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Spin Cavitronics System: From Strong to Ultra-Strong Coupling



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Introduction

Experimental study of ultra strong coupling (up to 60%) at room temperature with reconfigurable double re-entrant cavities and a millimetric YIG slab.

Currently used models no longer describe the observed hybridization between cavity photon and magnon above the strong coupling regime.

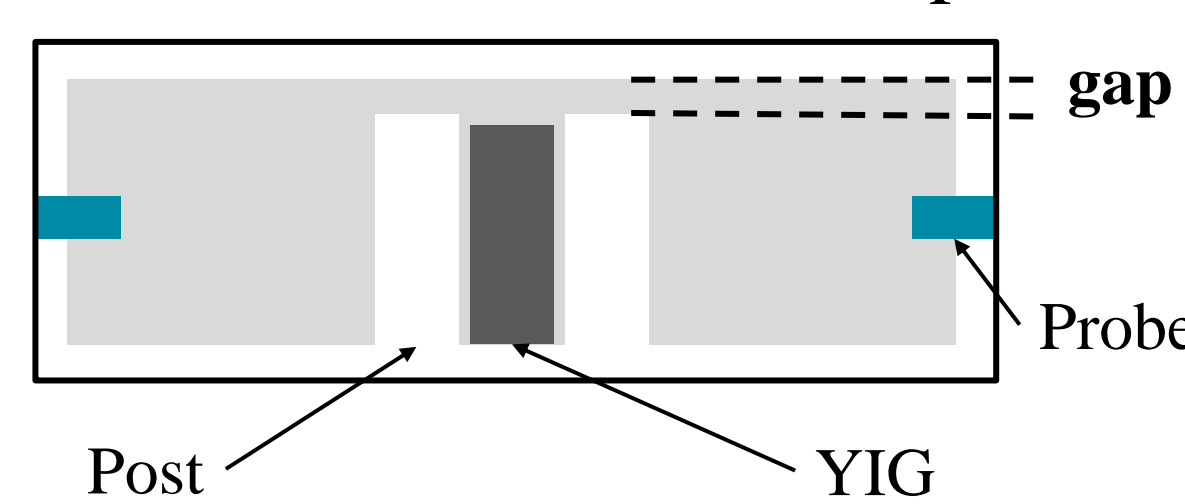
Advantages:

- ▶ Tunable (magnons and photons)
- ▶ Long coherence times (YIG)
- ▶ Ability to be coupled to other systems (e.g. qubits)

Cavity Design & Optimization

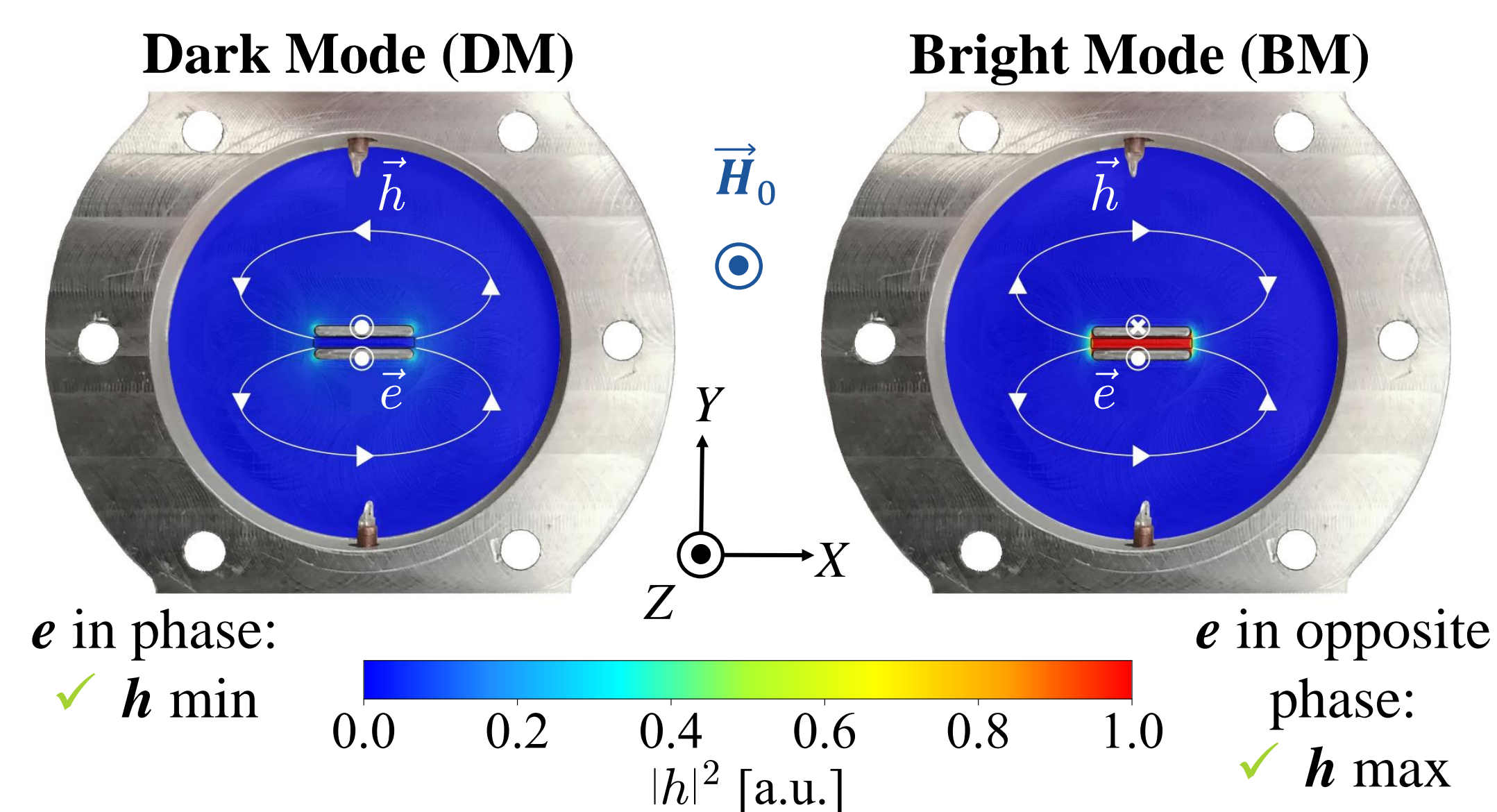
Double re-entrant cavity [1]:

- ▶ RF H -field in the YIG
- ▶ RF H and E -fields separated



Slab dimensions:

3.82×6.09×0.61 mm³



Coupling strength:

$$\frac{g}{2\pi} = \eta \sqrt{\omega} \frac{\gamma}{4\pi} \sqrt{\frac{\mu}{g_1 \mu_B}} \mu_0 \hbar n_s \quad \omega/2\pi: \text{Cavity frequency}$$

$$\eta: \text{Filling factor}$$



Optimization:

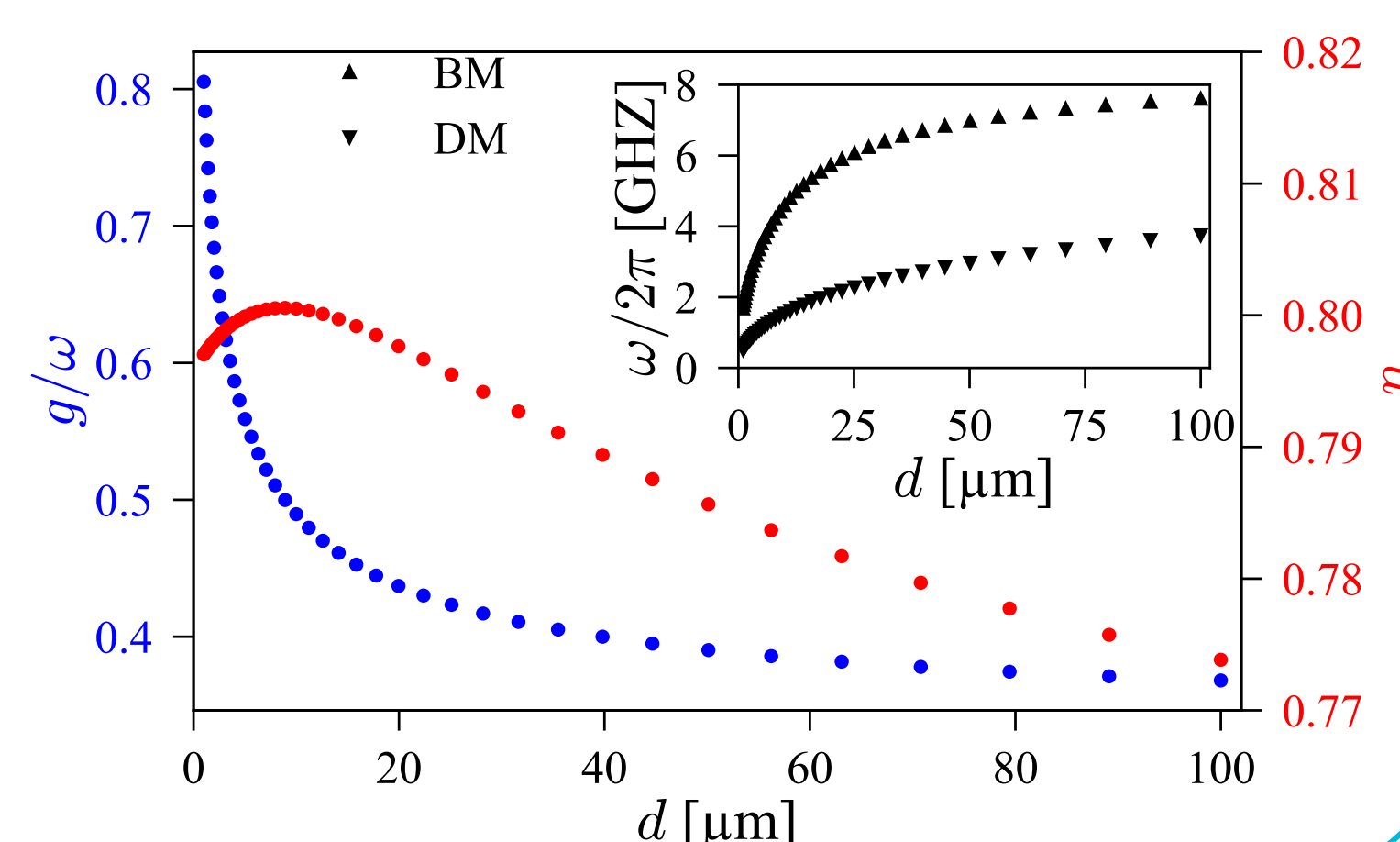
COMSOL simulation with EigenMode (EM) Solver:

- ▶ Maximize η

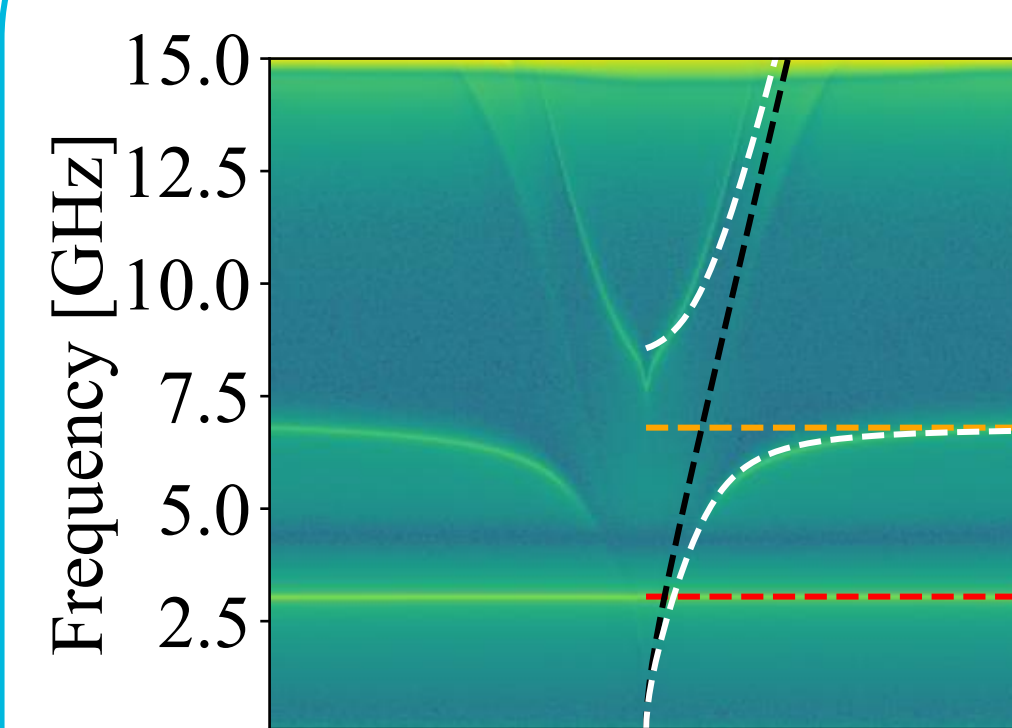
$$\eta = \frac{\left(\int_{V_m} \mathbf{h} \cdot \mathbf{x} dV \right)^2 + \left(\int_{V_m} \mathbf{h} \cdot \mathbf{y} dV \right)^2}{V_m \cdot \int_{V_c} |\mathbf{h}|^2 dV} \quad [2]$$

Gap dependence of the coupling strength

Post dimensions:
6×4.2×0.6 mm³
Cavity radius:
12 mm



Measurements & Modelling

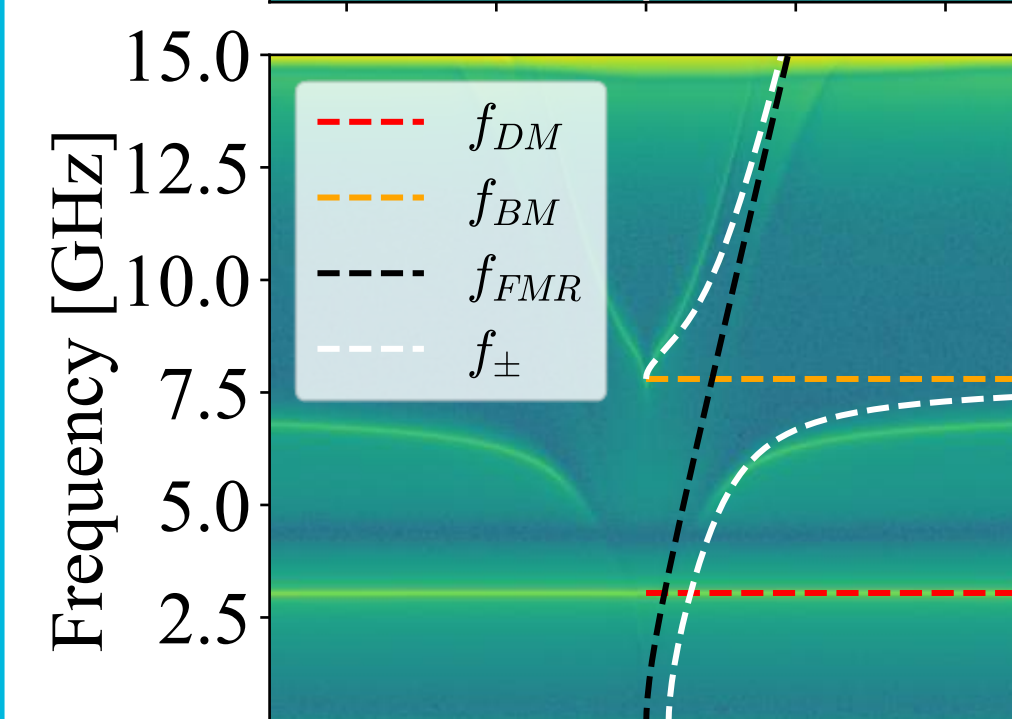


Hopfield model [3]:

$$\hbar \omega_c \hat{a}^\dagger \hat{a} + \hbar \omega_m \hat{b}^\dagger \hat{b} + \hbar g (\hat{a}^\dagger + \hat{a})(\hat{b}^\dagger + \hat{b}) + \hbar D (\hat{a}^\dagger + \hat{a})^2$$

Eigen frequencies:

$$2\omega_{\pm}^2 = \omega^2 + \omega_m^2 + 4g^2 \pm \sqrt{(\omega^2 - \omega_m^2 + 4g^2)^2 + 16g^2\omega_m^2}$$

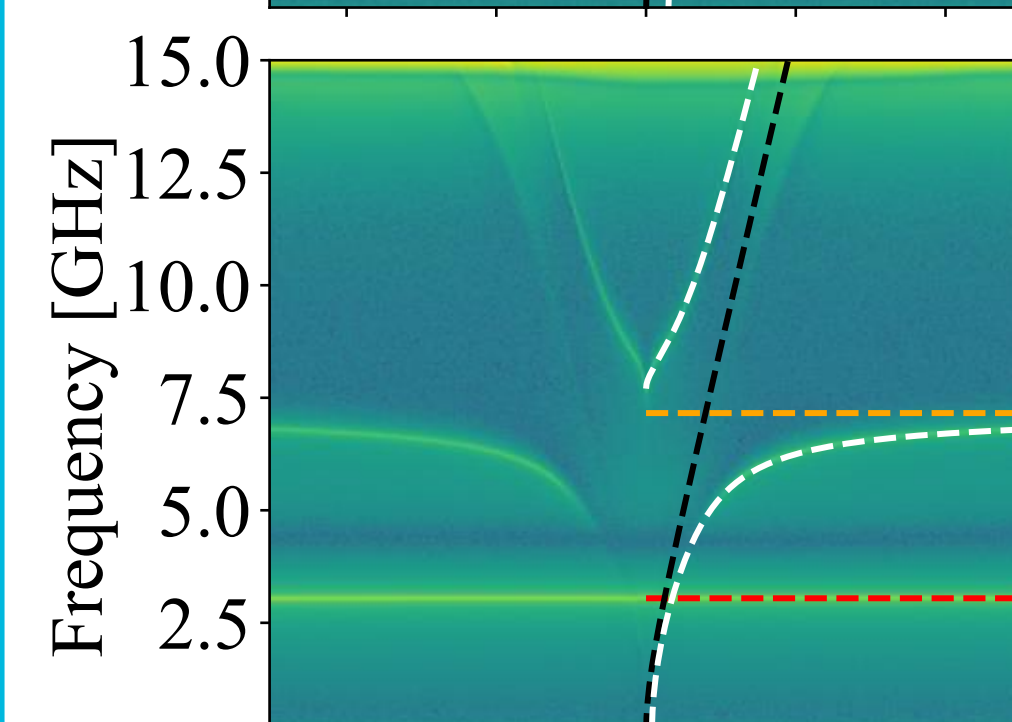


Dicke model [3]:

$$\hbar \omega_c \hat{a}^\dagger \hat{a} + \hbar \omega_m \hat{b}^\dagger \hat{b} + \hbar g (\hat{a}^\dagger + \hat{a})(\hat{b}^\dagger + \hat{b})$$

Eigen frequencies:

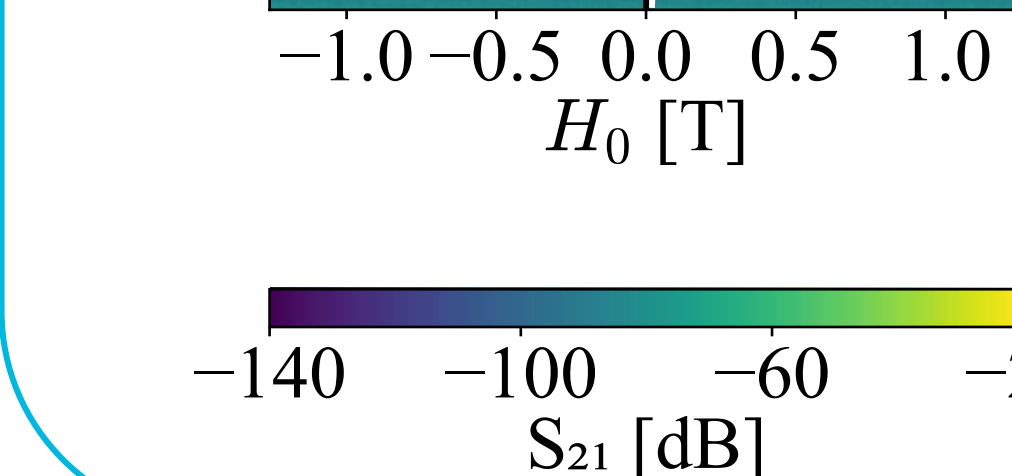
$$2\omega_{\pm}^2 = \omega^2 + \omega_m^2 \pm \sqrt{(\omega^2 - \omega_m^2)^2 + 16g^2\omega\omega_m}$$



Modified Dicke model:

Following [3] and [4], it was also necessary to modify standard model:

$$\omega_{MD}^\pm = \omega_D^\pm (\omega_m \rightarrow \omega_m + \Delta_m)$$

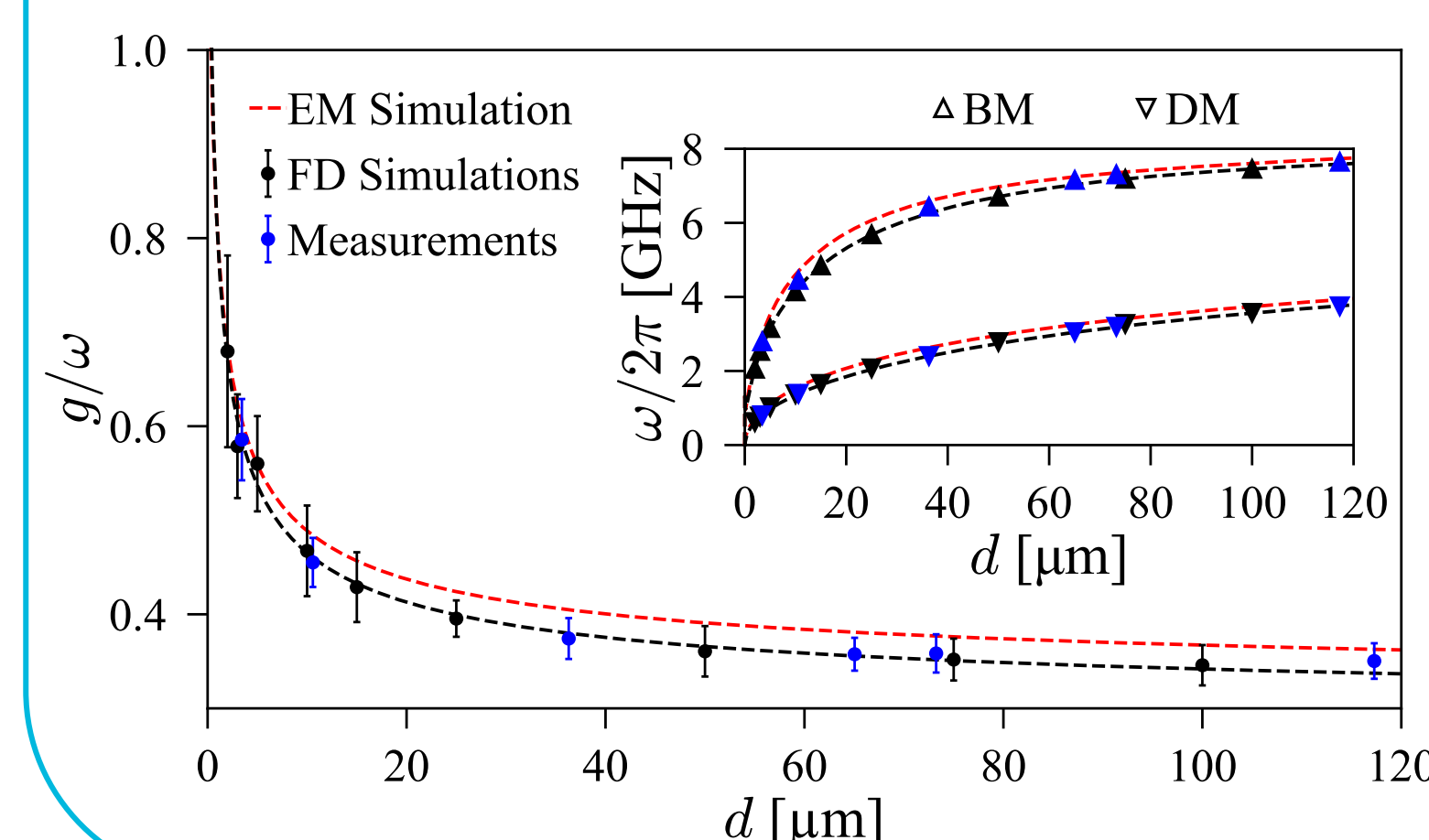


- ✗ Standard model can not be used
- ✓ Adding a frequency shift to the Dicke model is useful

Measurements & Simulations

COMSOL simulation with Frequency Domain (FD) Solver:

- ▶ S-parameters extraction through static field H_0 sweep.
- ▶ Including Polder tensor permeability, excitation probes, cavity electric losses, and demagnetizing field [5].



Gap dependence of the coupling strength

✓ COMSOL model confirmed

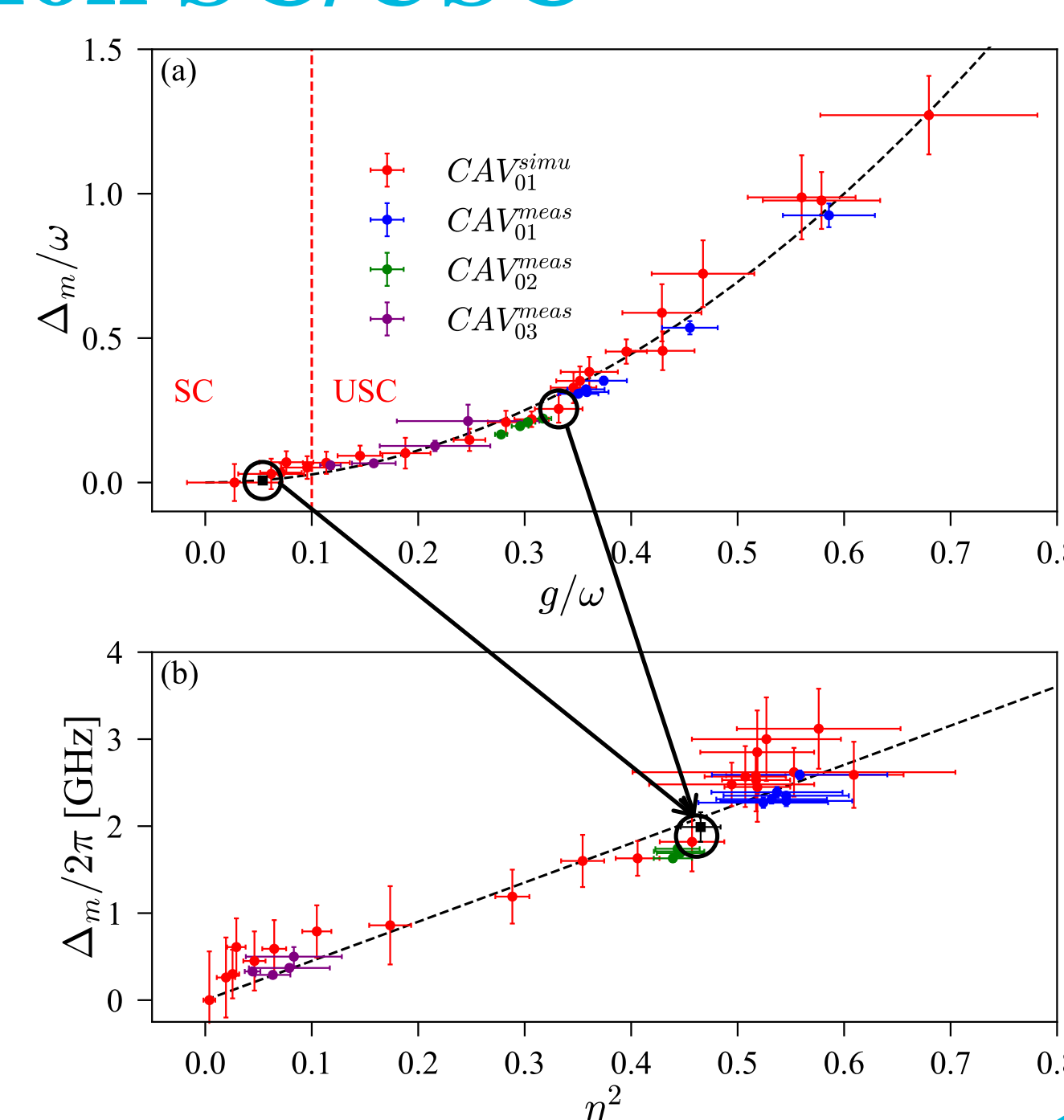
Study of the Transition SC/USC

Reduce slab dimensions in simulations up to 1/5 with same aspect ratio allows g/ω up to 2,7%.

Analysis:

- ▶ Δ_m function of g^2/ω , hence of η^2
- ▶ Δ_m negligible when $g/\omega < 0.1$

✓ SC converges to the standard Dicke model



Conclusion

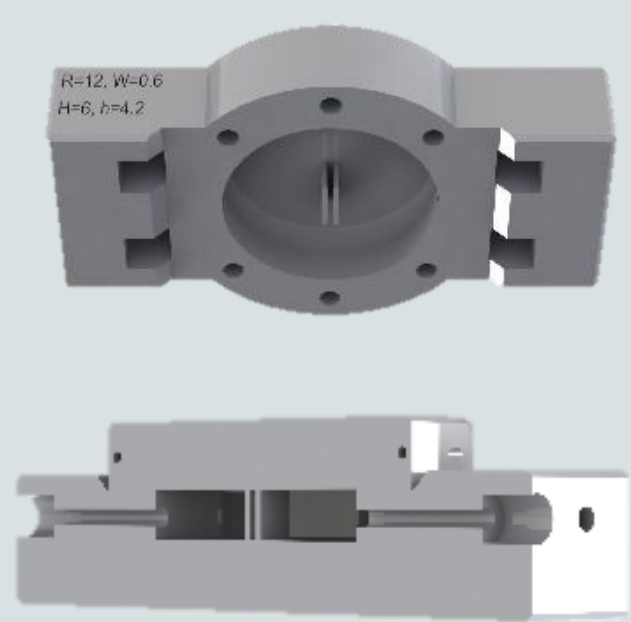
- ✓ USC reached in a double re-entrant cavity
- ✓ Cavity tunable in frequency
- ✓ Adding Δ_m in the Dicke Model: A new Hamiltonian is needed

Applications potentials:

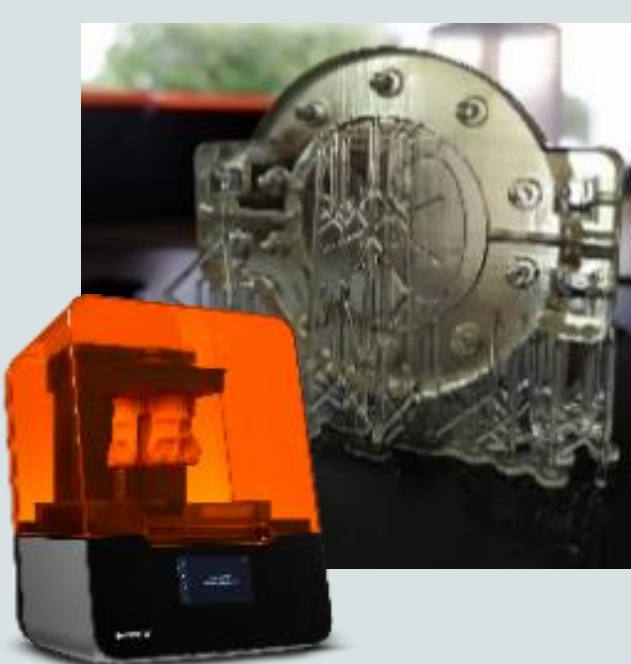
- ▶ Information transfer
- ▶ Sensors (dark matter, magnetometry...)
- ▶ RF components (insulators, circulators...)

Design steps

SolidWorks



3D printing



Metallization



$g/\omega = [0.28; 0.32]$

Machining



$g/\omega = [0.35; 0.58]$



$g/\omega = [0.13; 0.23]$

References

- [1] Phys. Rev. Applied **2**, 054002 (2014)
- [2] Journal of Applied Physics **128**, 073904 (2020)
- [3] Phys. Rev. B **101**, 075301 (2020)
- [4] Phys. Rev. Applied **16**, 034029 (2021)
- [5] Journal of Applied Physics **36**, 1579 (1965)