# Non-linear Dynamics of Coupled Cavity-Magnon System

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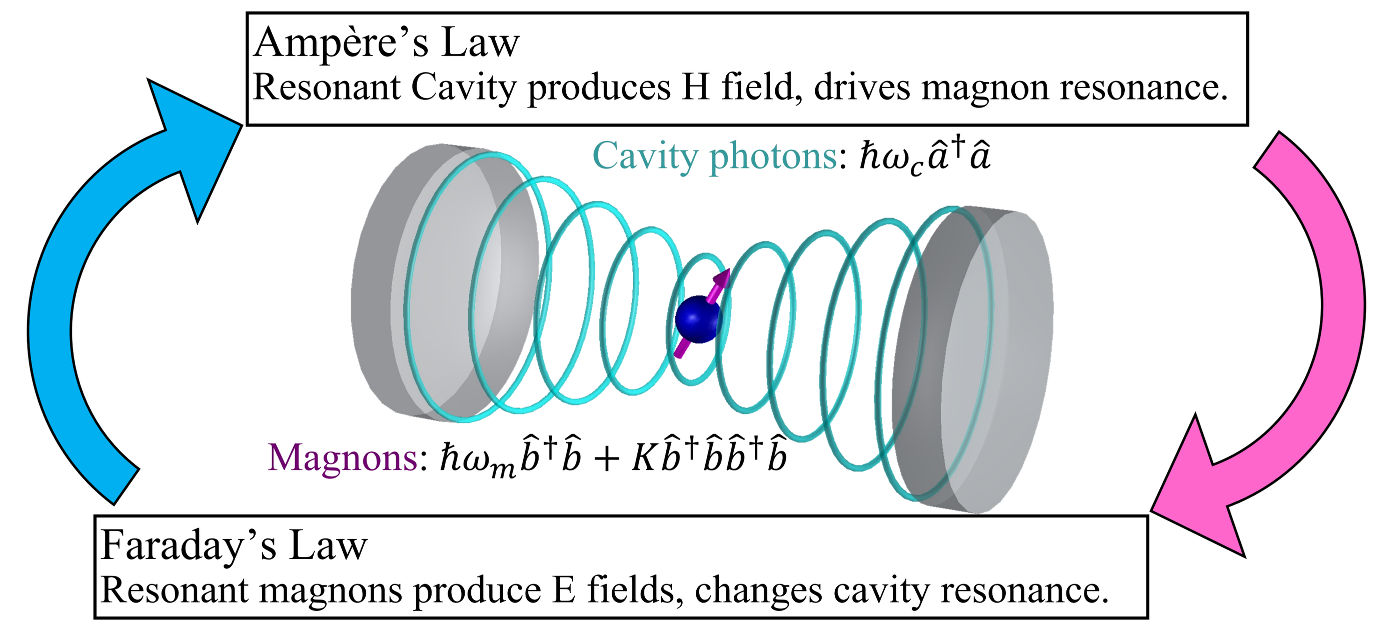
## What are Cavity-Magnon-Polaritons (CMPs)?




$\omega_c, \omega_m$ - resonant frequency of cavity and magnon

$\hat{a}^\dagger$ ($\hat{a}$) - creation (annihilation) operators of cavity photons

$b^\dagger$ ($b$) - creation (annihilation) operators of magnons

$K$ - Kerr coefficient of magnon

- CMPs are quasi-particles generated by magnons coupled with cavity photons.
- Strong coupling between a cavity and a ferromagnetic material allows CMPs to exchange quantum information between cavity photons and magnons.
- Potential application in quantum information processing such as data storage and data reading.

## Non-linear Magnons:

If we consider ferromagnetic sphere as a macro-spin, the Hamiltonian is given by:

$$\mathcal{H} = -\gamma B_0 \hat{S}_z + \frac{\mu_0 \gamma^2 K_{an}}{M^2 V_m} \hat{S}_z^2$$

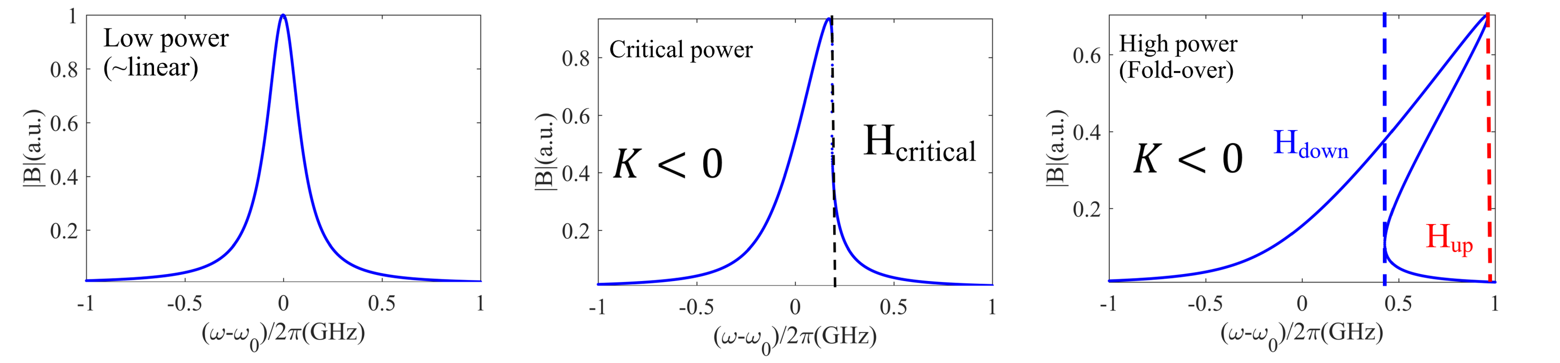
$\gamma$ - gyromagnetic ratio
$\mu_0$ - vacuum permeability
$B_0$ - external magnetic field
$K_{an}$ - first-order magnetocrystalline anisotropy constant
$M$ - saturation magnetization
$V_m$ - volume of the YIG sample
all are constants

$\hat{S}_z$ - Spin projection operator on z-axis

By applying the Holstein-Primakoff transformation $\hat{S}_z = \hat{S} - \hat{b}^\dagger \hat{b}$ and dropping the constant terms, it is easy to derive the magnon Hamiltonian as following:

$$\mathcal{H} = \underbrace{\boxed{\hbar\omega_m \hat{b}^\dagger \hat{b}}}_{\text{Linear term}} + \underbrace{\boxed{\hbar K \hat{b}^\dagger \hat{b} \hat{b}^\dagger \hat{b}}}_{\text{Non-Linear term}}$$

- For low input microwave powers, the nonlinear effect is neglectable.
- For high input microwave powers, the foldover behavior can be observed.




## Acknowledgements

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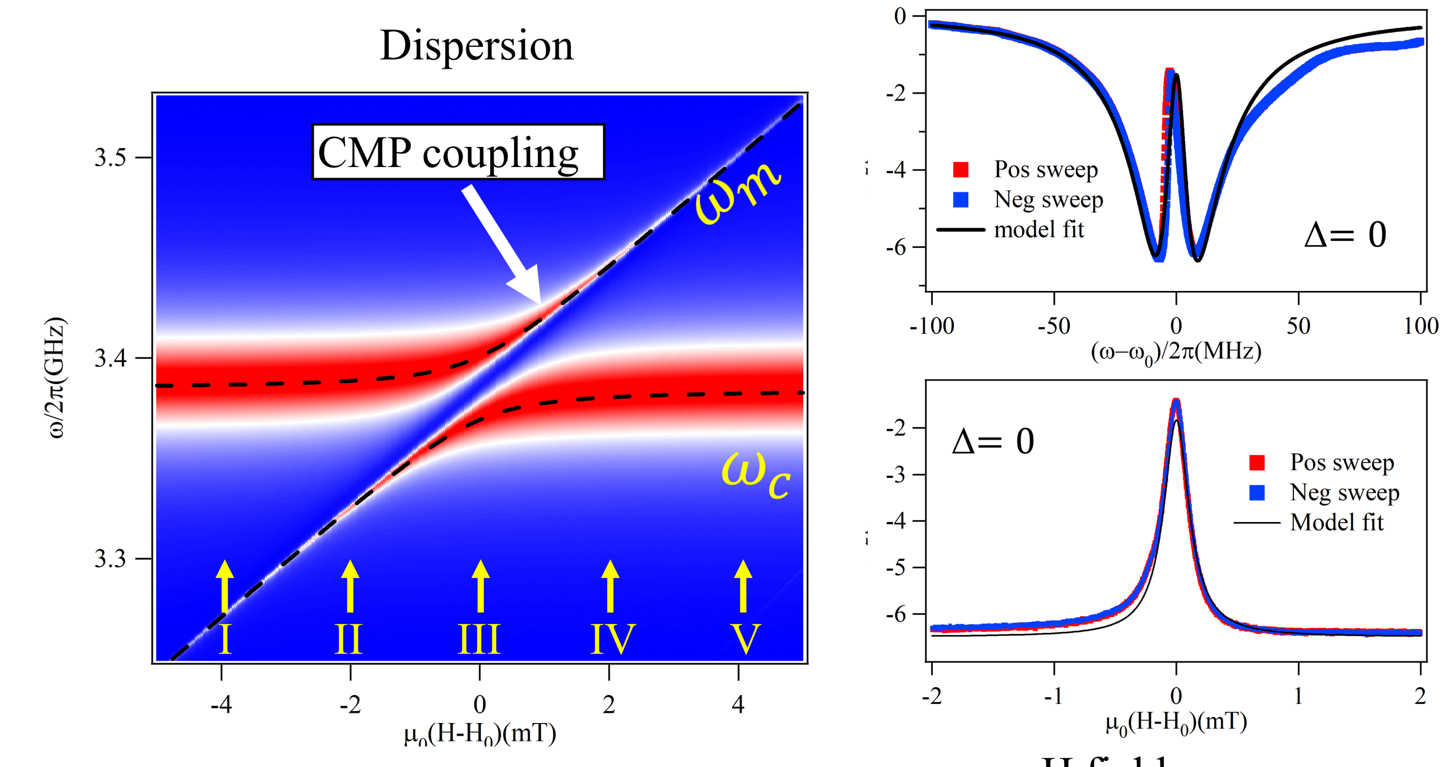
[1]. Y.S. Gui, A. Wirthmann, and C.-M. Hu, Phys. Rev. B 80, 184422 (2009)

[2]. Y.P. Wang, G.Q.Zhang, D. Zhang, T.F. Li, C.-M. Hu, and J.Q. You, Phys. Rev. Lett. 120, 057202 (2018).

## Low Power Experiments




Detuning: $\Delta = \omega_c - \omega_m$

## Non-Linear CMP Dynamics:

The Hamiltonian of the system is given by:

$$\mathcal{H} = \underbrace{\boxed{\hbar(\omega_c - \omega)\hat{a}^\dagger \hat{a}}}_{\text{Cavity photons}} + \underbrace{\boxed{\hbar(\omega_m - \omega)\hat{b}^\dagger \hat{b} + K\hat{b}^\dagger\hat{b}\hat{b}^\dagger\hat{b}}}_{\text{Non-linear Magnons}} + \underbrace{\boxed{g(\hat{a}^\dagger \hat{b} + \hat{a}\hat{b}^\dagger)}}_{\text{Coupling}} + \underbrace{\boxed{\Omega(\hat{a}^\dagger + \hat{a})}}_{\text{Driving field}}$$

$$2K|B|^2 = \frac{kP_{in}}{\left(\omega_m - \omega + 2K|B|^2 - \eta(\omega_c - \omega_m)\right)^2 + (\alpha\omega + \eta\beta\omega)^2}$$

Multiple $|B|^2$ solutions for large $P_{in}$

$$S_{21} = 1 - \frac{\Omega}{i(\omega_c - \omega) + \beta\omega + \frac{g^2}{i(\omega_m - \omega + 2K|B|^2) + \alpha\omega}}$$

Transmission depends on $|B|^2$

Experimental observation on $S_{21}$, expecting multiple stable measures on $S_{21}$.

$$\eta = \frac{g^2}{(\omega_c - \omega)^2 - (\beta\omega)^2}$$

$|B|$ - stable oscillation magnitude of magnon

$\omega$ - frequency of the driving force

$k$ - constant relating $P_{in}$ to power reaching magnons

$g$ - coupling strength between cavity photon and magnon

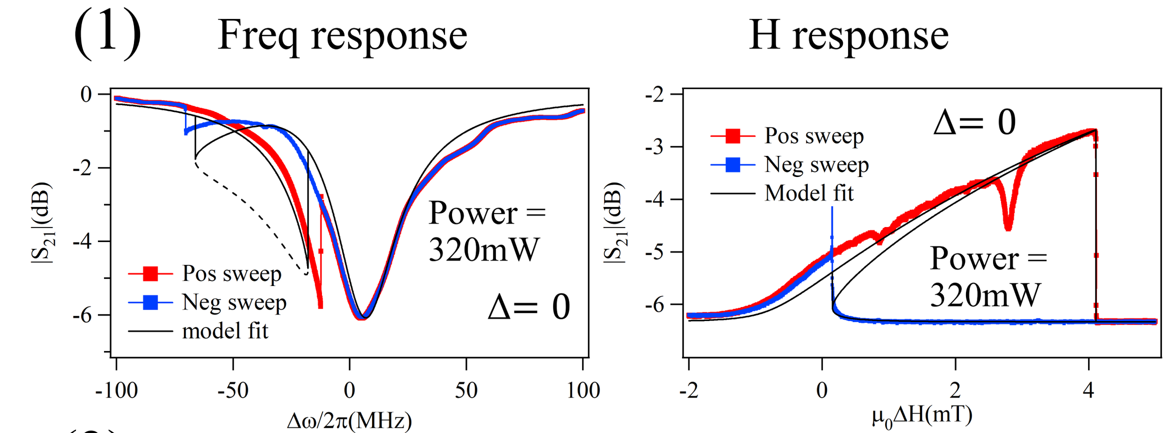
$\Omega$ - parameter relates with input power $P_{in}$

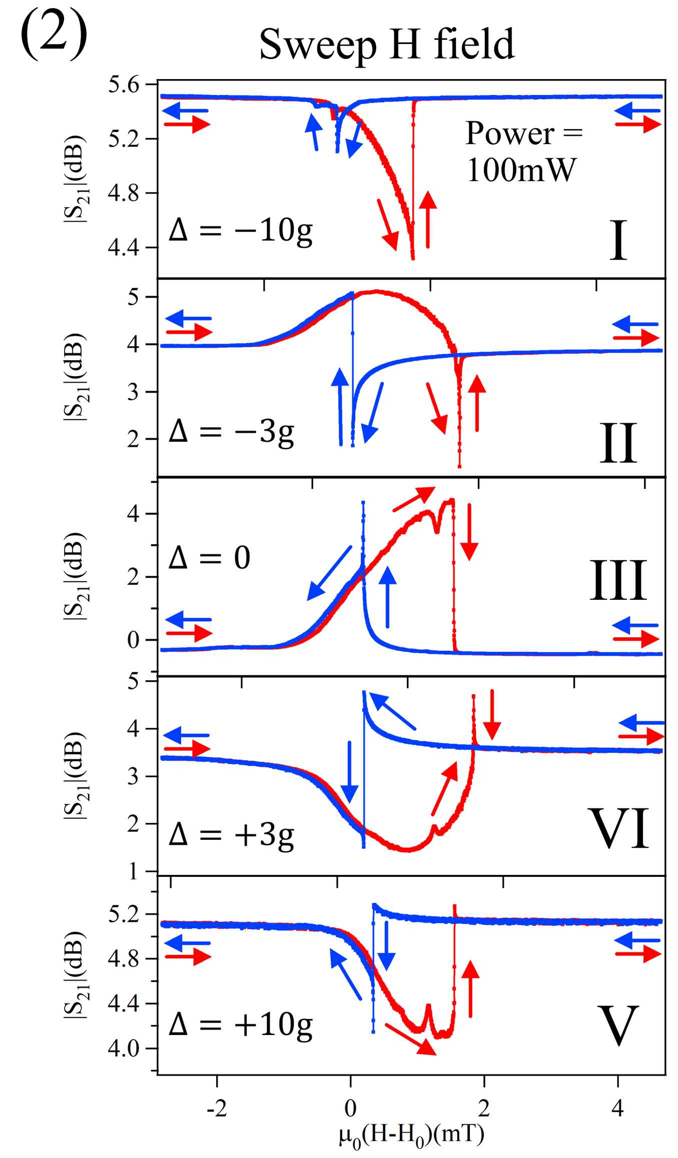
## High Power Experiments:

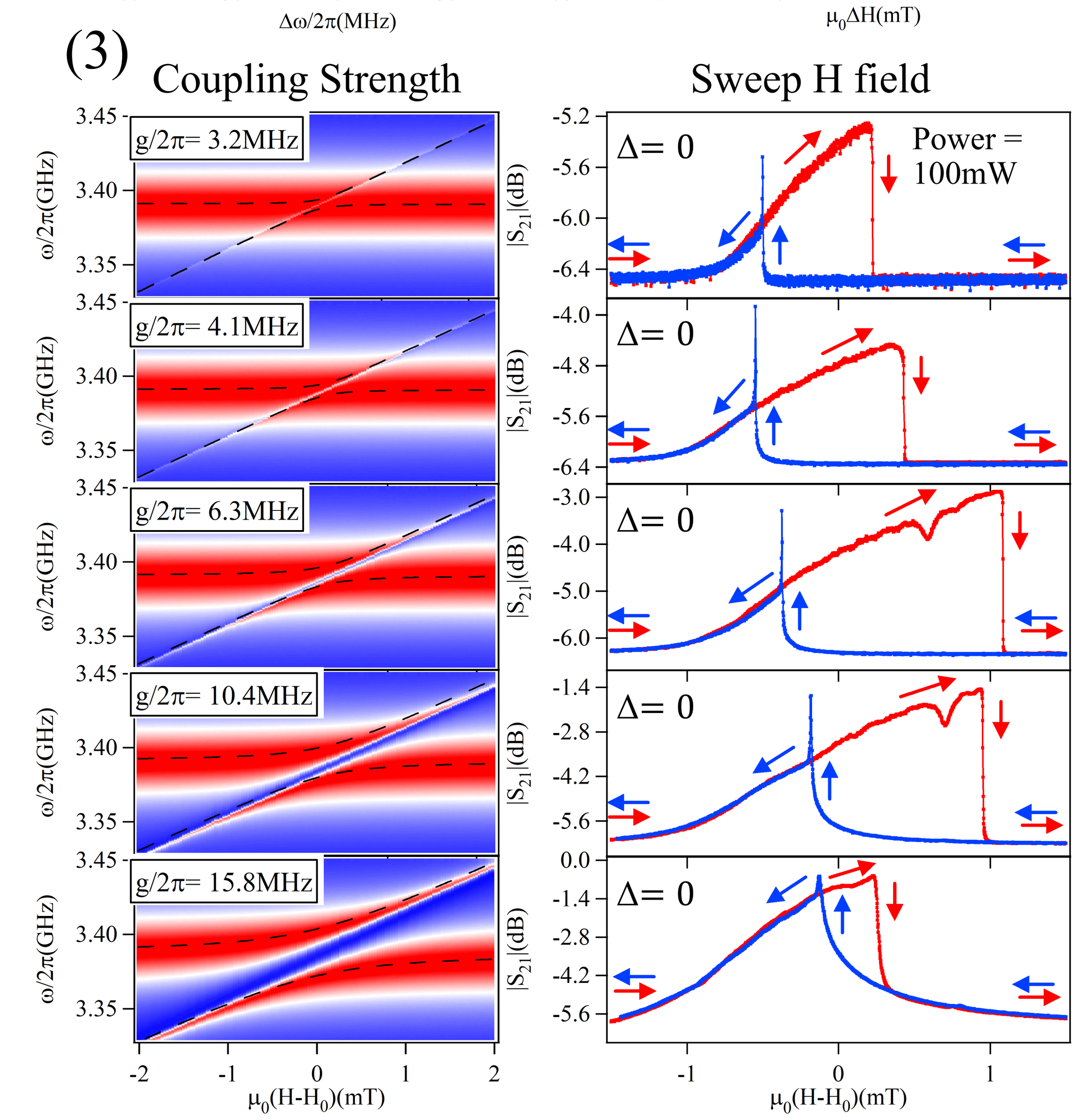
(1) The frequency and magnetic field response at high power (power = 320mW).

(2) The magnetic field response at different detuning. (power fixed at 100mW)

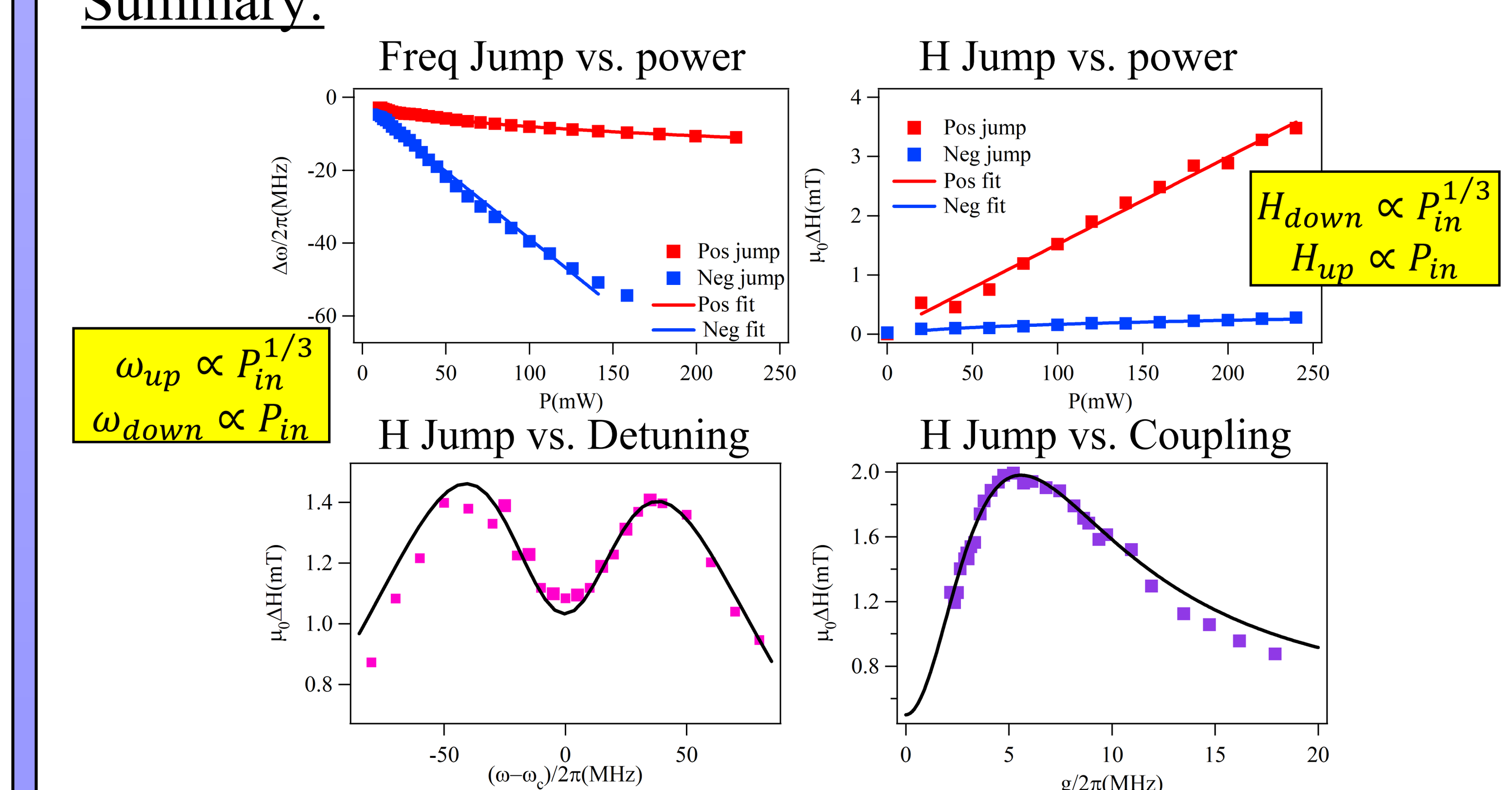
(3) The magnetic field response at different coupling strength. (power fixed at 100mW)




## Summary:




- The experiment results under different coupling strengths and various detuning can be well explained by the theory model we put forward.

## Discussion:

1. The foldover behavior yields bistable states and one unstable state which results in the different negative and positive sweep loops at high input power.
2. Bistable solutions produced by the foldover effect can be accessed by changing either microwave frequency or applied H field.
3. Non-Linear CMP behavior can be described by adding a non-linear Hamiltonian term to the linear magnon Hamiltonian using quantum mechanics.
4. Jump positions at different powers are observed in frequency and H field sweep loops.
5. The relation of Jump differences in H field has been studied by varying coupling and detuning of the CMP system.
6. Data in modern computer is stored in bistable magnetic systems (bits), bistable CMP systems could play an important role in data storage/processing of future quantum information systems.