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Alan Gardin, Jeremy Bourhill, V. Vlaminck, Christian Person, Christophe Fumeaux, et al.. The coupling phase in cavity magnonics. JEMS 2023: 13th Joint European Magnetic Symposia, Aug 2023, Madrid, Spain. . hal-04213510

HAL Id: hal-04213510

<https://hal.science/hal-04213510v1>

Submitted on 21 Sep 2023

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The coupling phase in cavity magnonics

Alan Gardin^{1,2}, Jeremy Bourhill^{2,3}, Vincent Vlaininck², Christian Person², Christophe Fumeaux¹, Vincent Castel² & Giuseppe Tettamanzi¹



Abstract

- Cavity magnonics relevant for quantum transducers, quantum memories (using dark mode physics), non-reciprocal devices [1]: such applications justify studying cavity magnonics in multimode systems.
- Microwave photon/magnon coupling due to Zeeman coupling involves a *coupling phase* factor which is usually rightfully neglected.
⇒ unless the system is “loop-coupled” (see next section for definition and examples), coupling phases are unobservables.
- (Experimentally) Simplest system in which the coupling phases manifest: two magnon modes coupling simultaneously to two cavity modes. The various coupling phases accumulate in a single quantity θ : *the physical phase*. Physical phase found to influence the presence of dark modes, and the strength of the cavity-mediated coupling.

Relevance of the coupling phase

- Origin of the coupling phase φ : Zeeman coupling between macrospin $\mathbf{S} = S_x\hat{x} + S_y\hat{y} + S_z\hat{z}$ and the cavity mode’s RF magnetic field $\mathbf{h} = h_x\hat{x} + h_y\hat{y}$ ($\mathbf{h} \perp H_0\hat{z}$ static applied magnetic field)
- Interaction Hamiltonian using the rotating wave approximation [2]:

$$H_I = \int_{V_m} d^3r \mathbf{S} \cdot \mu_0 \mathbf{h} \quad (1)$$

$$= \hbar g \left(e^{i\varphi} c m^\dagger + e^{-i\varphi} c^\dagger m \right) \quad (2)$$

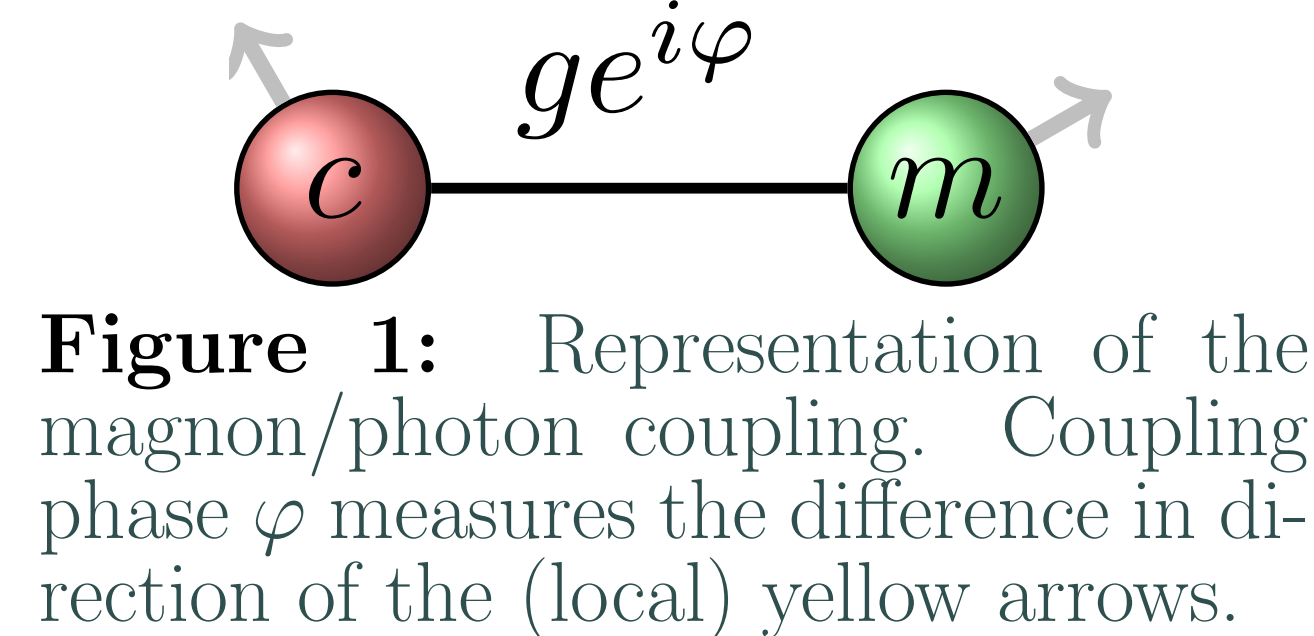


Figure 1: Representation of the magnon/photon coupling. Coupling phase φ measures the difference in direction of the (local) yellow arrows.

with coupling strength $g/2\pi \propto \eta\sqrt{\omega_c}$ and

$$\eta = \sqrt{\frac{\left(\int_{V_m} d^3r h_x\right)^2 + \left(\int_{V_m} d^3r h_y\right)^2}{V_m \int_{V_c} d^3r |\mathbf{h}|^2}}, \quad \varphi = \arg \left\{ \int_{V_m} d^3r h_x + i \int_{V_m} d^3r h_y \right\} \quad (3)$$

- A unitary transformation can gauge the phase away by rotating one of the modes \Rightarrow if φ can be eliminated, it cannot have physical consequences
- Coupling phase can be “rotated away” when the system is not “loop-coupled”, i.e. we have n modes but $k < n$ couplings between modes: we have n degrees of freedom but only $k < n$ constraints

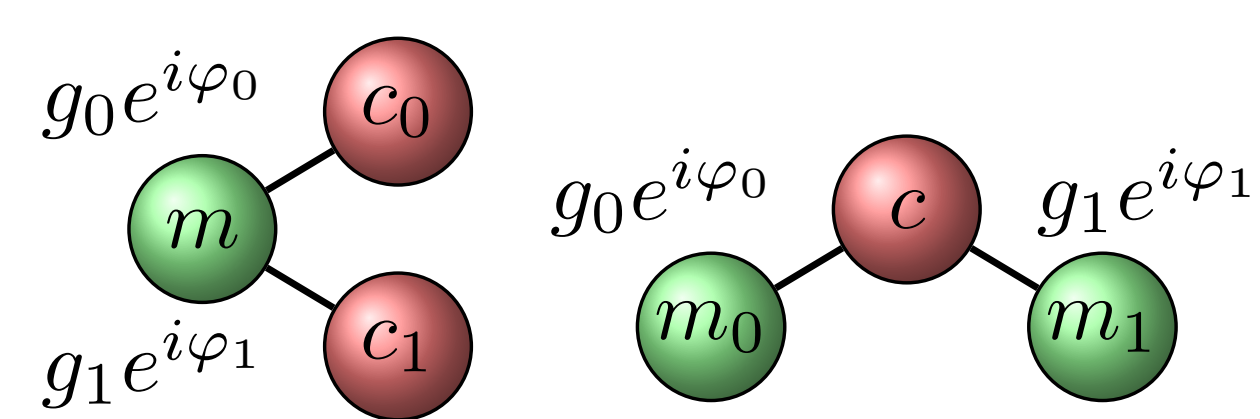


Figure 2: Non loop-coupled systems ($k < n$)

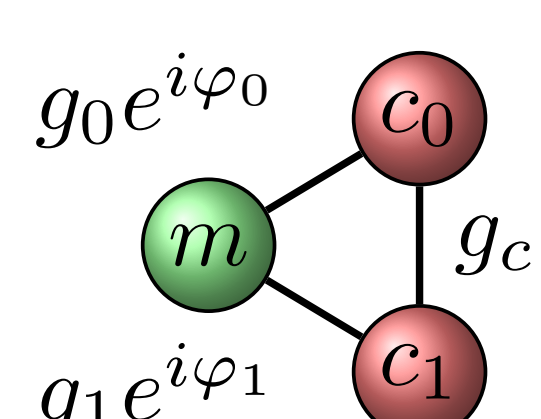


Figure 3: Loop-coupled systems ($k \geq n$)

An example with a physical phase

System definition

- System under study: two magnon modes (annihilation operators m_0 and m_1 , angular frequencies $\omega_m - \delta_m$ and $\omega_m + \delta_m$) coupling to two cavity modes (c_0 and c_1 , angular frequencies $\omega_c - \delta_c$ and $\omega_c + \delta_c$), with coupling strength $g_0/2\pi$ to c_0 and $g_1/2\pi$ to c_1 .
- Loop-coupled system: the various coupling phases combine to form a *physical phase* θ characterising the physics:

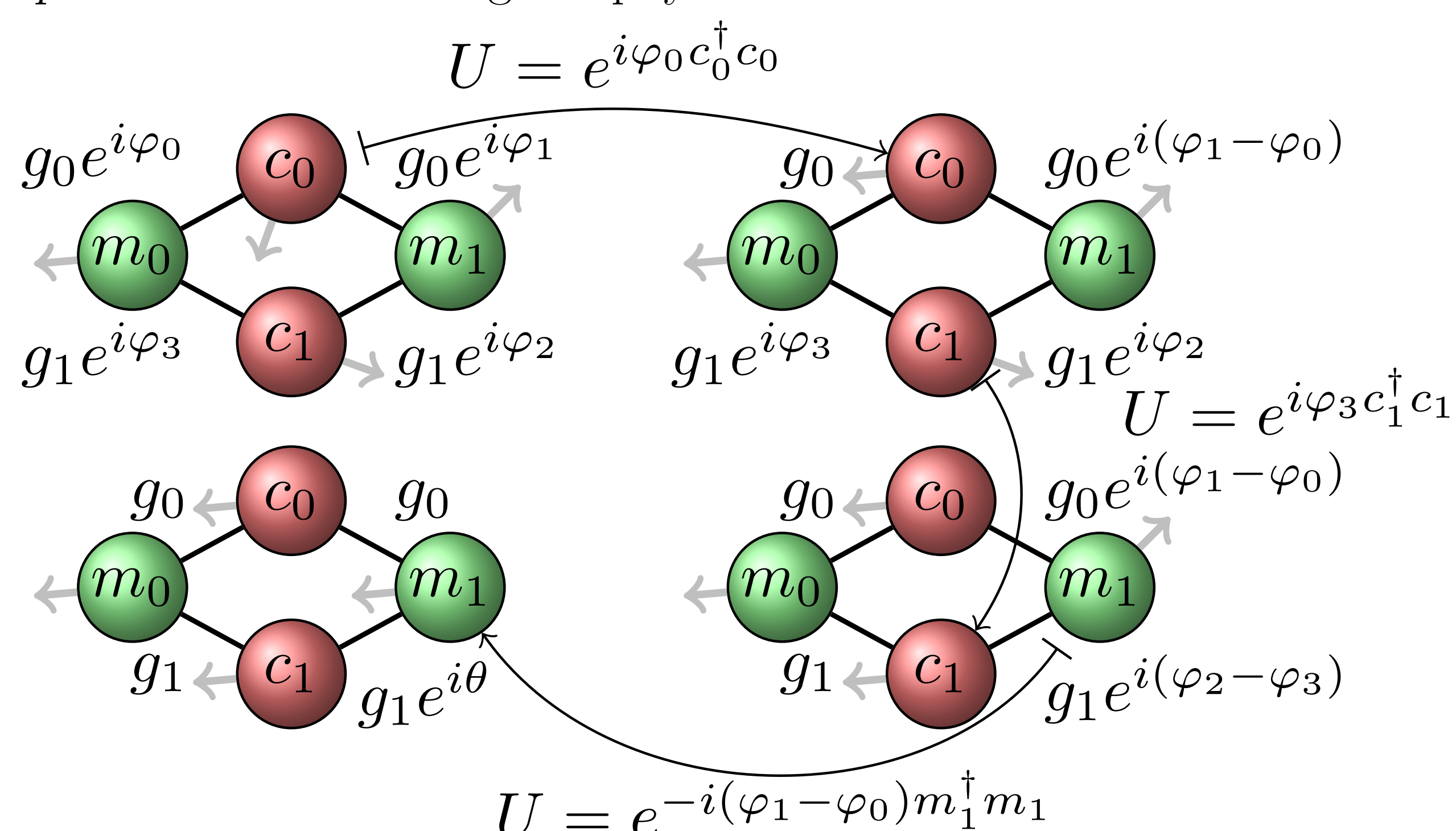


Figure 4: Reduction of the coupling phases to a single physical phase θ through unitary transformations.

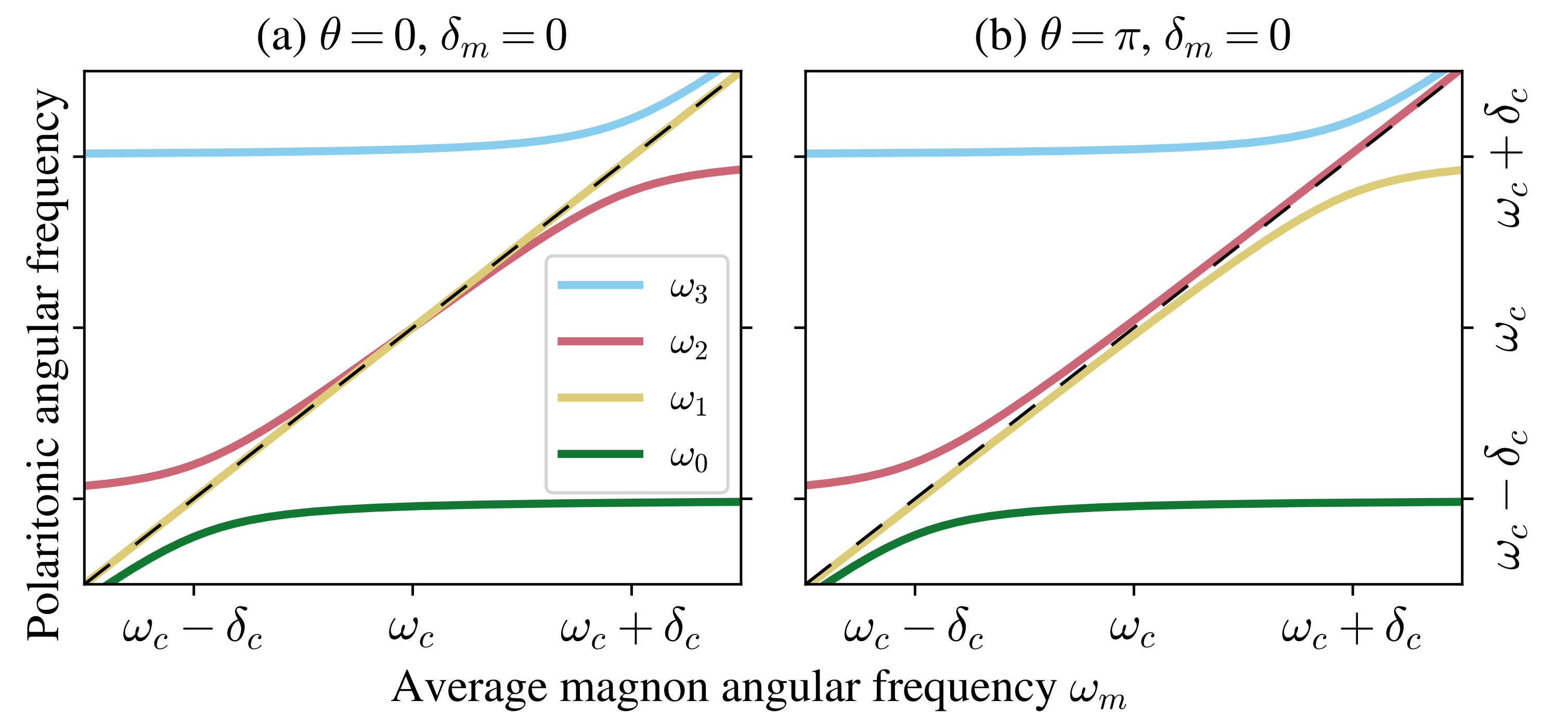


Figure 5: Spectra for $g_0 = g_1 = 0.03\omega_c$, $\omega_c/2\pi = 5$ GHz and $\delta_c/2\pi = 1$ GHz. The black dashed line is ω_m . Polaritons ω_1, ω_2 cross for $\theta = 0$ and anti-cross for $\theta = \pi$.

Indirect magnon/magnon coupling at $\omega_m = \omega_c$

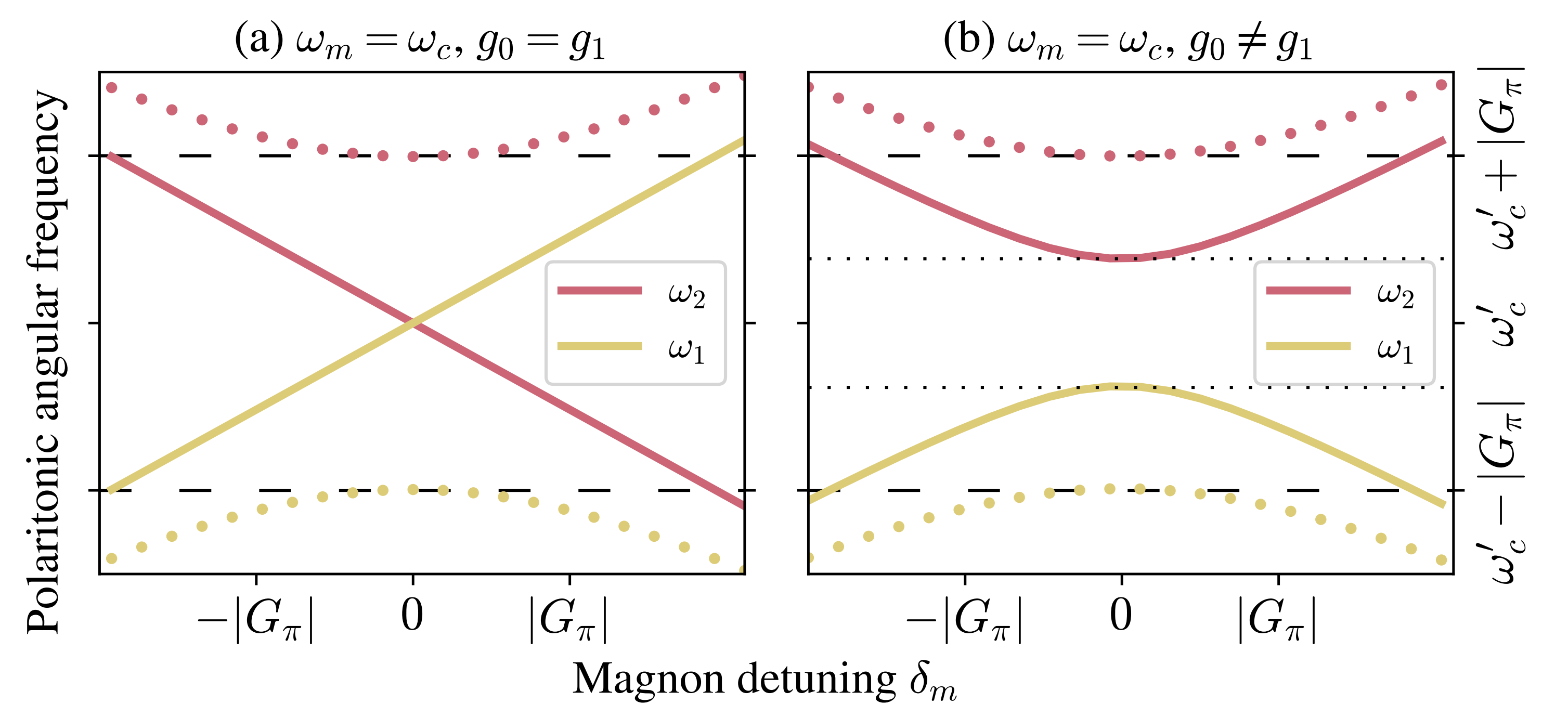


Figure 6: Spectra for $\theta = 0$ in solid lines and $\theta = \pi$ in dots. Other parameters same as in Fig 5. G_θ is given by equation (4) below.

with θ -dependent indirect magnon/magnon coupling strength $G_\theta/2\pi$:

$$G_\theta = \frac{\delta_c}{\delta_c^2 - \delta_m^2} \left(g_0^2 - e^{i\theta} g_1^2 \right). \quad (4)$$

Dark mode physics

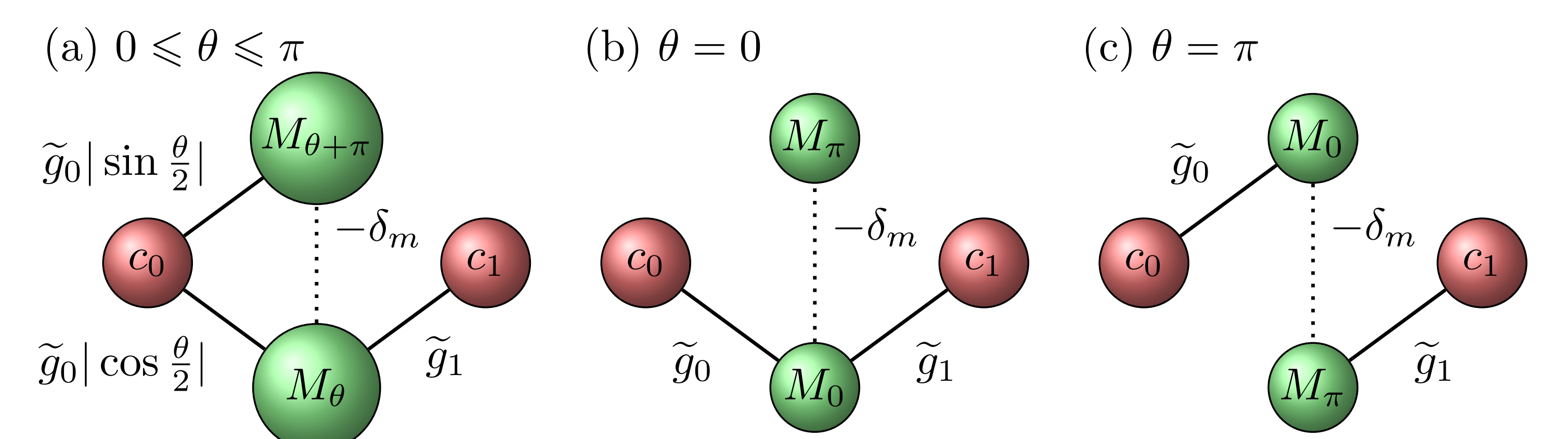


Figure 7: Illustration of the different couplings in the system.

where

$$M_\theta = \frac{m_0 + e^{-i\theta} m_1}{\sqrt{2}}, \quad \tilde{g}_i = \sqrt{2} g_i. \quad (5)$$

- Dark mode: eigenmode that does not couple to the readout mechanism
- Cavity magnonics readout: cavity photons
- For $\delta_m = 0$ and $\theta = 0$, M_π does not couple: dark mode

Outlook

- Coupling phase can have physical consequences in loop-coupled multimode systems
- Resulting discrete gauge-invariant phase θ akin to a synthetic gauge field, which can break time-reversal symmetry for specific values [3]
- Synthetic gauge field+dissipation engineering \Rightarrow non-reciprocal behaviour [4] However, the physical phase is fixed by the cavity geometry...

References

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