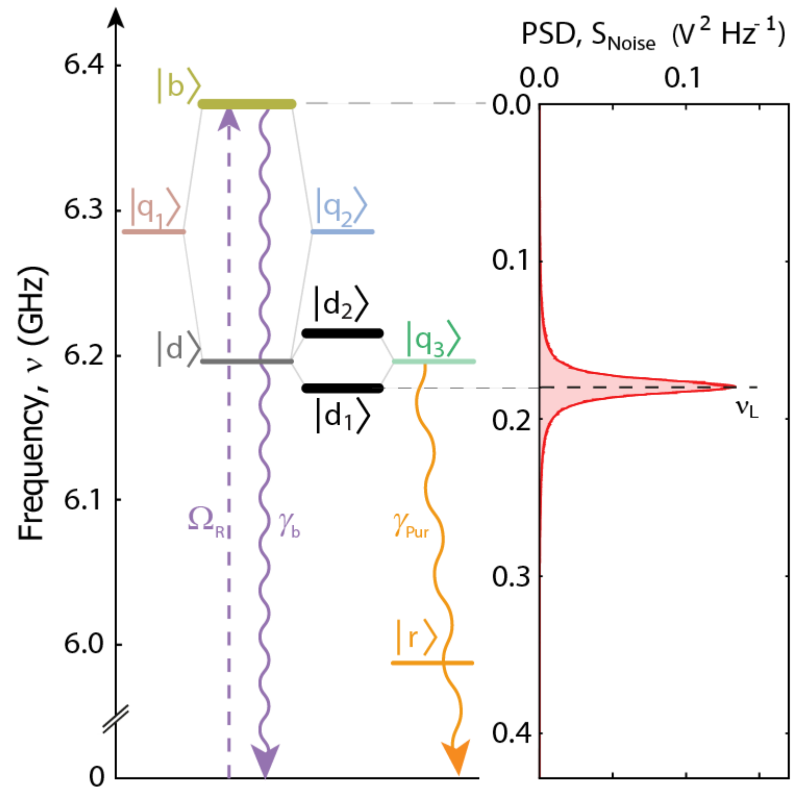



- Incoherent population transfer
- Maximum in transfer efficiency

# Structured noise

- Apply low frequency noise to $Q_2$ with adjustable BW/power through flux line

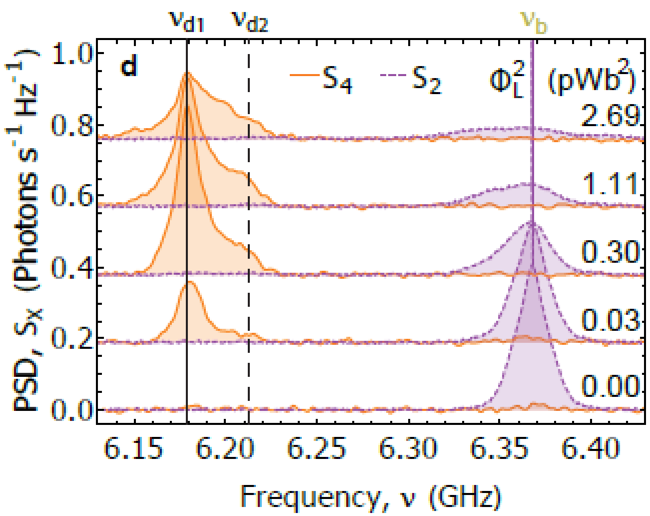


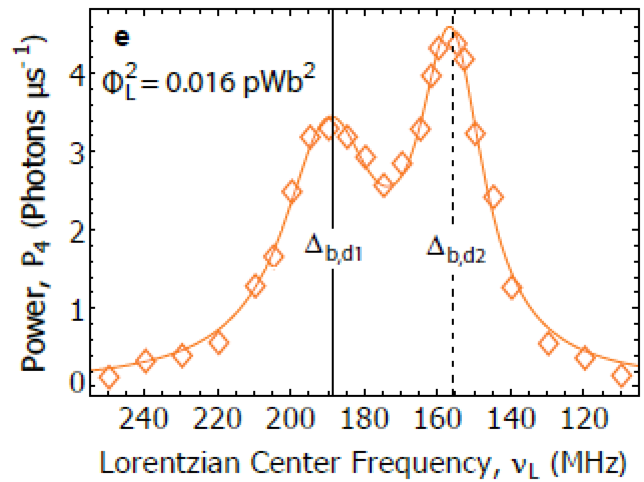



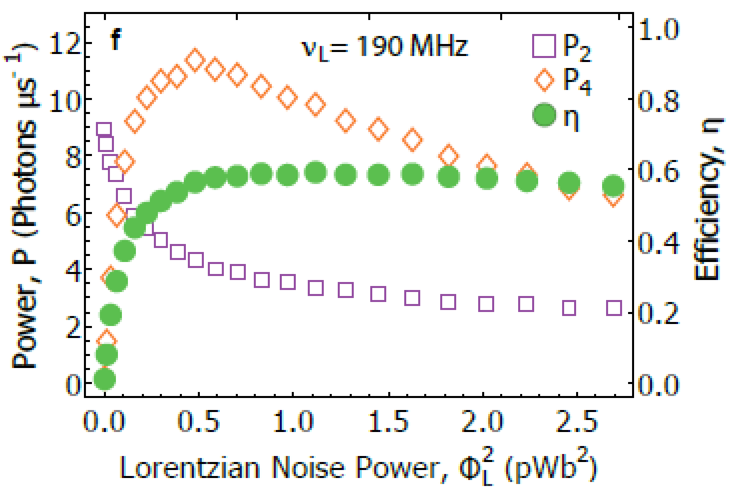



Potocnik *et al.* arxiv:1710.07466.

# Coherent Excitation and Colored Noise Environment



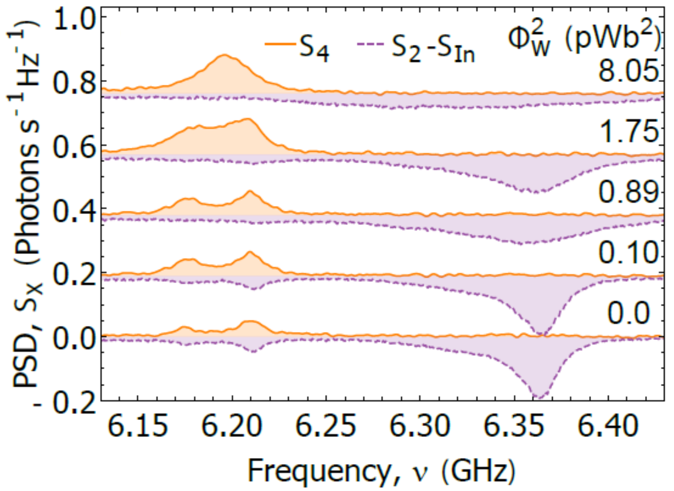



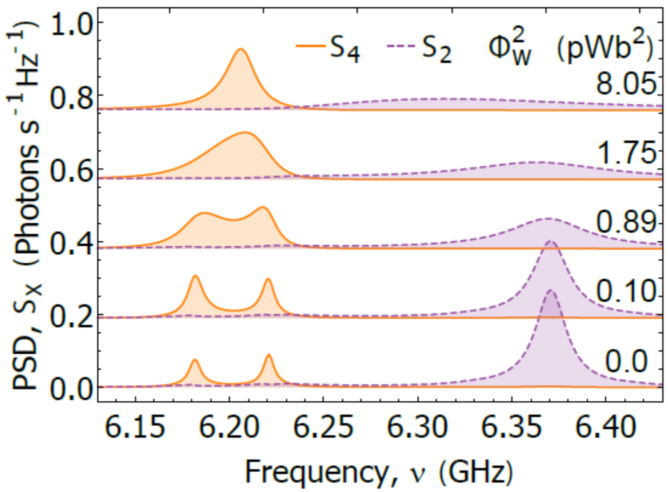

- Transfer only when noise spectrum matches b to $d_{1,2}$ transition
- Enhanced efficiency compared to white noise

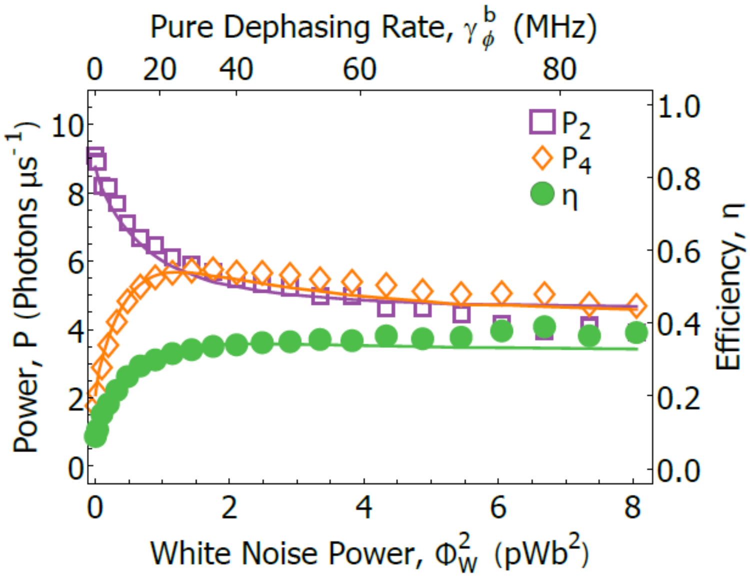
# Incoherent Excitation and White Noise Environment

Measured power spectra:




Master equation simulation:

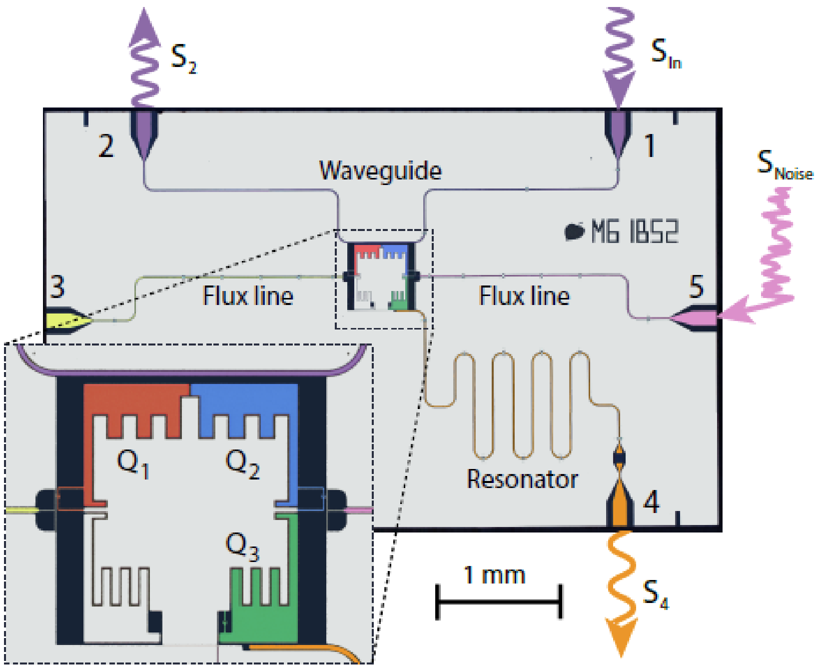



- finite power in $S_4$ without added environmental noise
- Incoherent excitation modeled in master equation simulation as finite temperature $n_{th}$ = 0.19
- coherent coupling (doublet) persists in incoherent excitation

# Conclusions

- Demonstrated bio-inspired noise assisted excitation transfer in superconducting model system
- Non-Markovian (resonant) environment observed to increase transfer efficiency
- Superconducting circuits are ideal for studying quantum effects in biological systems




- Outlook
  - Transient dynamics (2D spectroscopy)
  - Explore quantum environments
  - Model up to 8 qubits to investigate FMO complex

ETH zürich

# The Quantum Device Lab

## incl. undergrad and summer students

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

QSIT Quantum Science and Technology
National Centre of Competence in Research

FNSNF
SWISS NATIONAL SCIENCE FOUNDATION

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