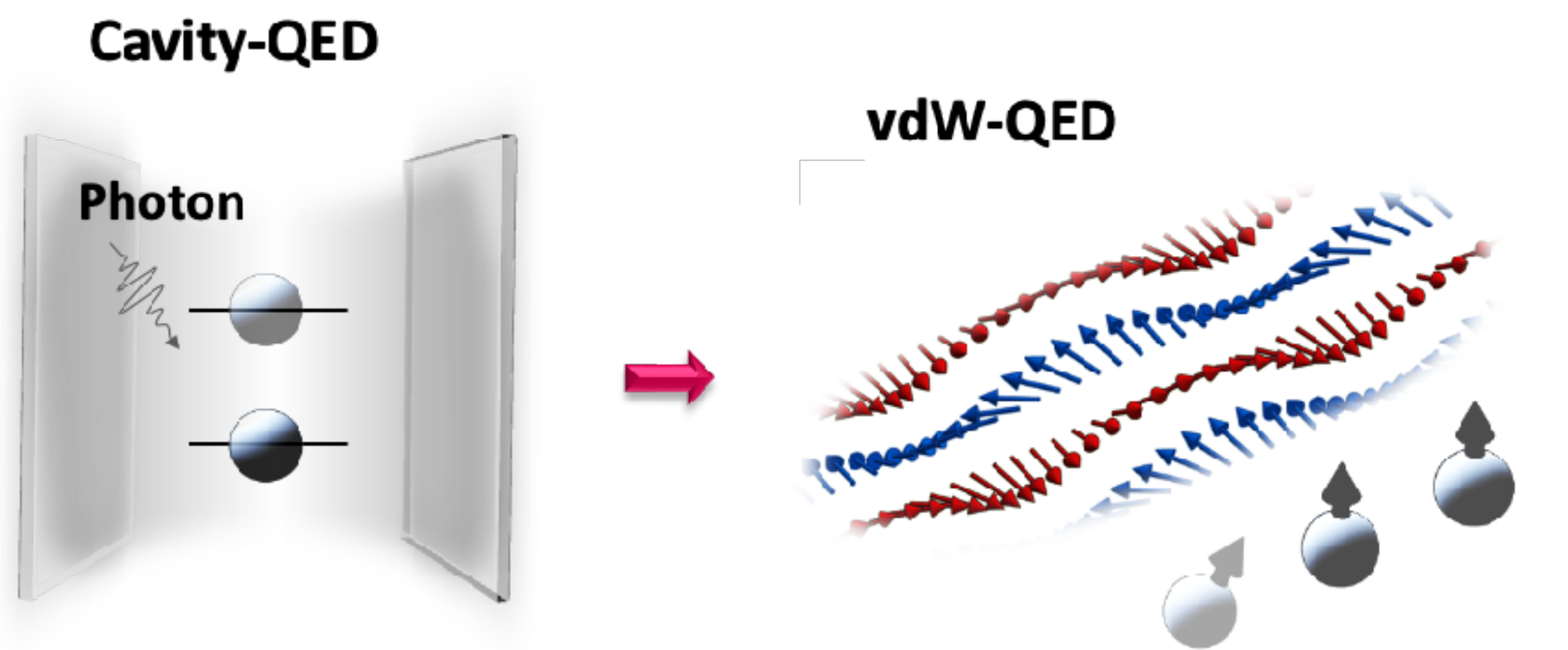
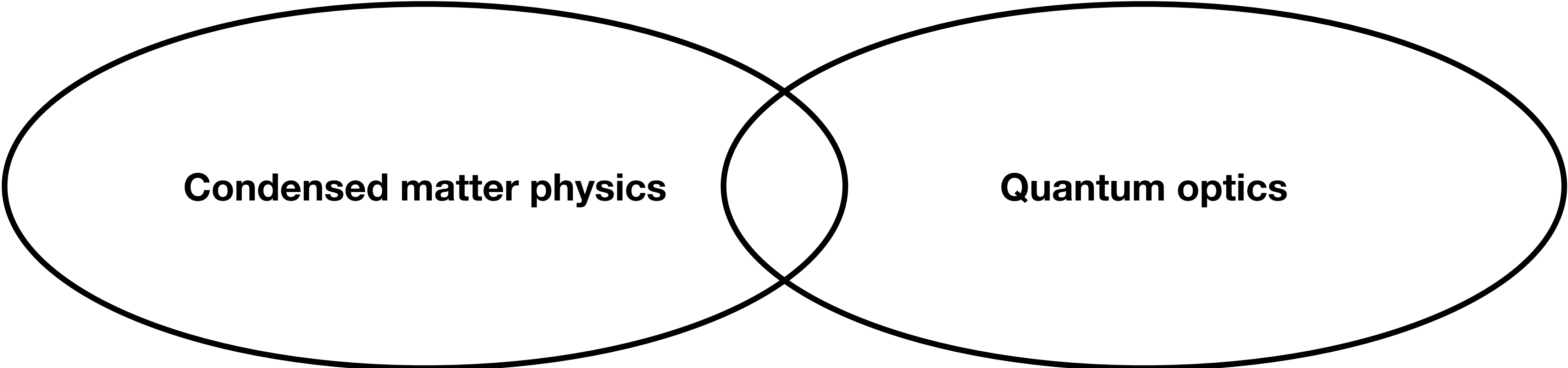


# Cavity QED with van der Waals chiral magnon cavities

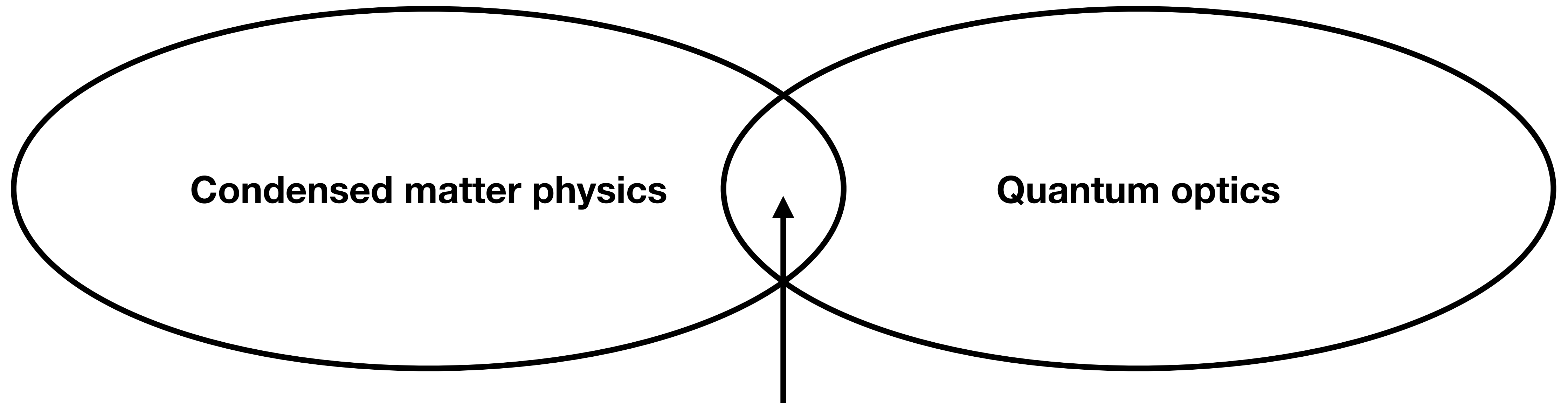
David Zueco, INMA CSIC-Unizar, Zaragoza (SPAIN)





**Condensed matter physics**

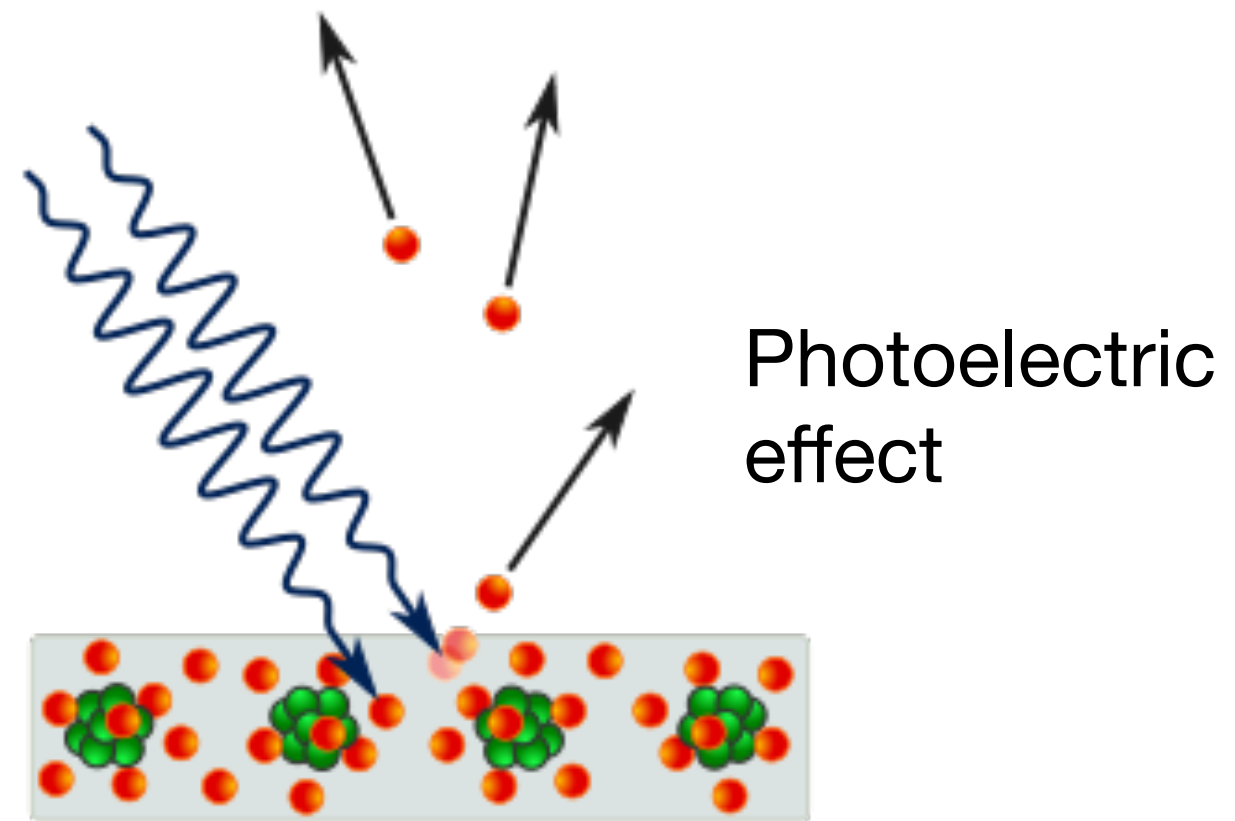
**Quantum optics**



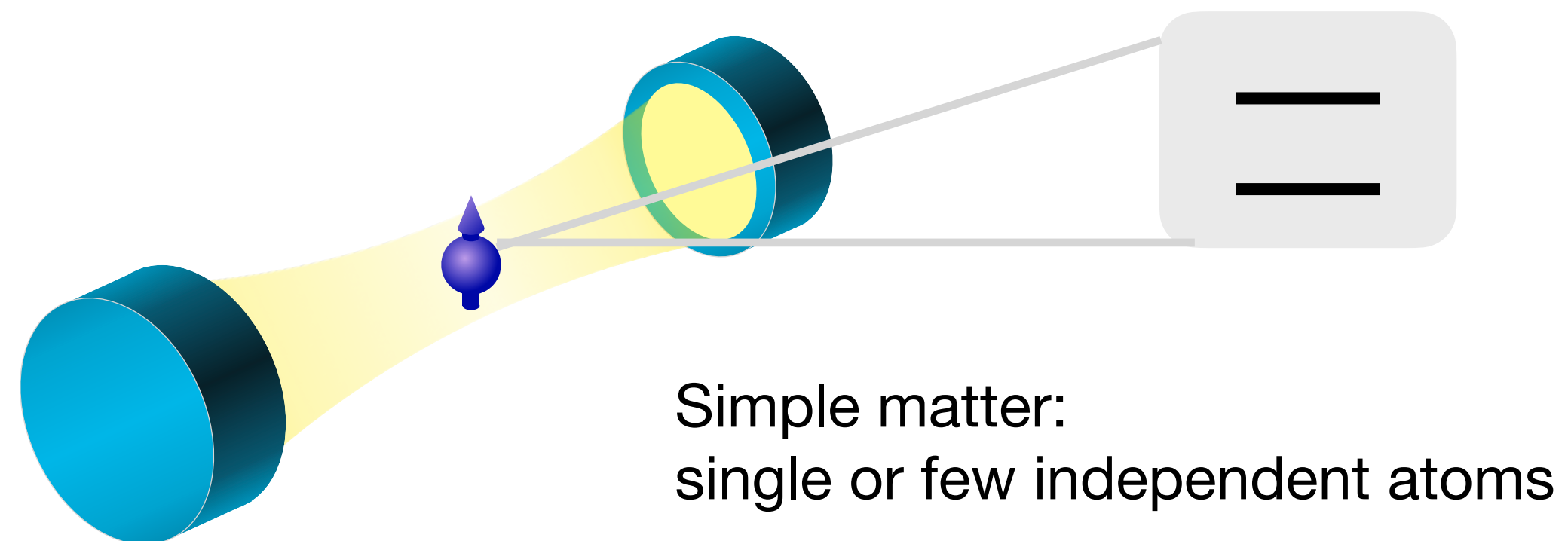
- Many Body optics
- Cavity QED Materials
- 2D materials → Magnon Cavities
- Spin-Magnon coupling

# Quantum optics

Photons: light quanta

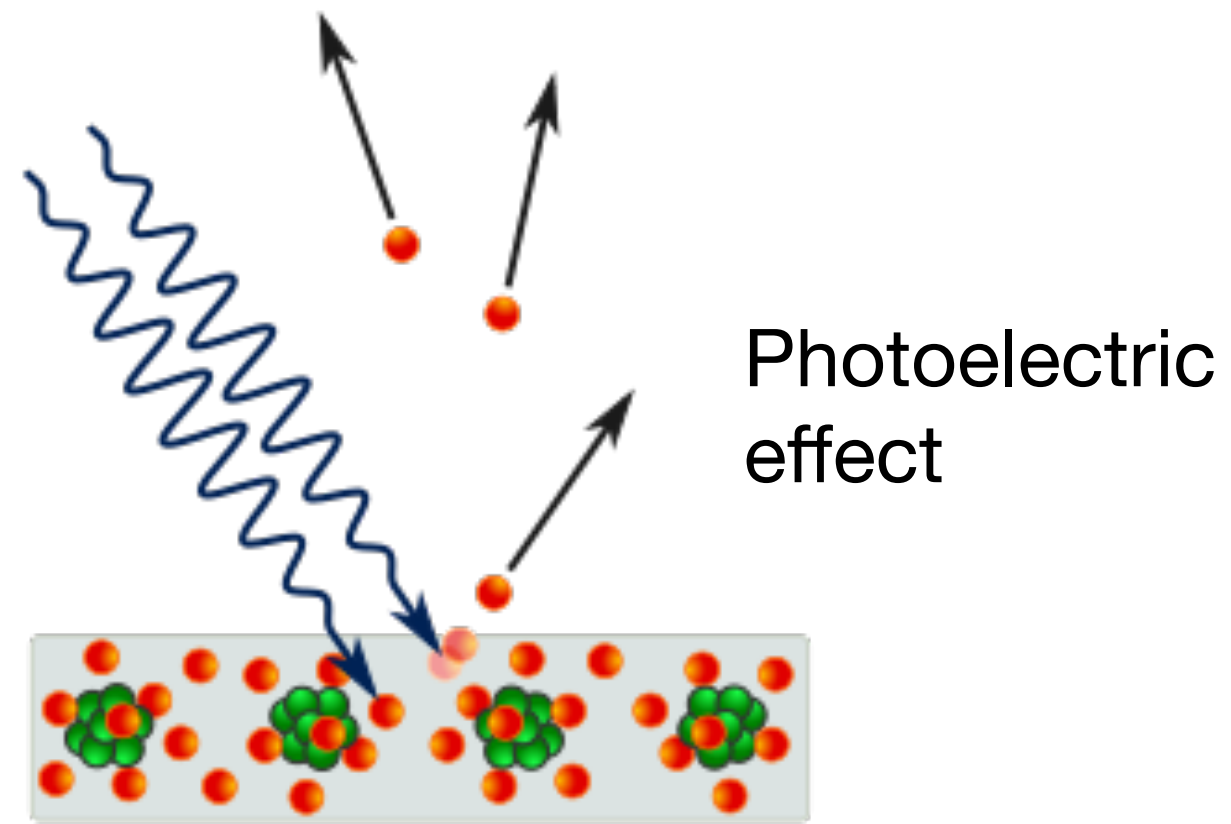


Cavity QED: quantum description of light and matter

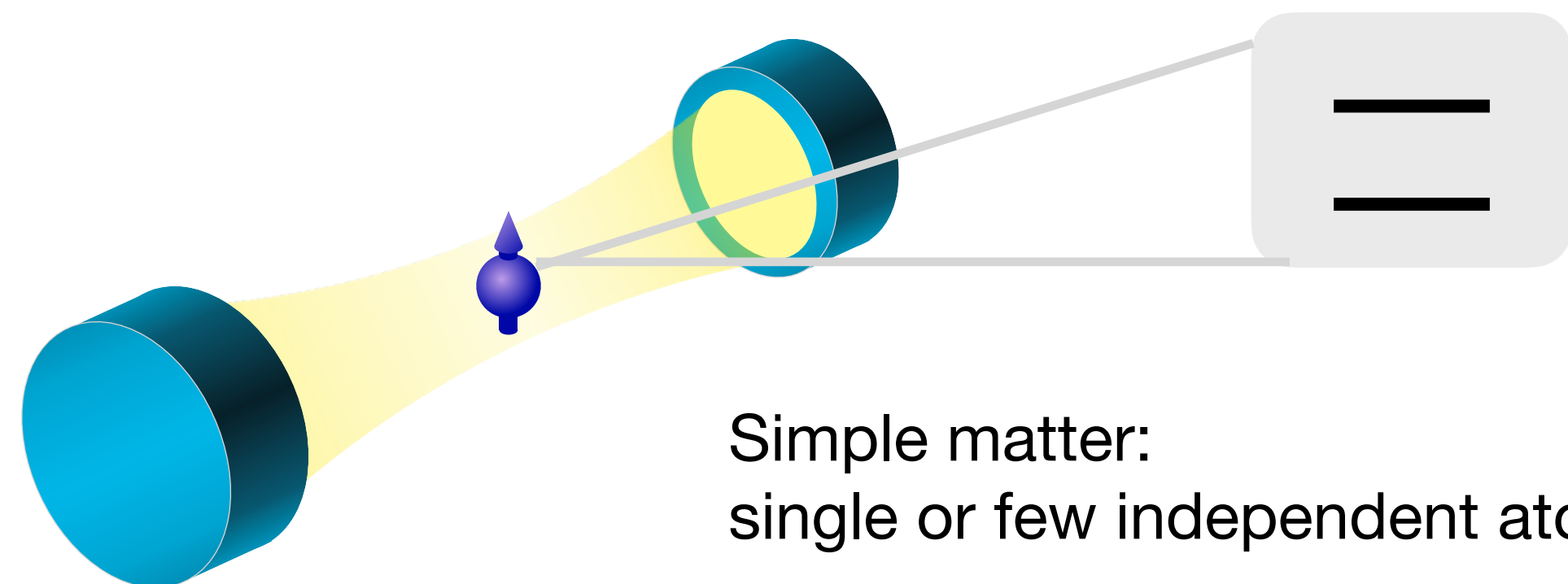


# Quantum optics

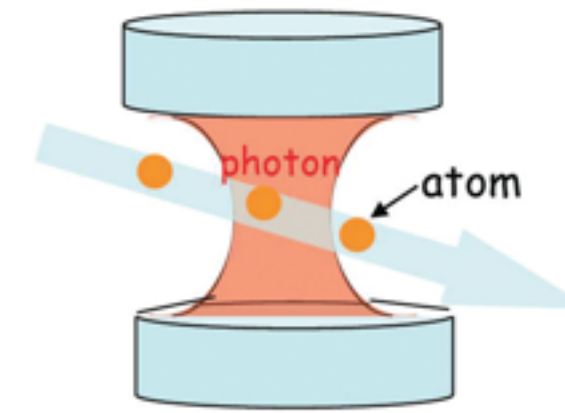
Photons: light quanta



Cavity QED: quantum description of light and matter

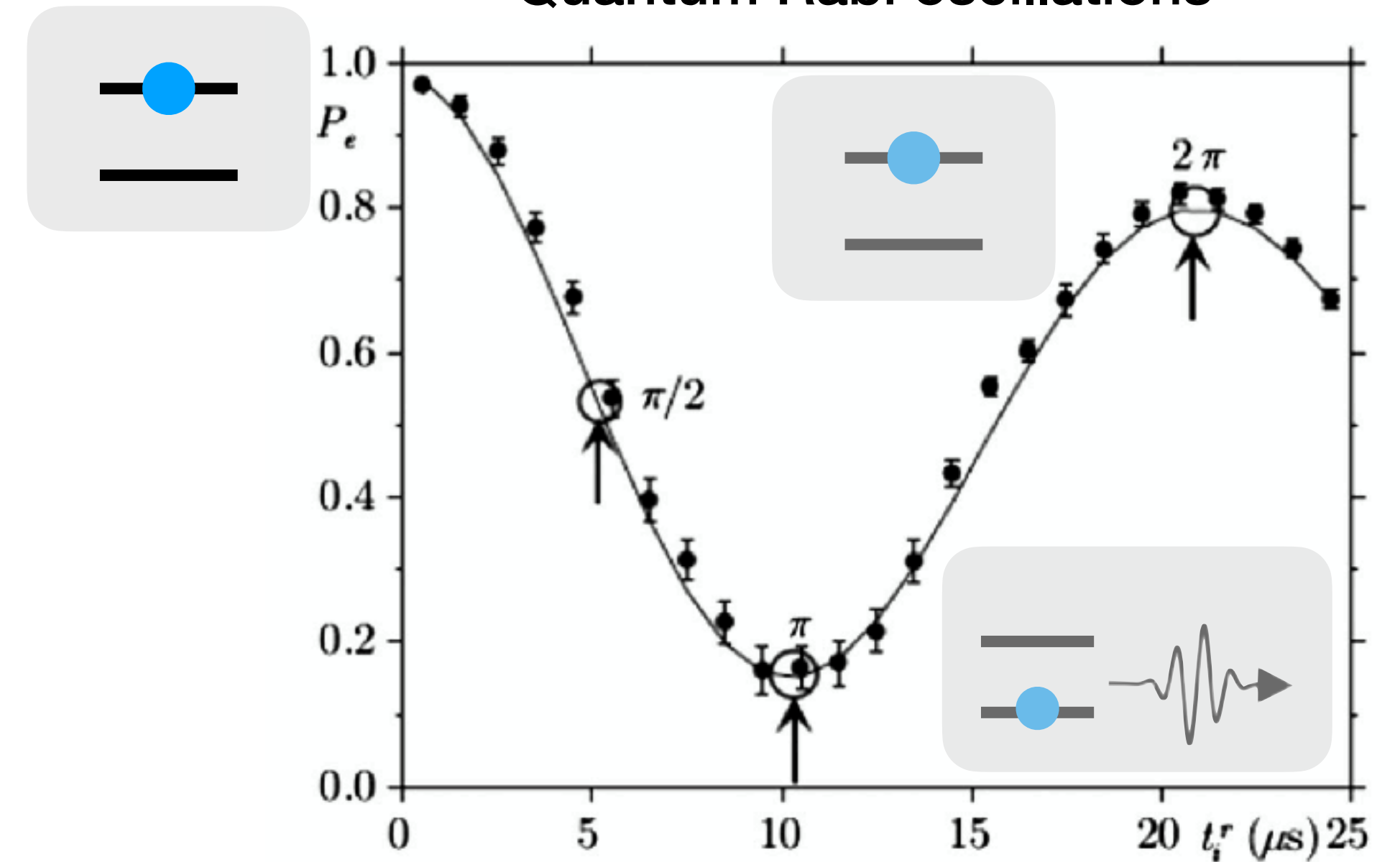


Simple matter:  
single or few independent atoms



ENS (Paris, 1996):  
Rubidium atoms and an open cavity

Quantum Rabi oscillations

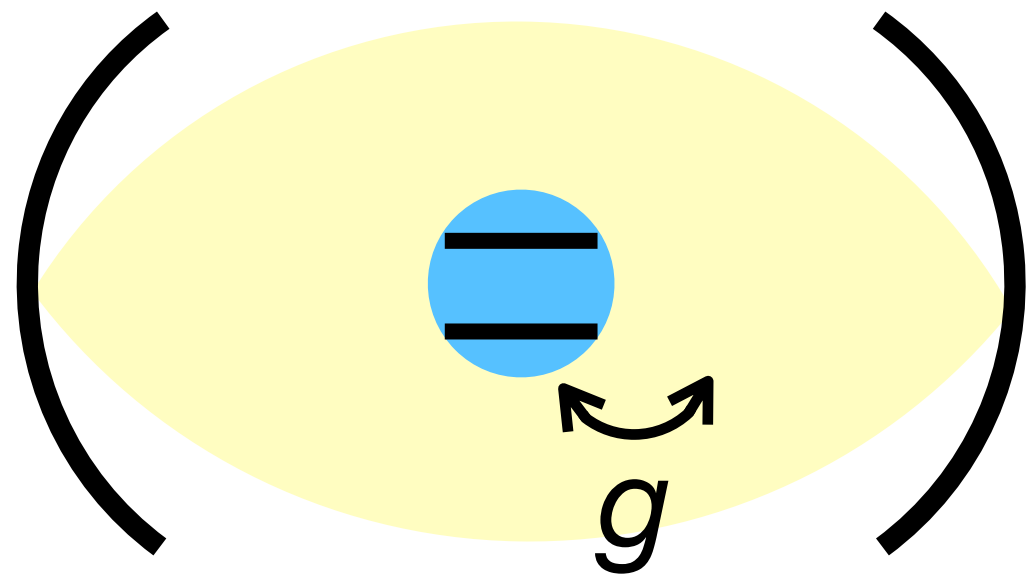


Haroche, Rev. Mod. Phys. 85, 1083 (2013)

Haroche, 2012 Nobel Prize (together with Wineland)

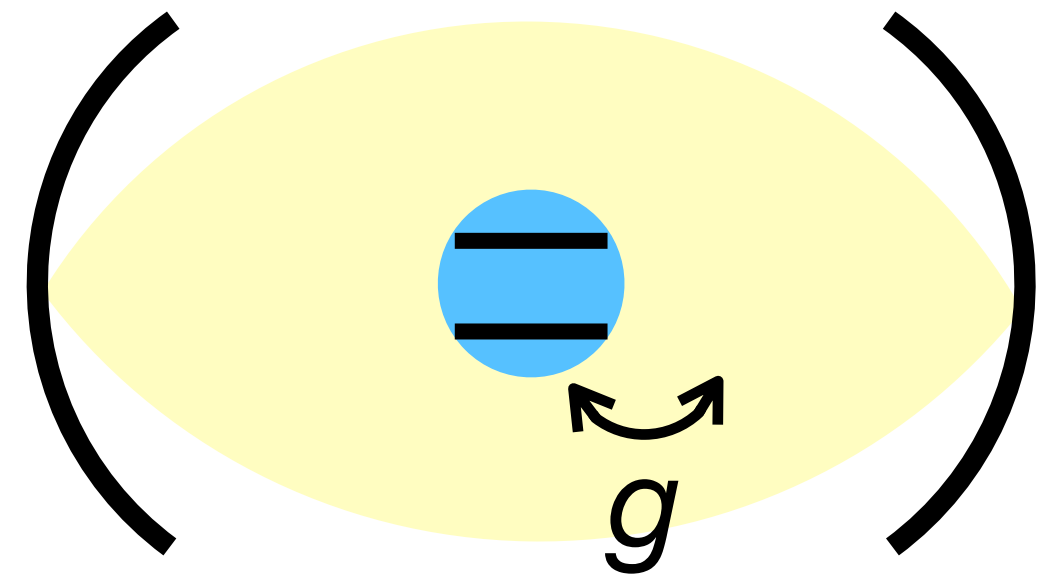


# Quantum Optics



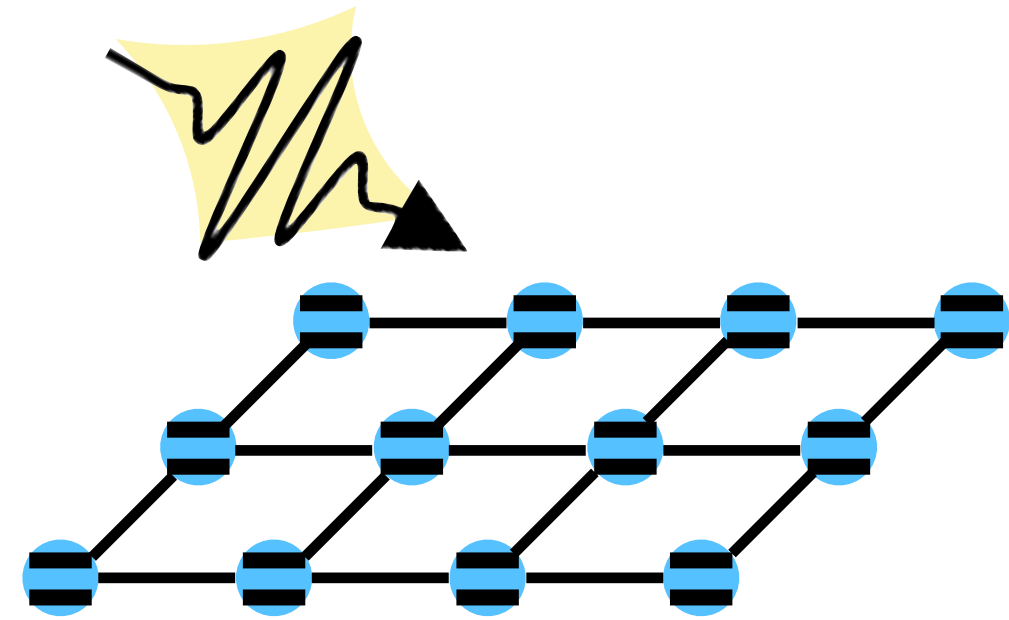
simple matter and light  
treated on the same  
(quantum) footing

## Quantum Optics



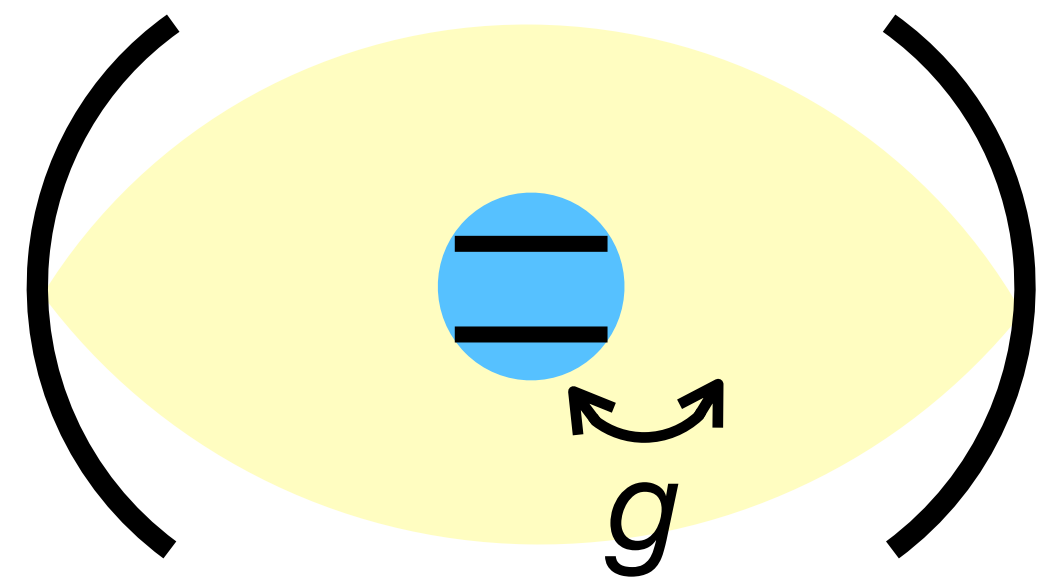
simple matter and light  
treated on the same  
(quantum) footing

## Condensed Matter



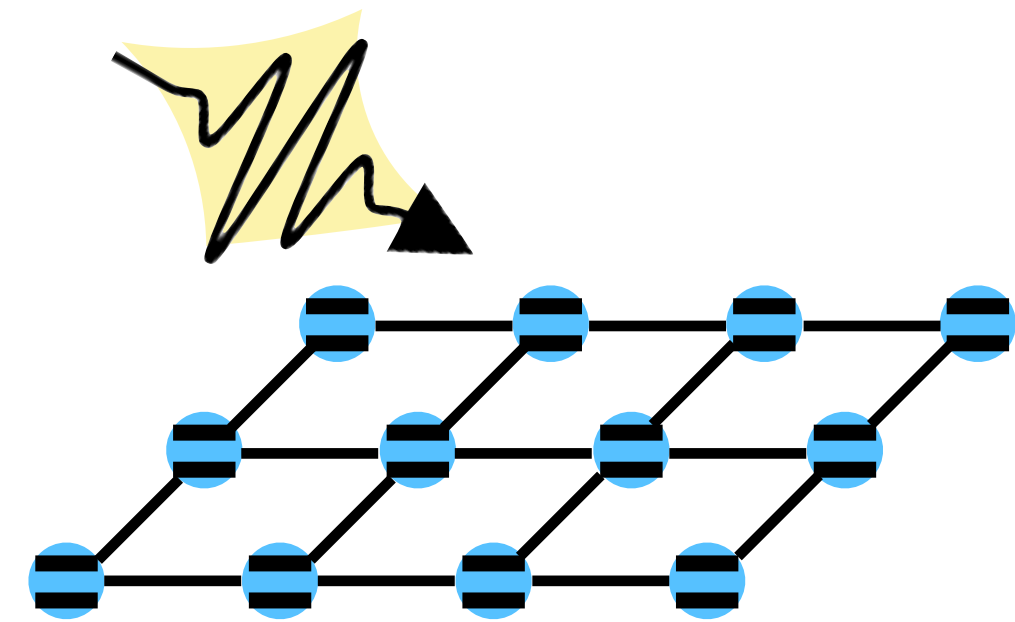
matter + classical light  
(as driving)

## Quantum Optics



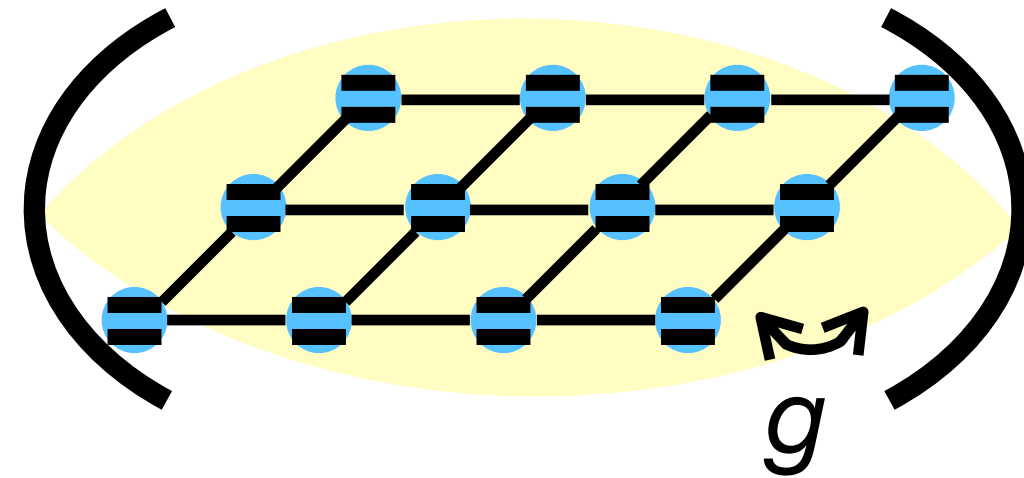
simple matter and light treated on the same (quantum) footing

## Condensed Matter



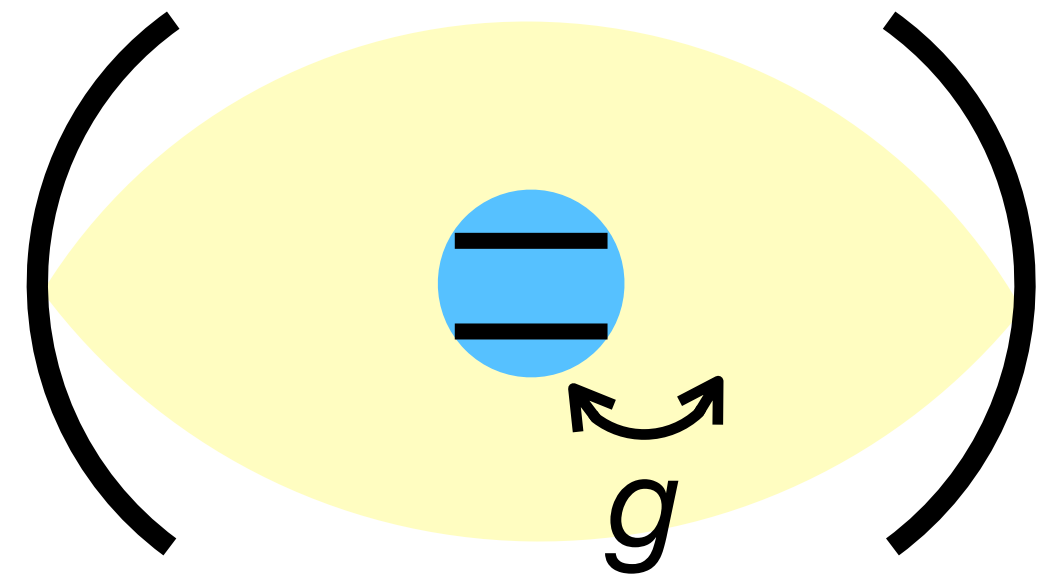
matter + classical light (as driving)

## CQED materials



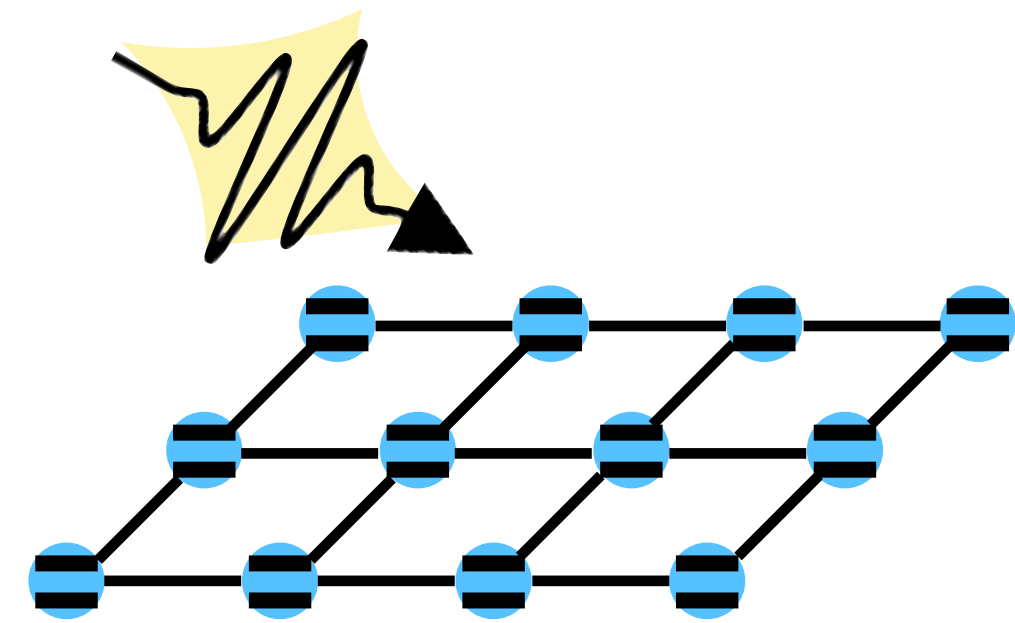
q-matter and q-light. Matter and light treated on the same footing

## Quantum Optics



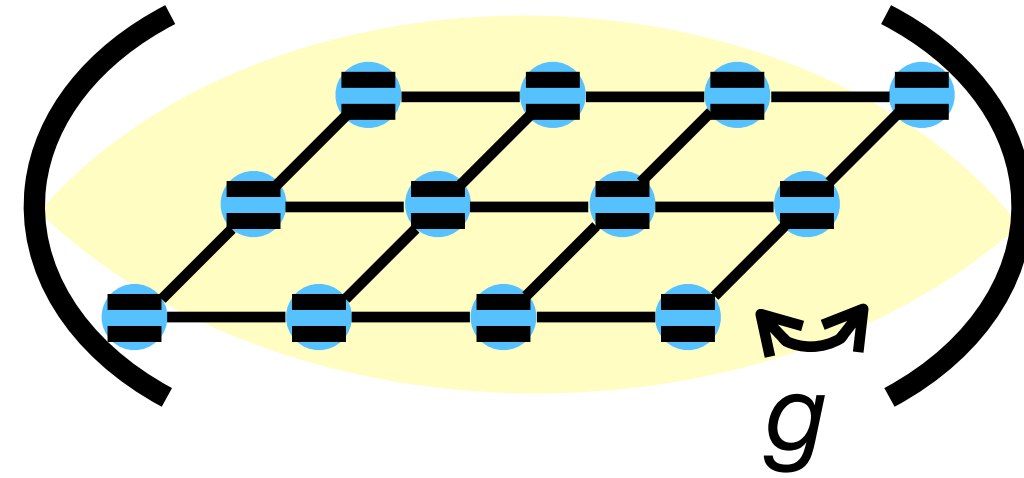
simple matter and light treated on the same (quantum) footing

## Condensed Matter



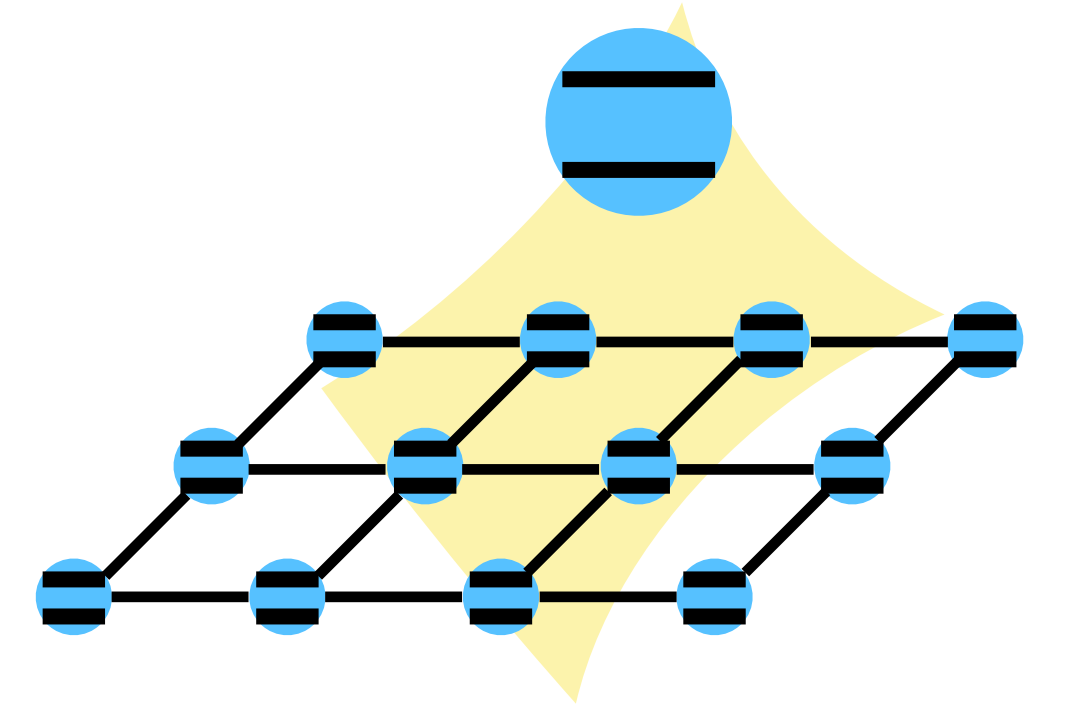
matter + classical light (as driving)

## CQED materials



q-matter and q-light. Matter and light treated on the same footing

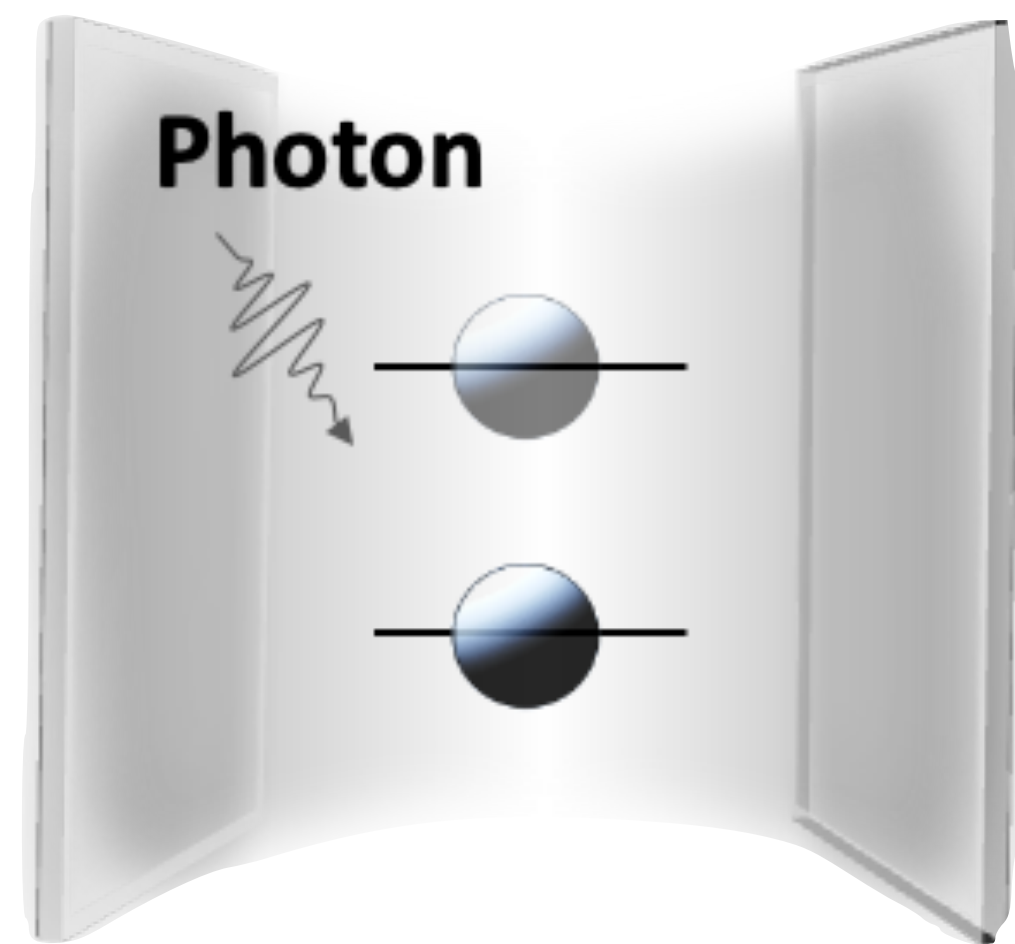
## materials as cavities



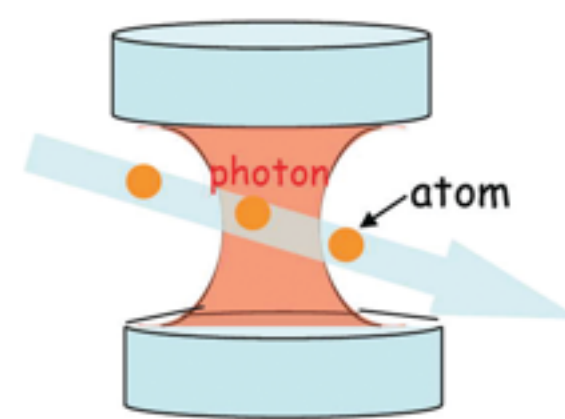
q-matter (excitations) → e.g. spin waves (magnons) → cavities :

spin-magnon coupling

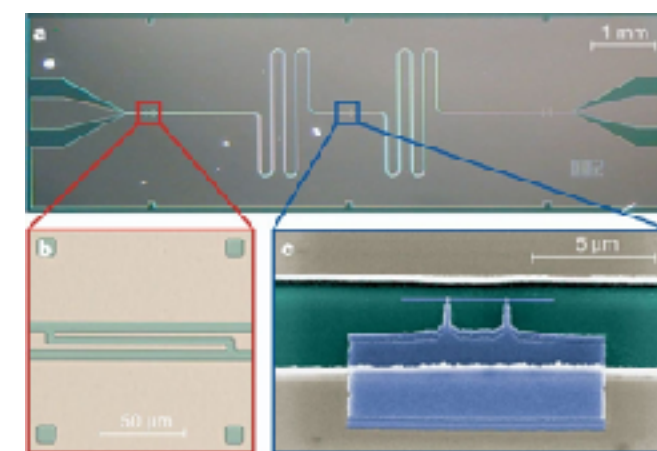
# Cavity QED



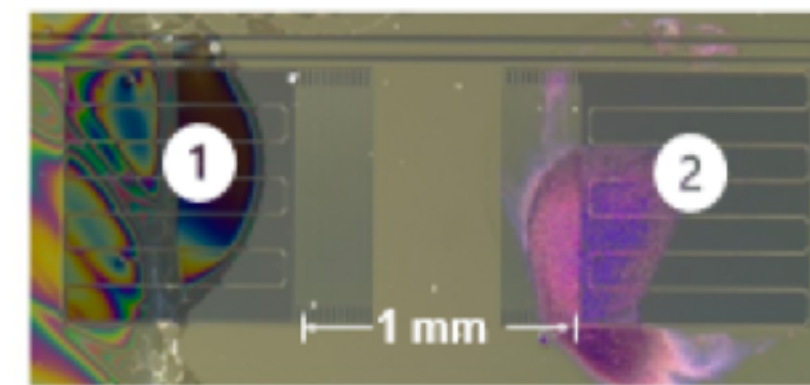
- Fundamental: light-matter states (polaritons), quantum control of matter, cavity modify phases of matter
- Applications: q-information, q-sensing and metrology
- photonics: single photon emitters, non linear optics



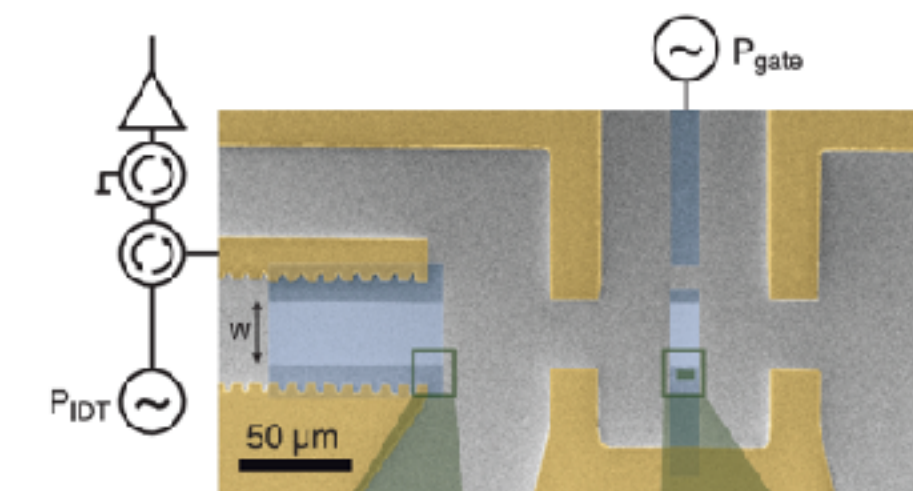
Brune et al 1996



Wallraff et al 2004

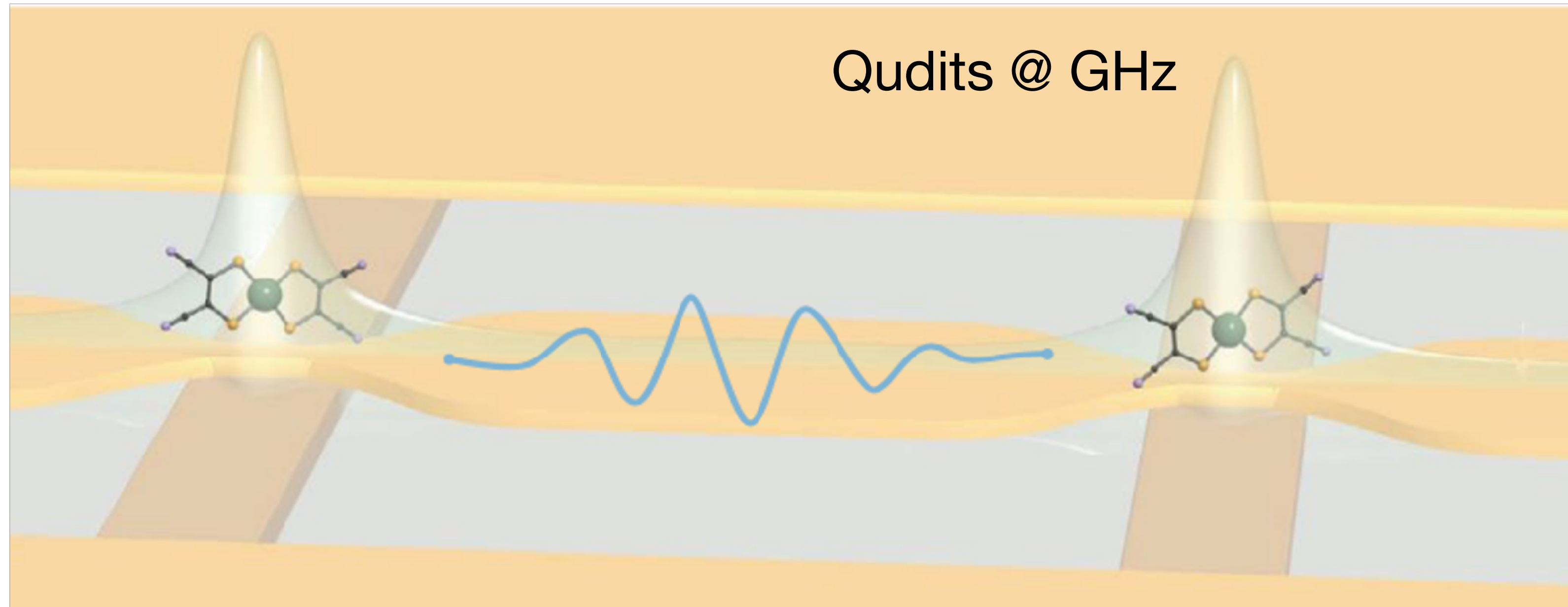


del Río et al 2025



Gustafsson et al 2014

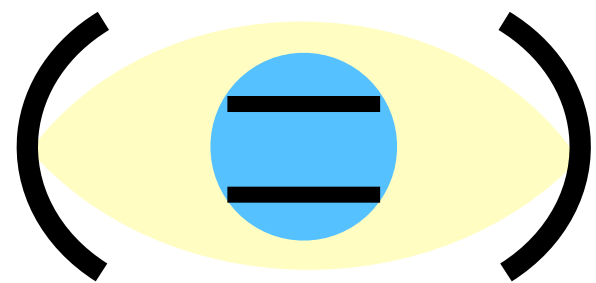
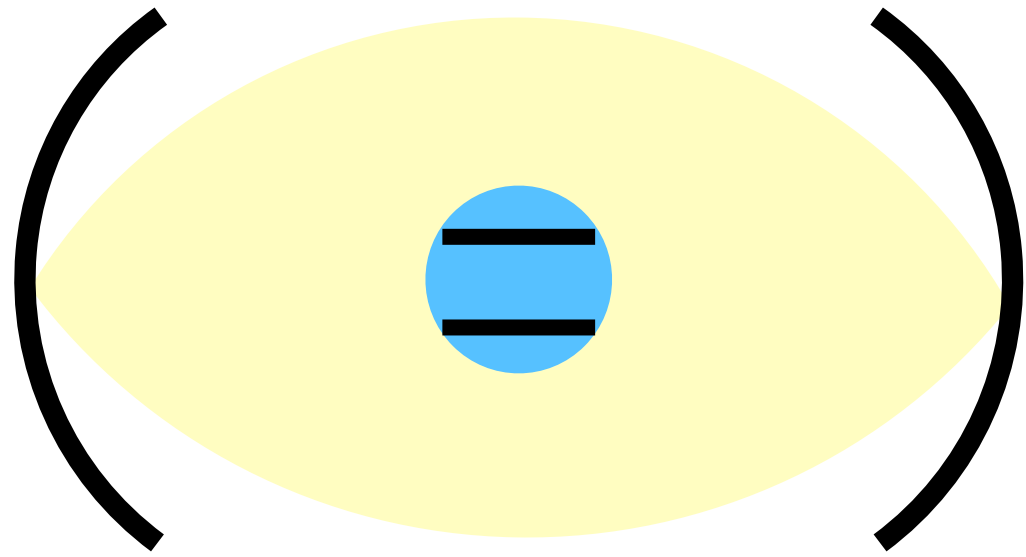
# wiring molecular qubits



- Sizes mismatch: superconducting circuits “too large” ( photon mode volume)

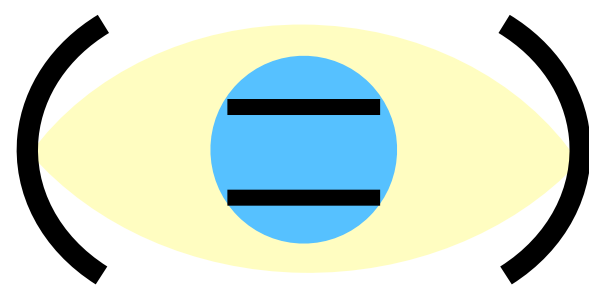
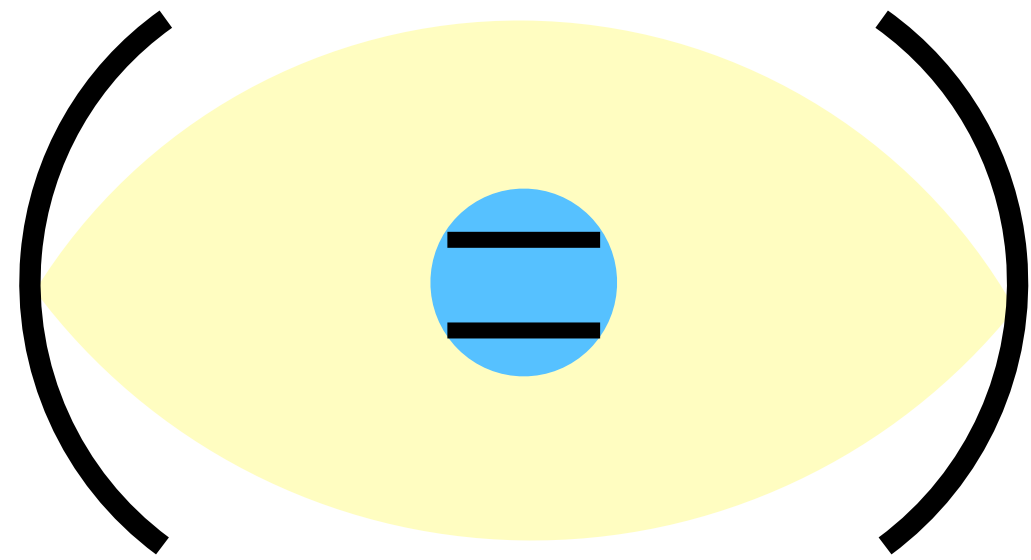
- Magnetic Coupling: 
$$\frac{g_{\text{Zeeman}}}{g_{\text{electric dipole}}} \sim \left( \frac{\mu B_0}{d E_0} \right)^2 = \left( \frac{\hbar}{2m_e a_0 c} \right)^2 \sim 10^{-5}$$

# Mode volume

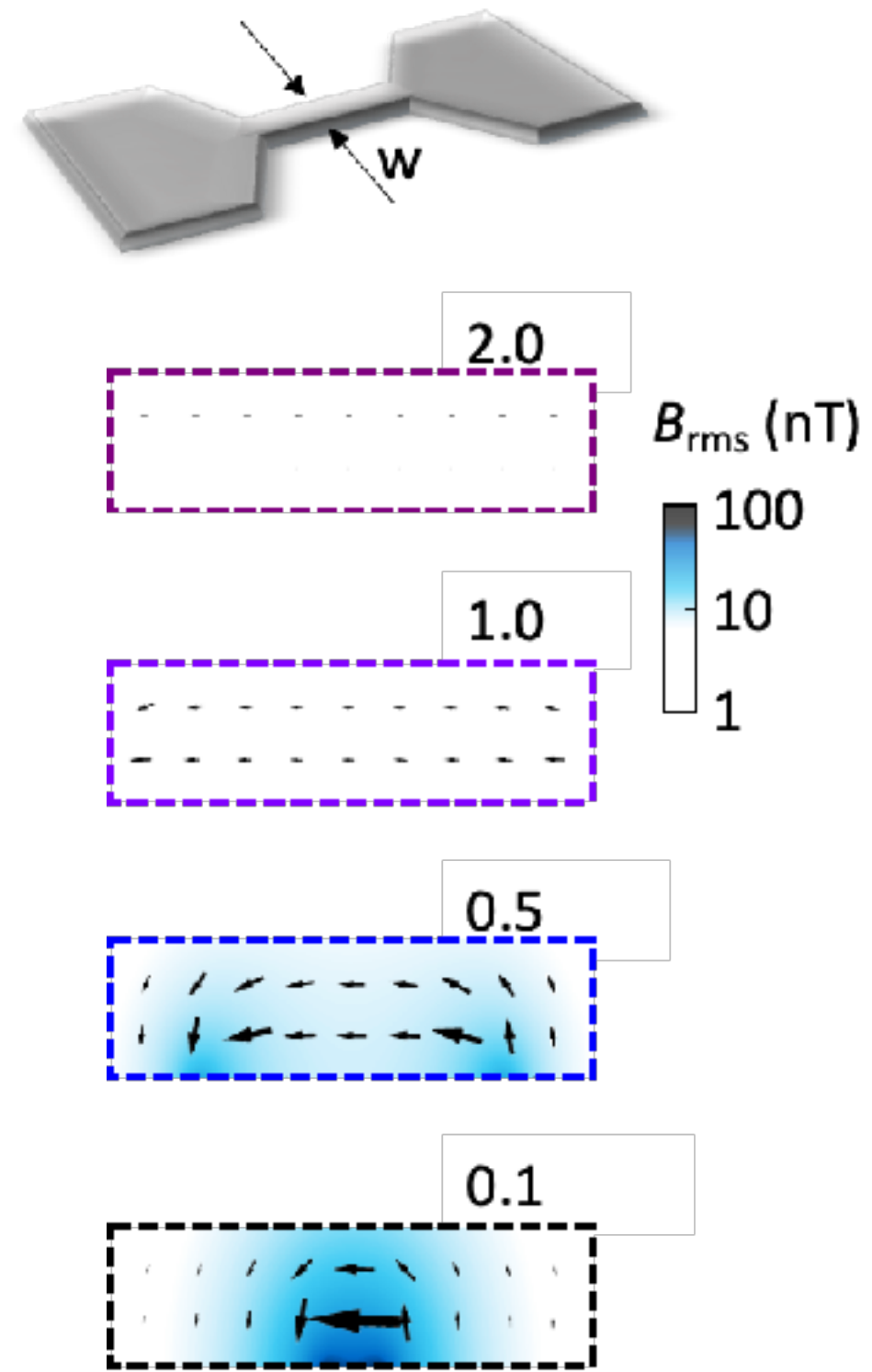


enlarge dipole, reduce  
mode volume

# Mode volume

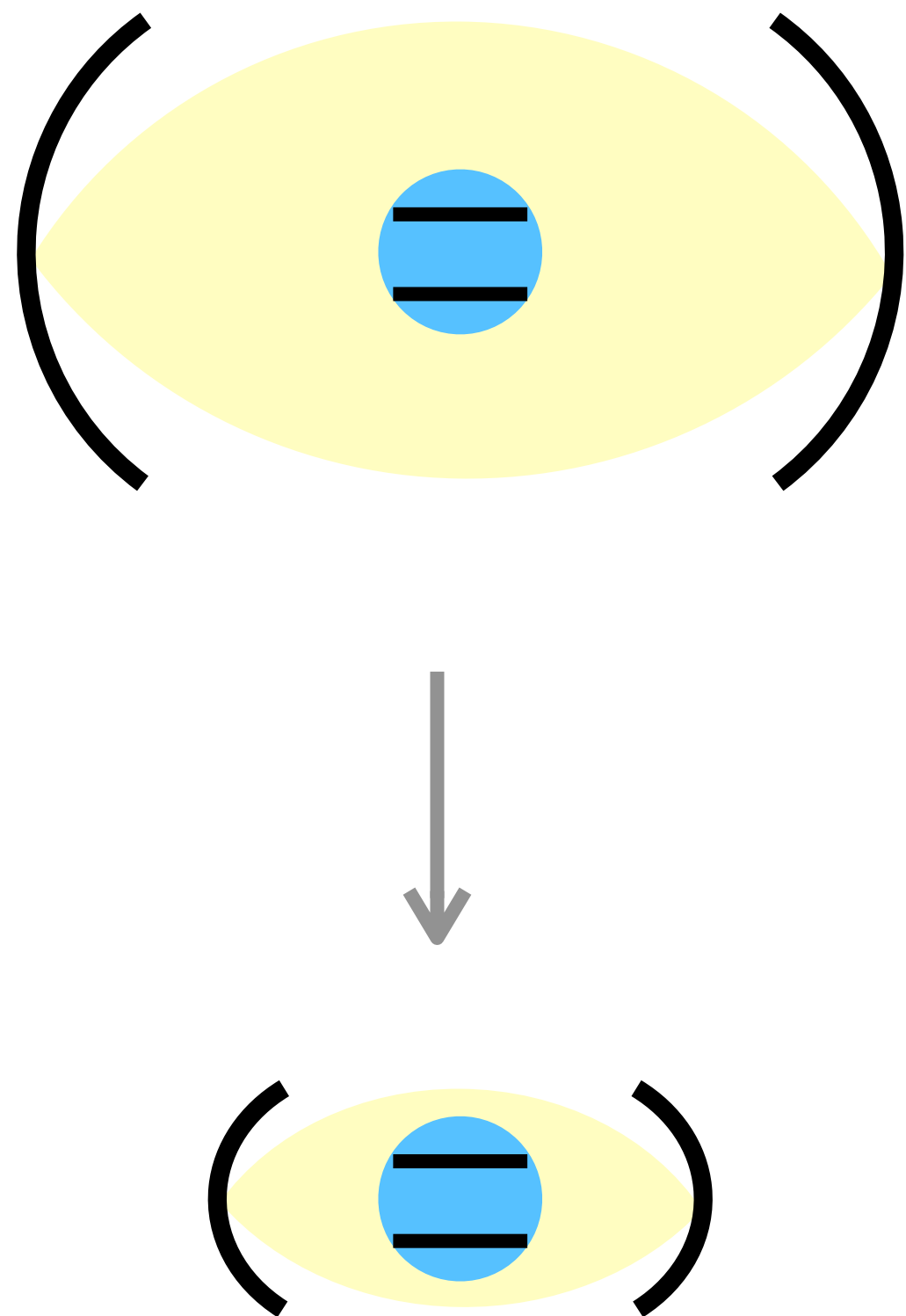


enlarge dipole, reduce mode volume

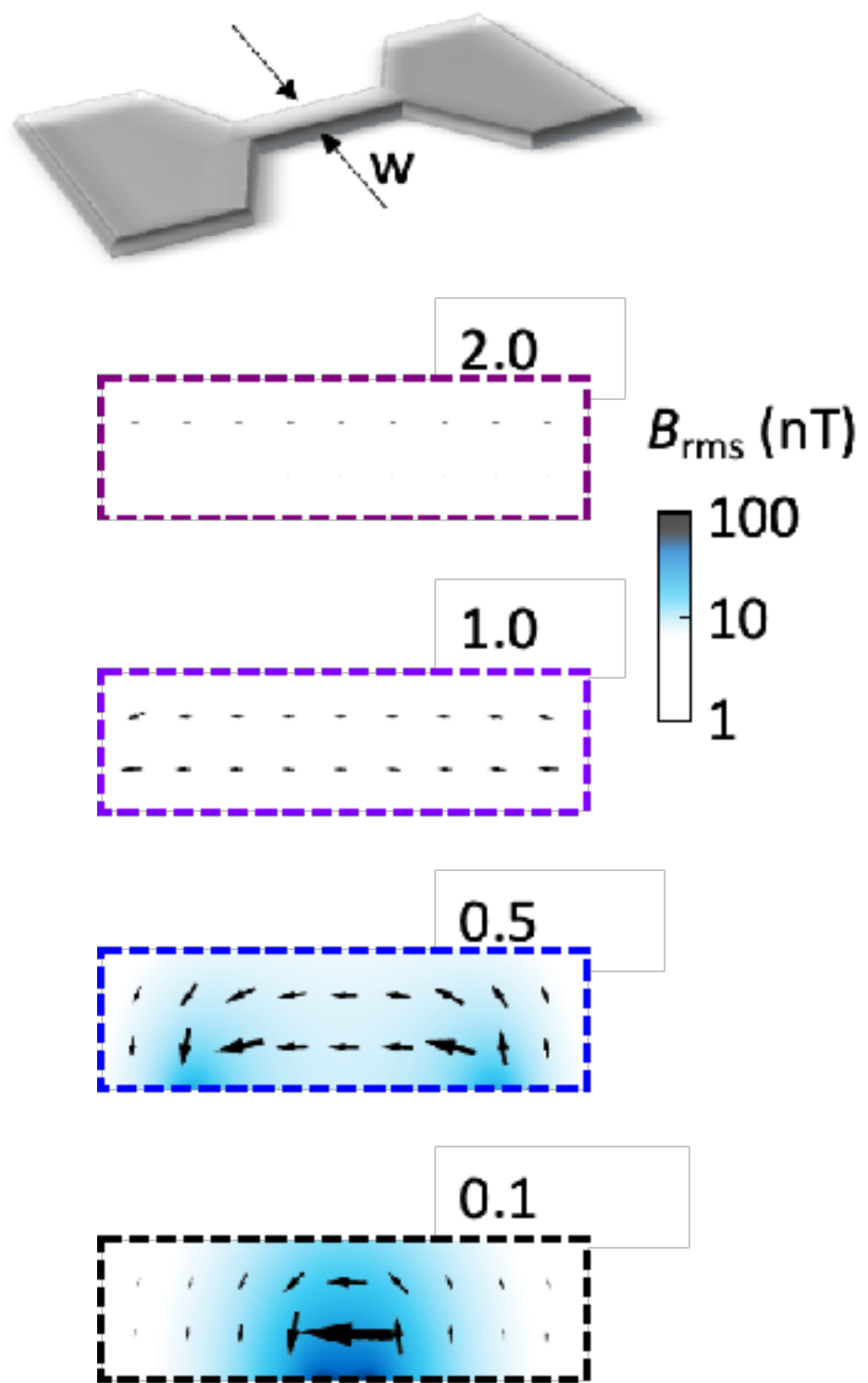


Nanoconstrictions: field enhancement

# Mode volume

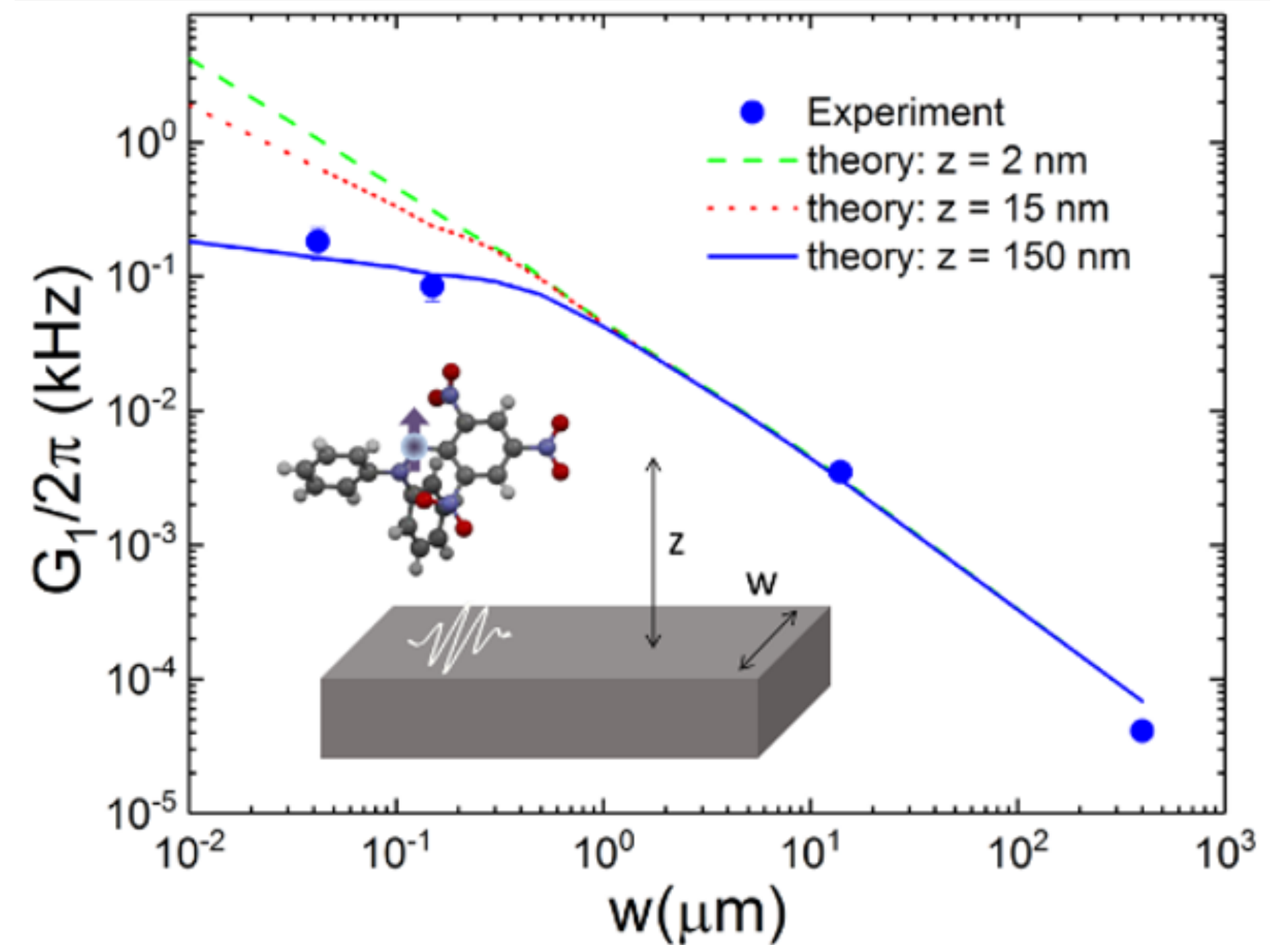


enlarge dipole, reduce mode volume

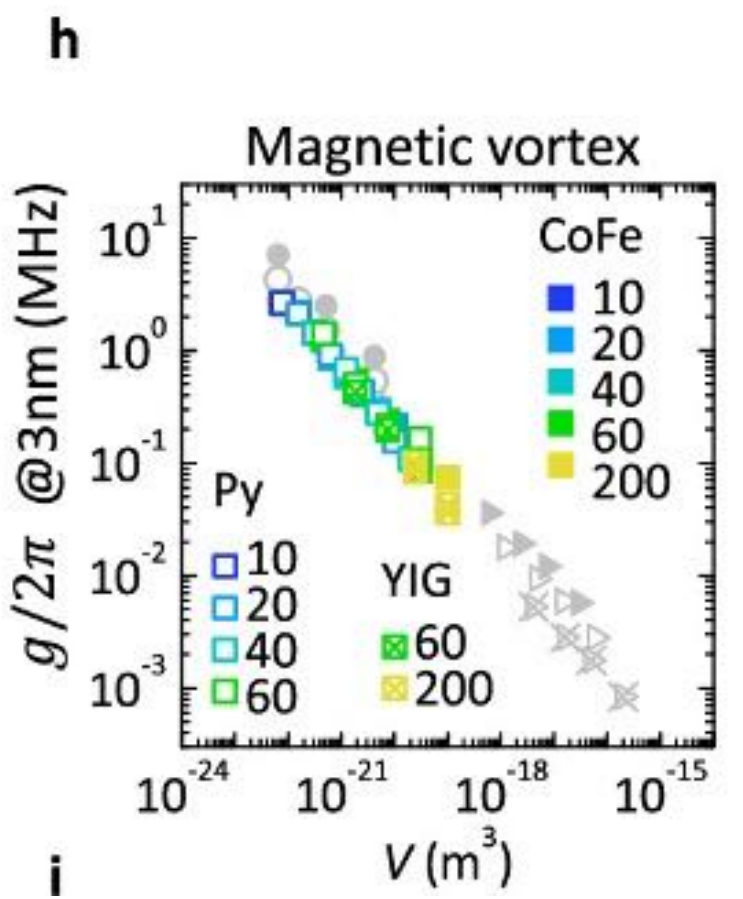
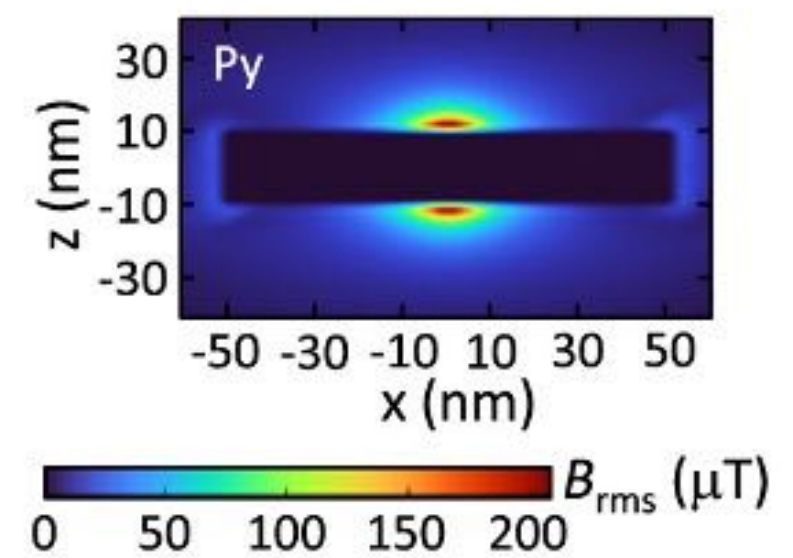
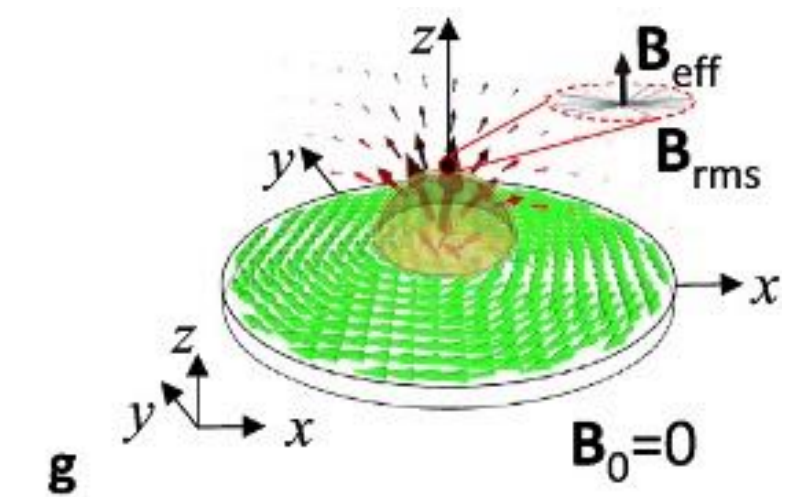
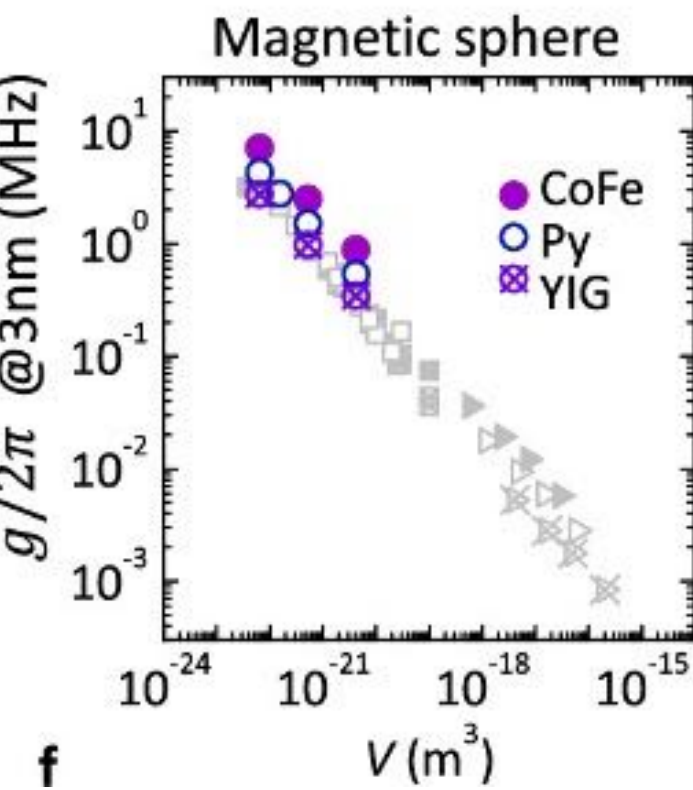
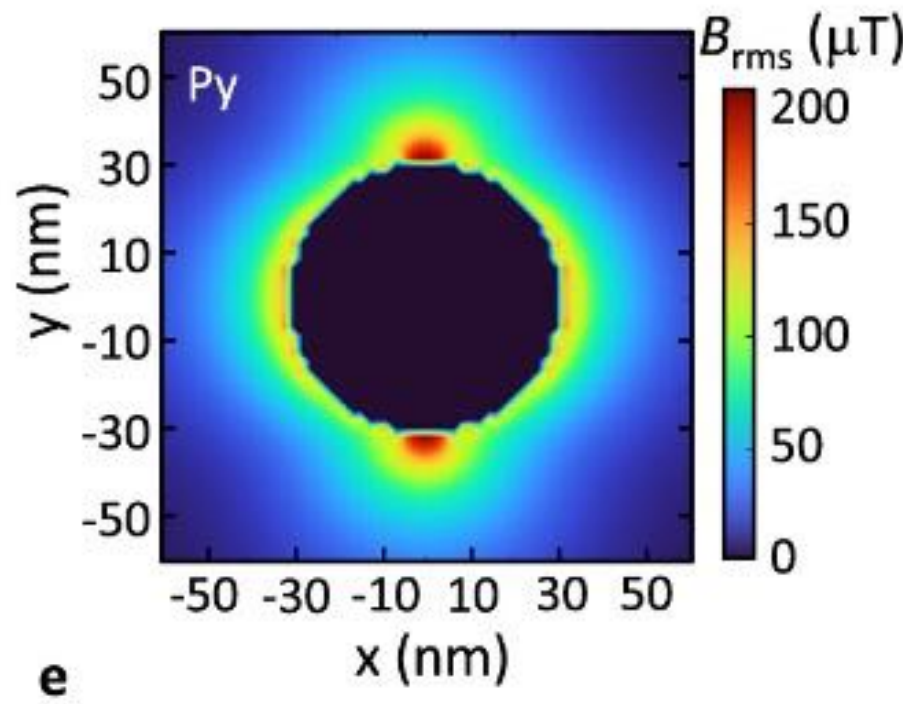
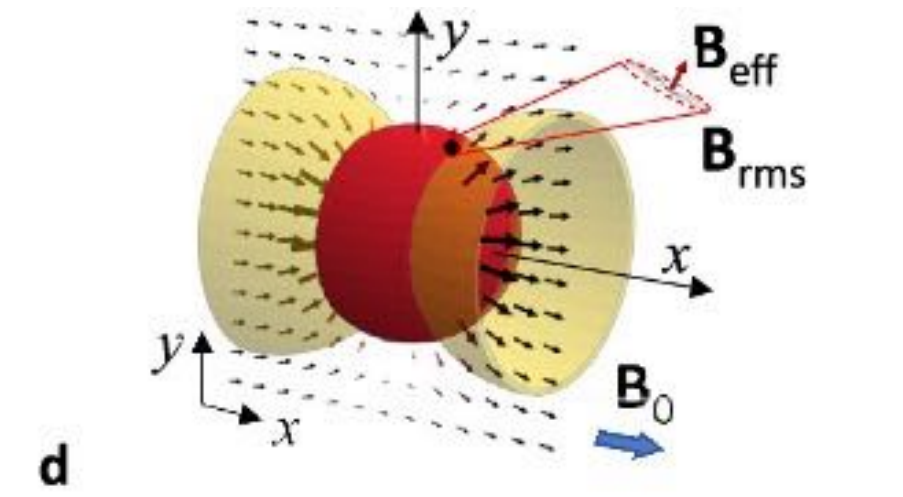
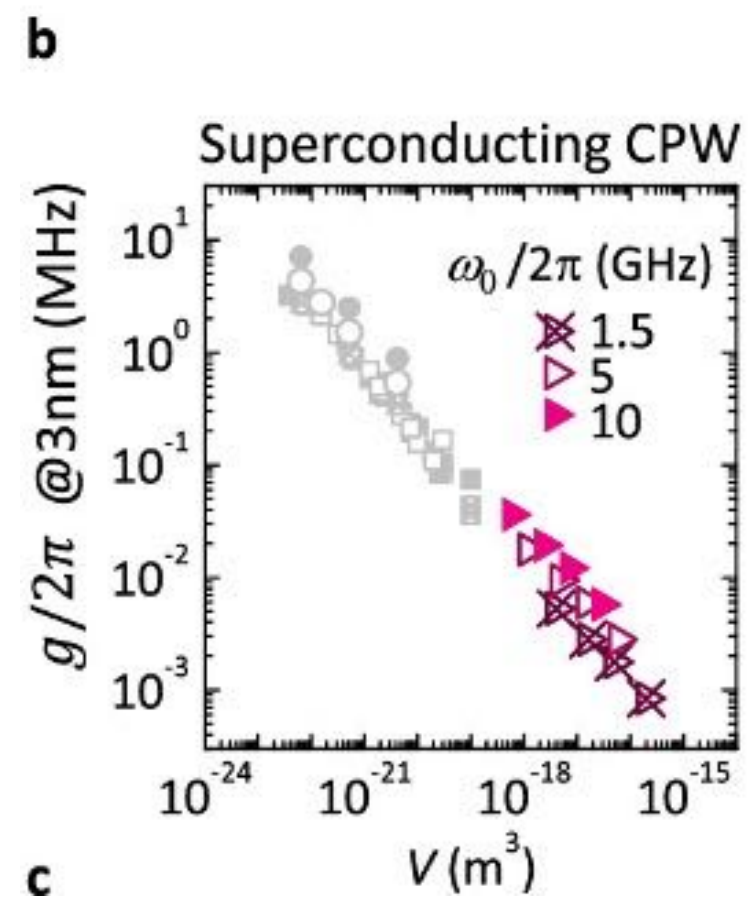
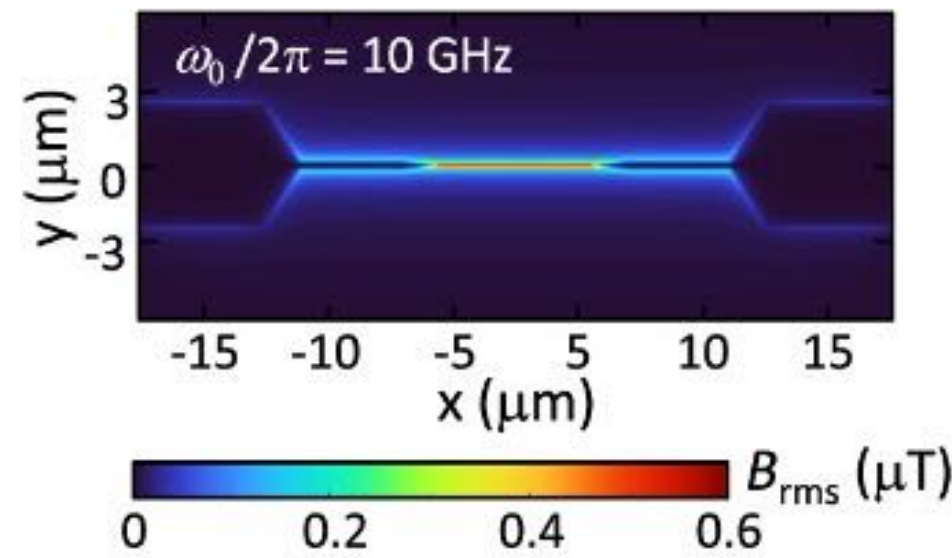
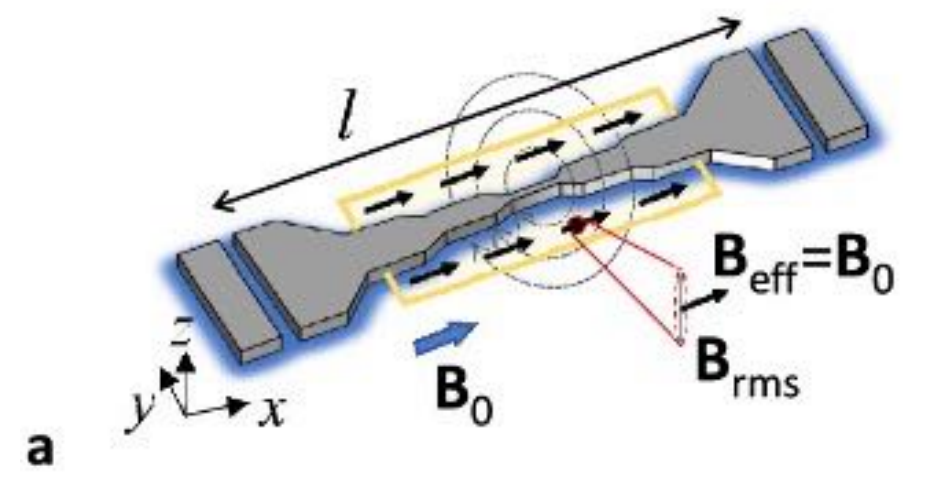


Nanoconstrictions: field enhancement

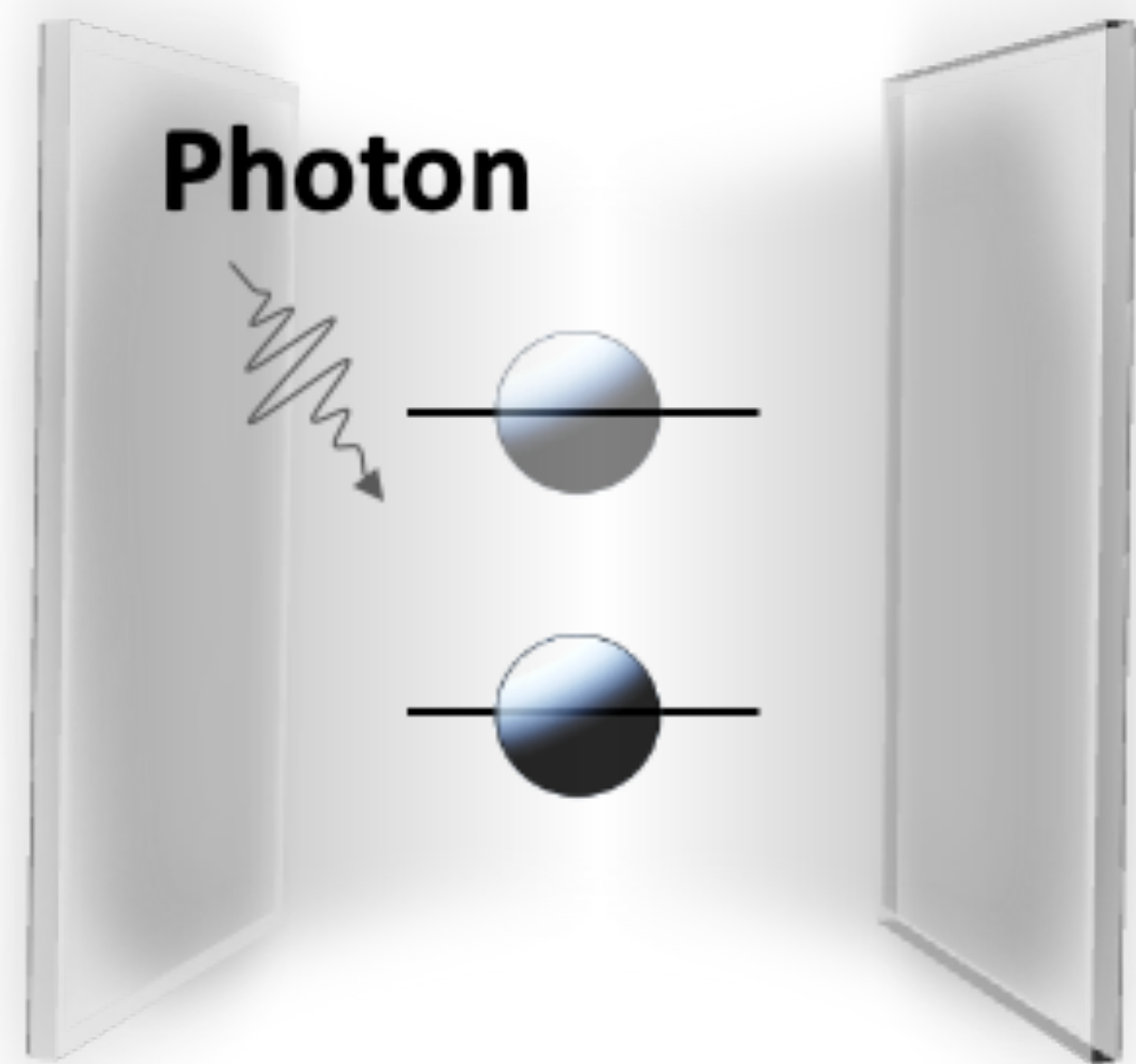
$$g \propto b_{\text{rms}} = \sqrt{\frac{\mu_0 \hbar \omega_r}{2V}} \sim \frac{\omega_r}{w}$$



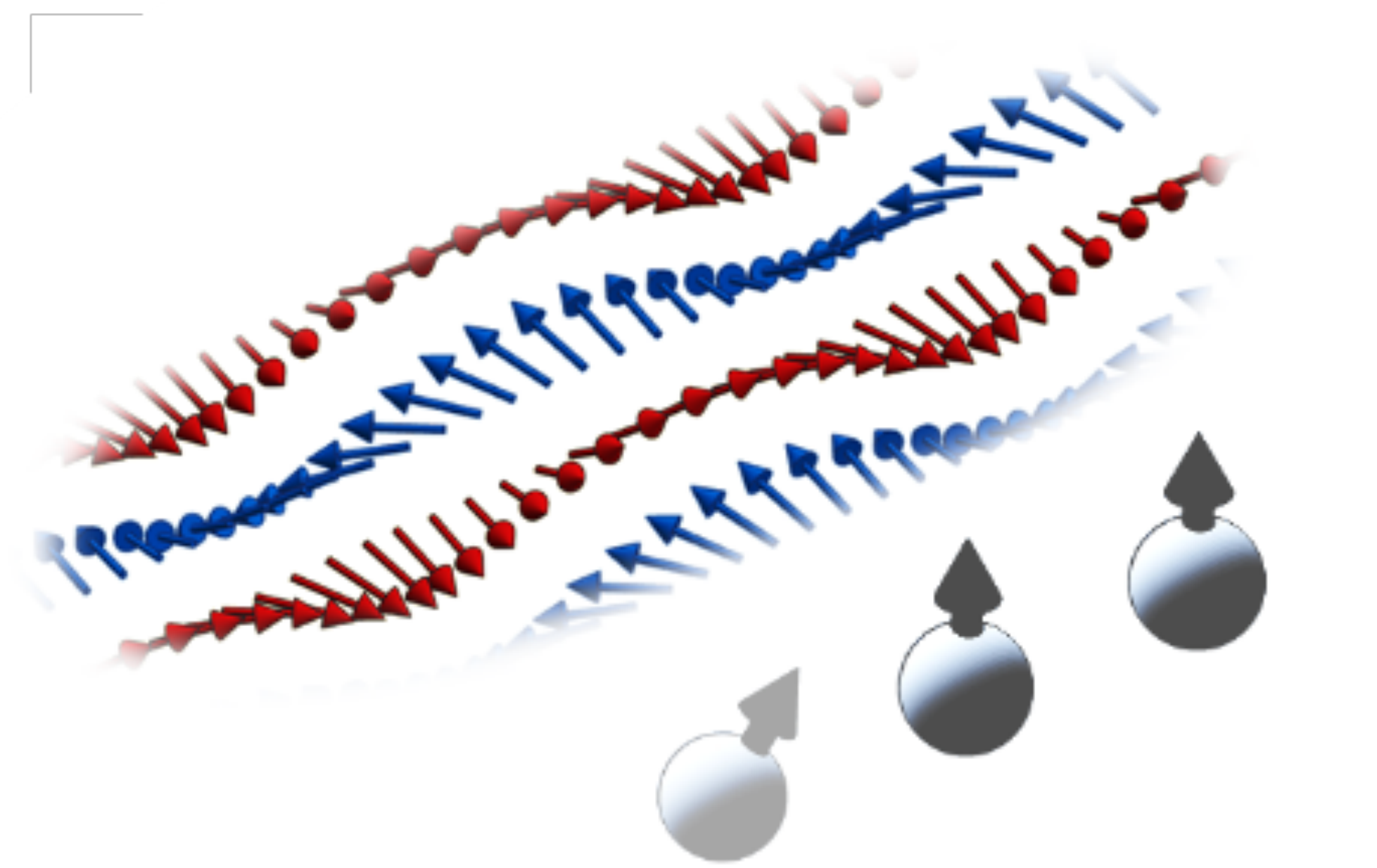
# Towards Microwave Magnonic Cavities



## Cavity-QED

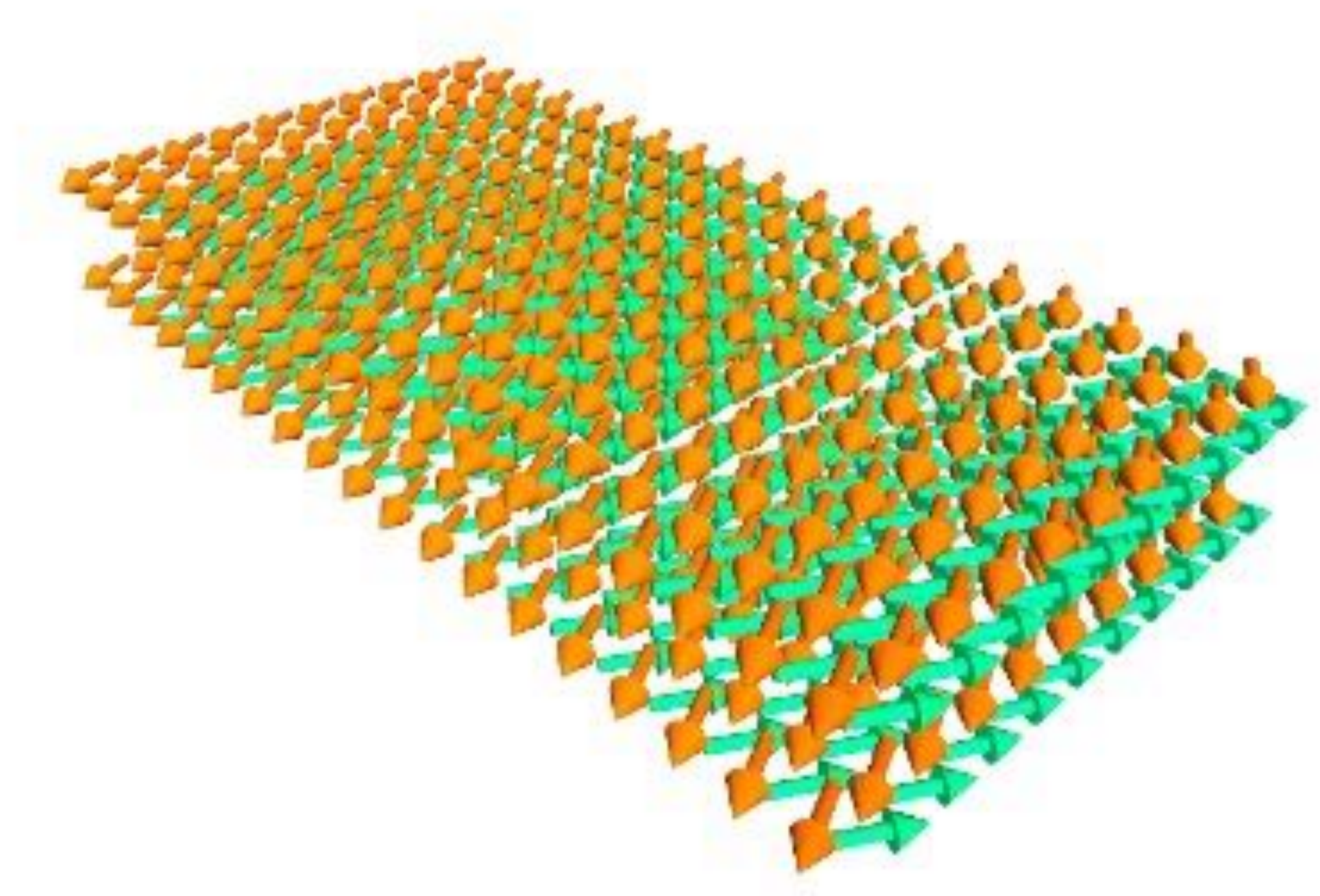


## vdW-QED



# AFM Spintronics

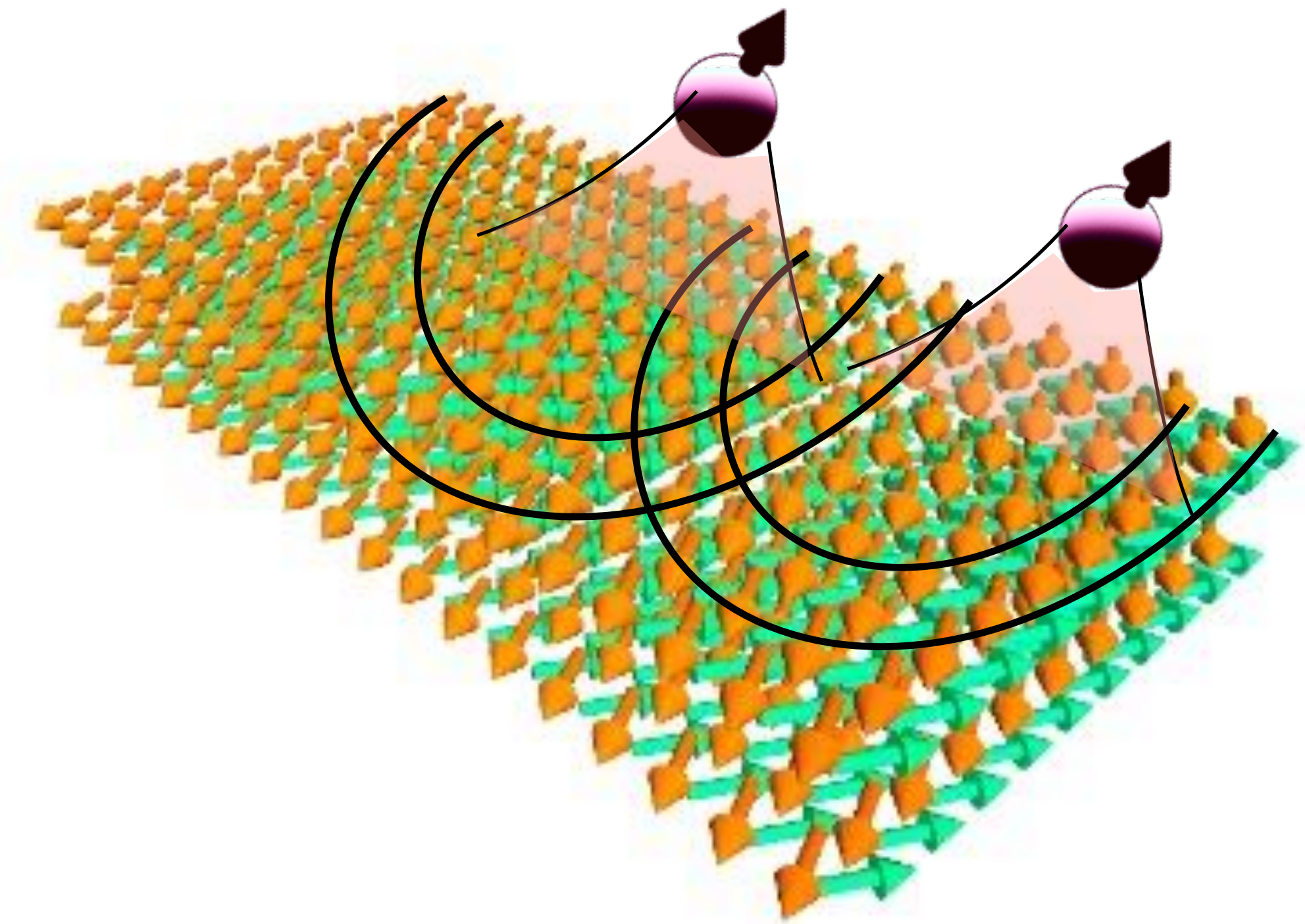
- Spintronics: Control & excitation spin waves (info carriers)
- AFM: low damping, no stray magnetic fields
- VdW: THz  $\rightarrow$  GHz



Reviews (AFM spintronics): Baltz et al, Jungfleisch et al 2018  
Review (Q-magnonics): Yan et al 2022

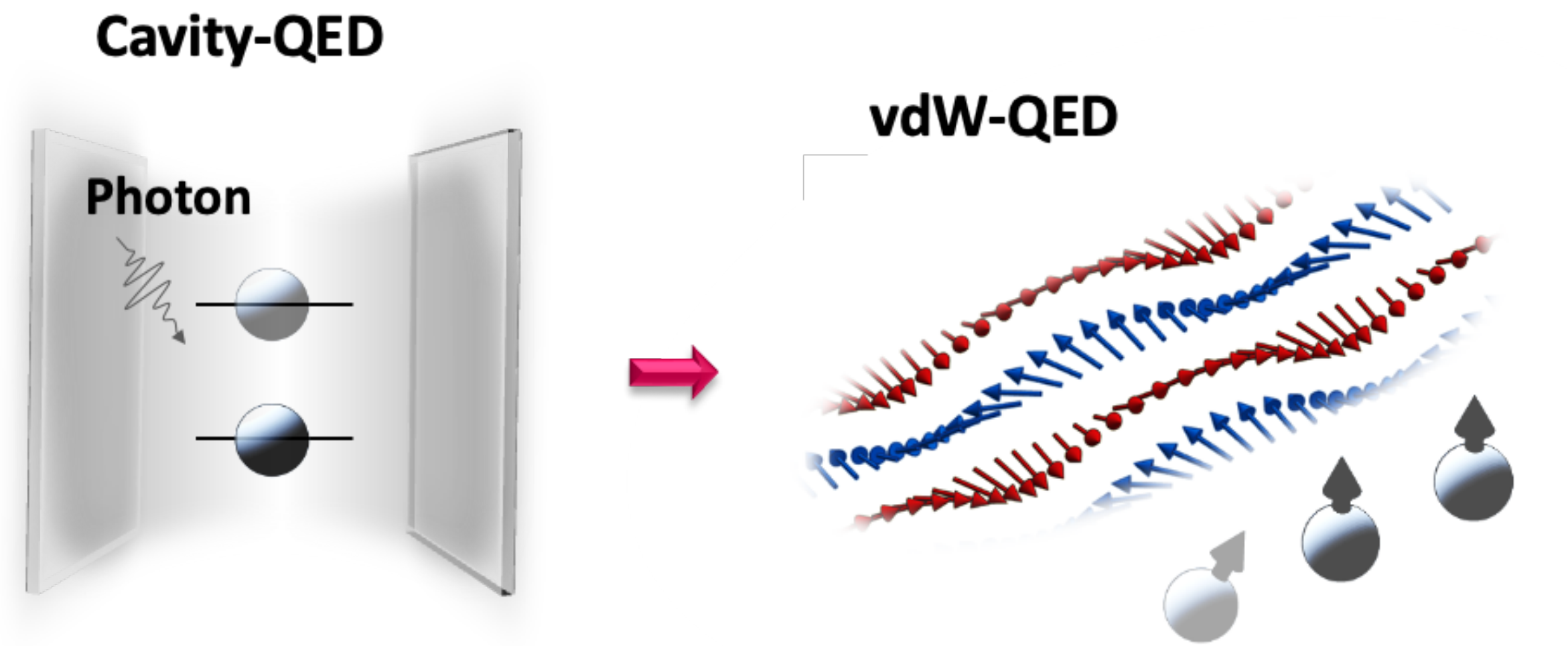
# AFM Spintronics

- Spintronics: Control & excitation spin waves (info carriers)
- AFM: low damping, no stray magnetic fields
- VdW: THz  $\rightarrow$  GHz
- Quantum Magnonics (hybrid systems)
- Quantum Spintronics: AFM (VdW + q-emitters)



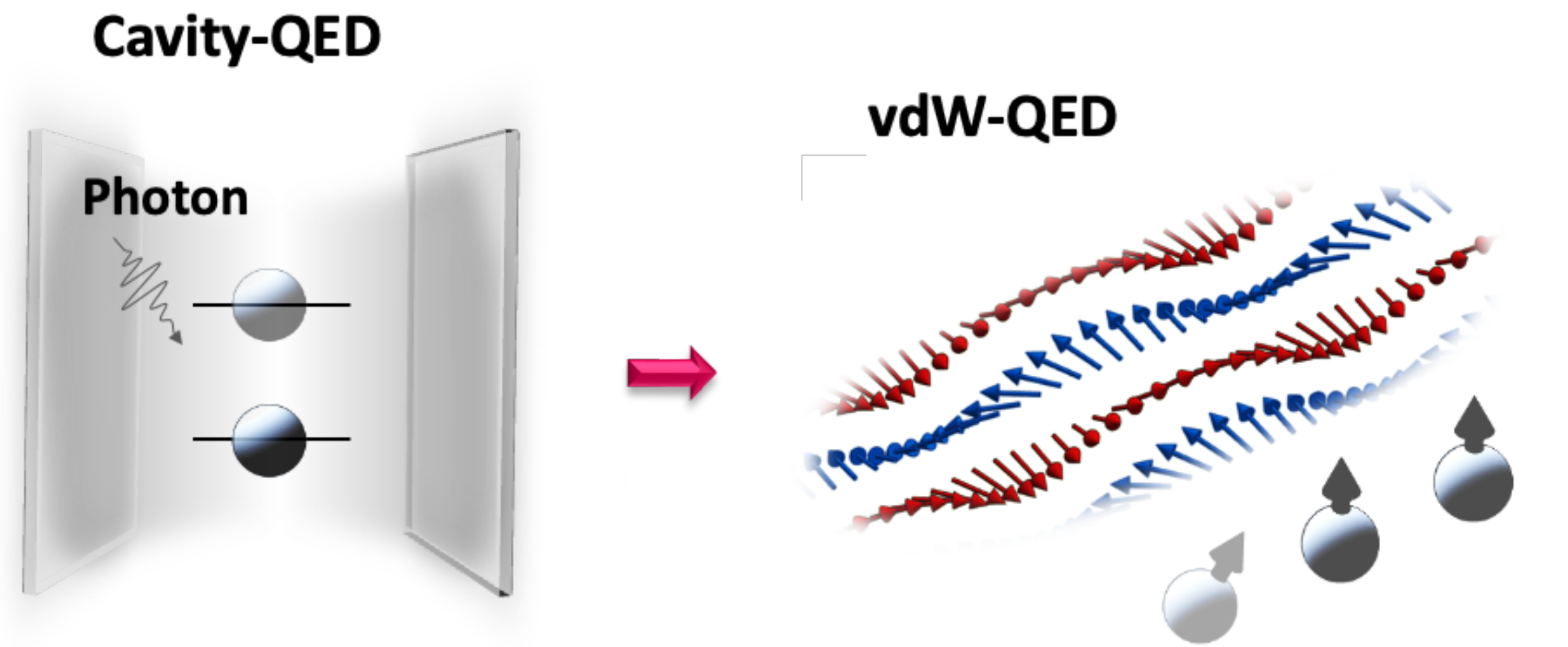
Reviews (AFM spintronics): Baltz et al, Jungfleisch et al 2018  
Review (Q-magnonics): Yan et al 2022

# Building vdW QED



➔ Why? Novel Physics: Chiral QED, stronger coupling, single magnon emission (q-spintronics)

# Building vdW QED



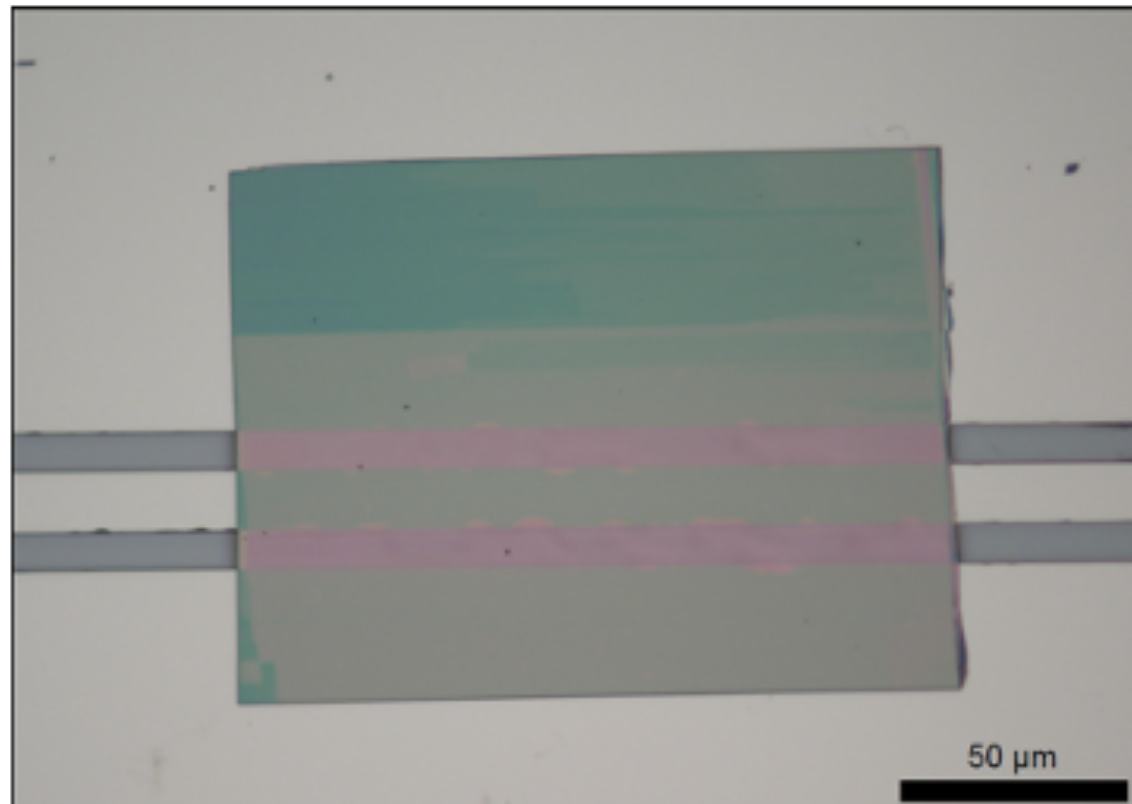
➔ Why? Novel Physics: **Chiral QED**, stronger coupling, single magnon emission (q-spintronics)

# VdW cavity

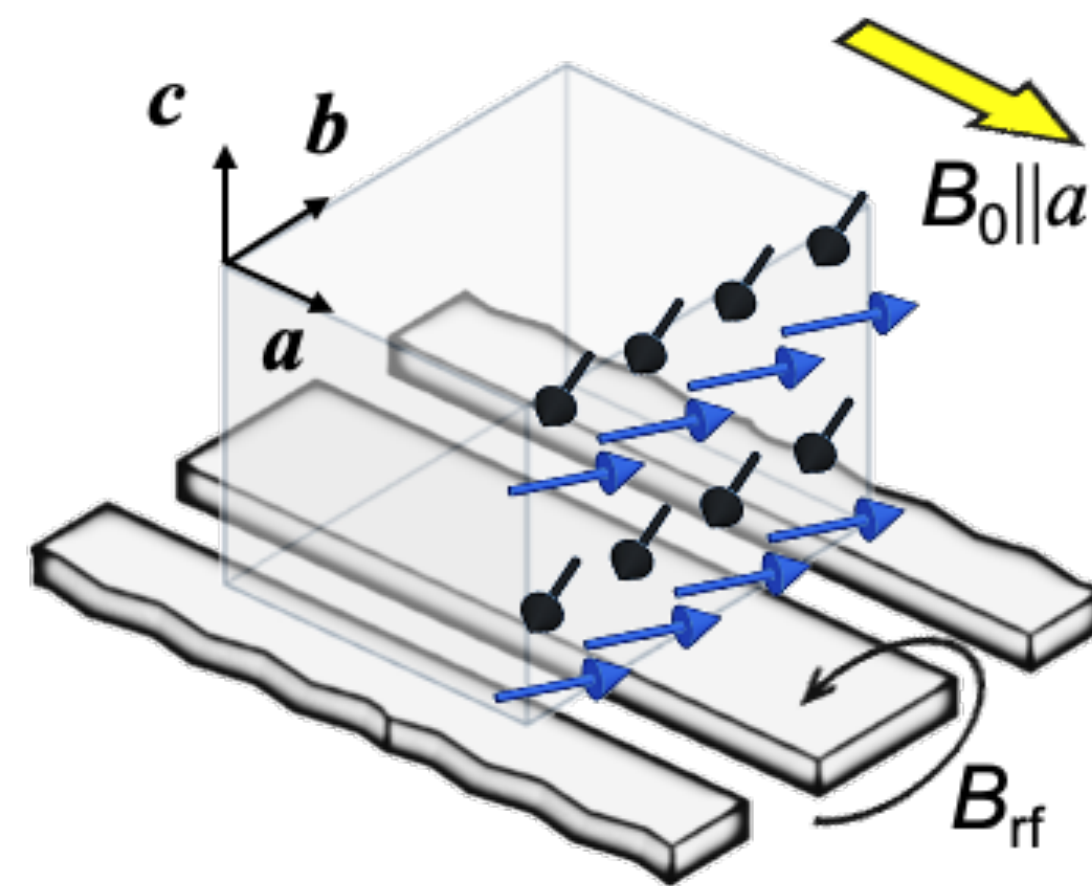
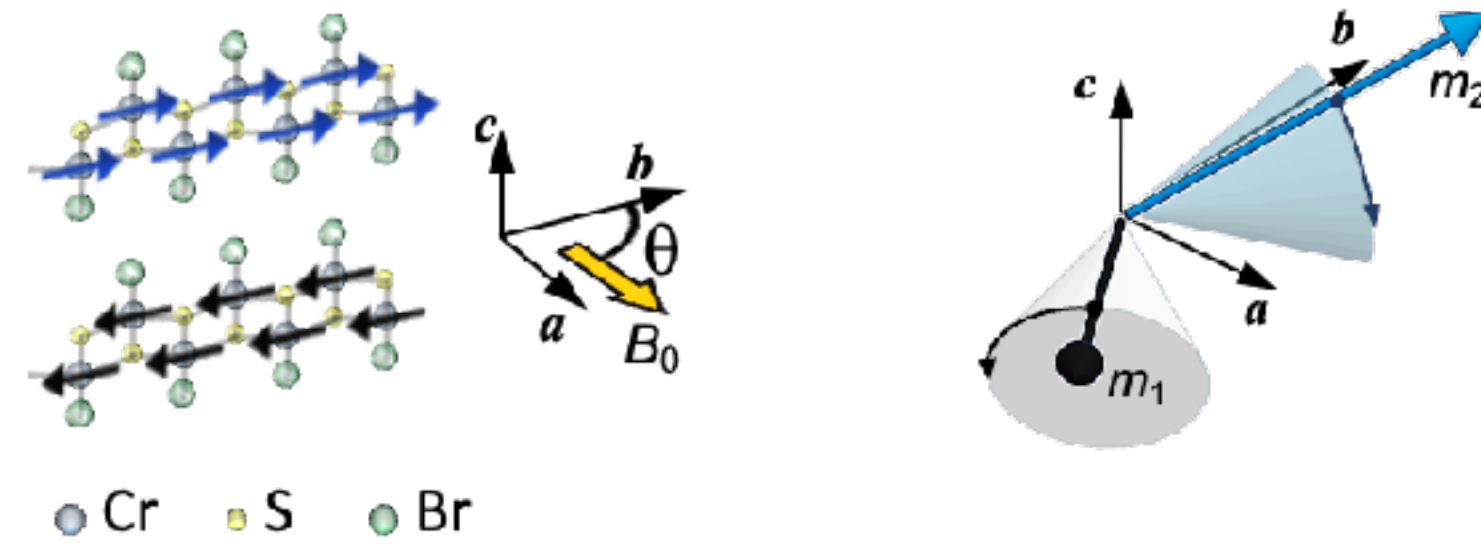
Bulk



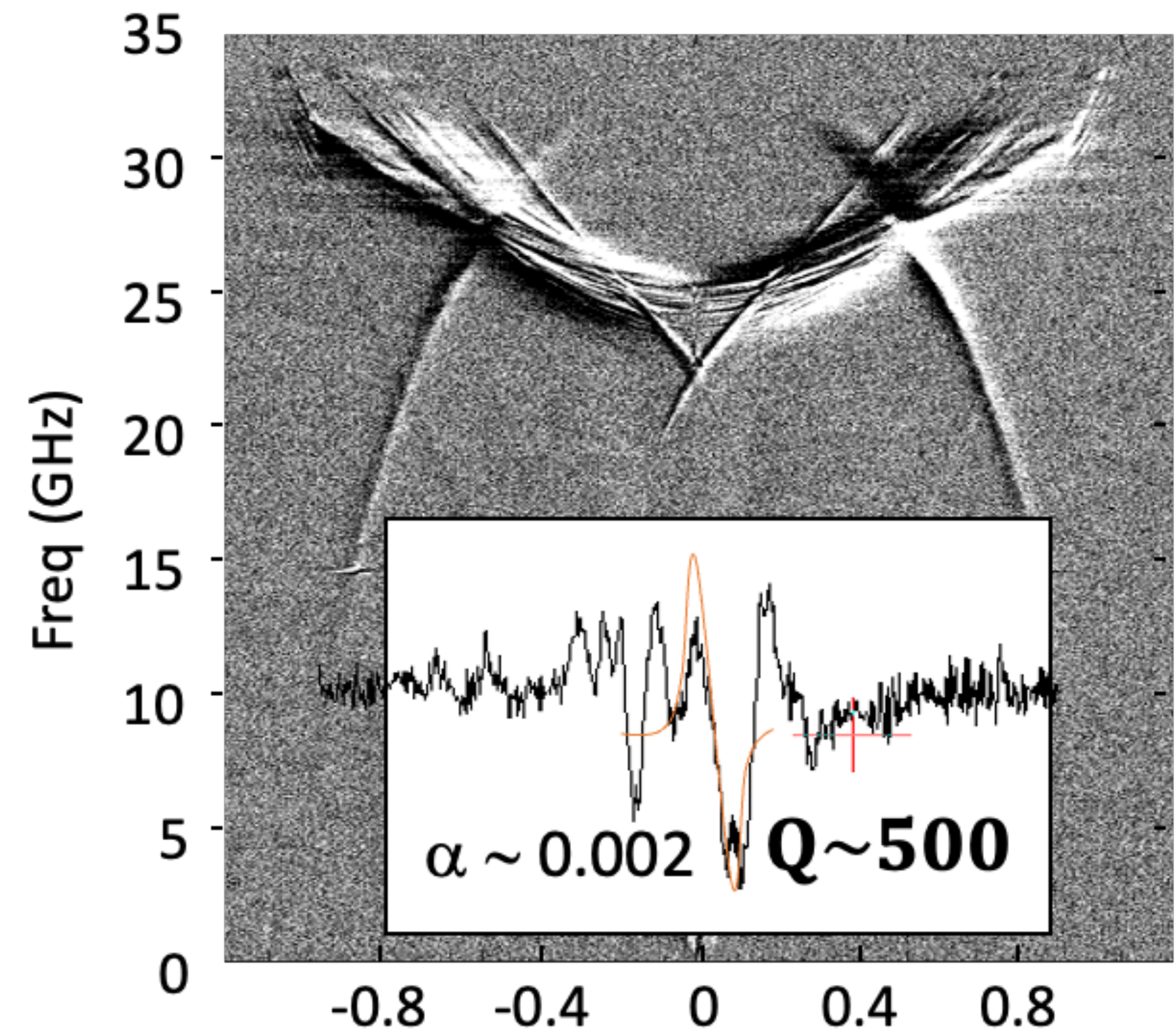
Flake



Device

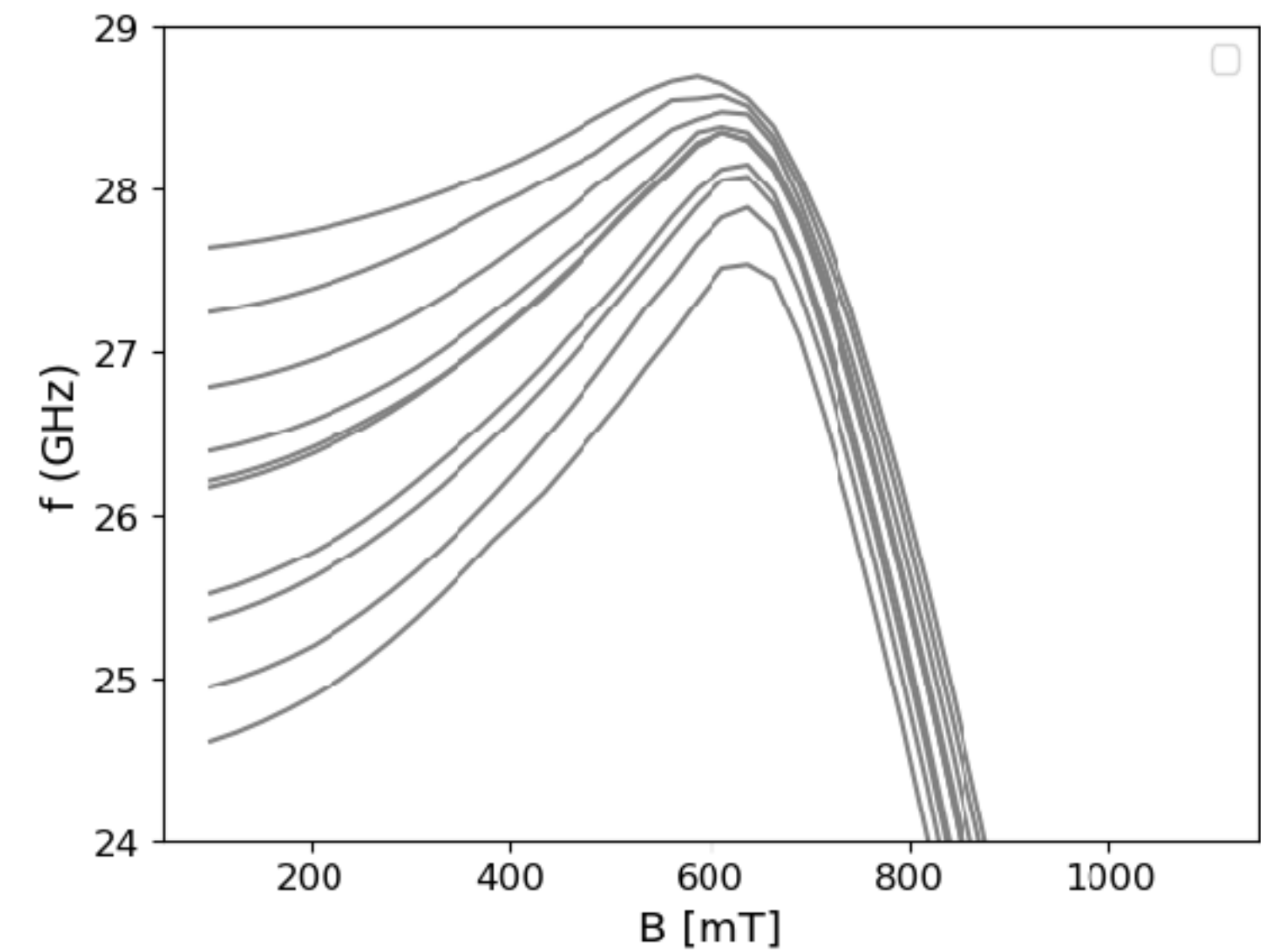
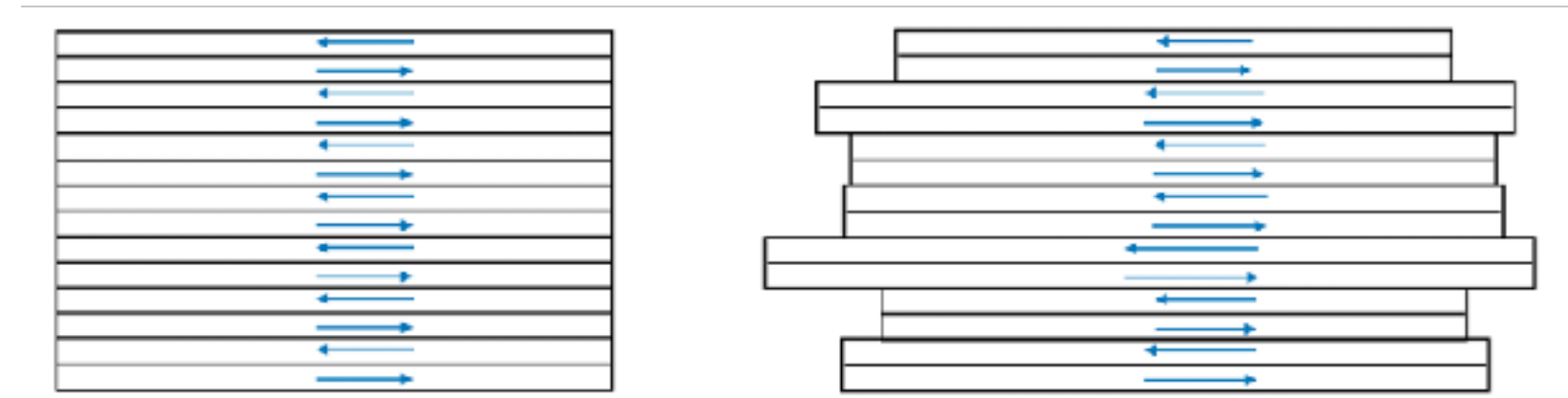
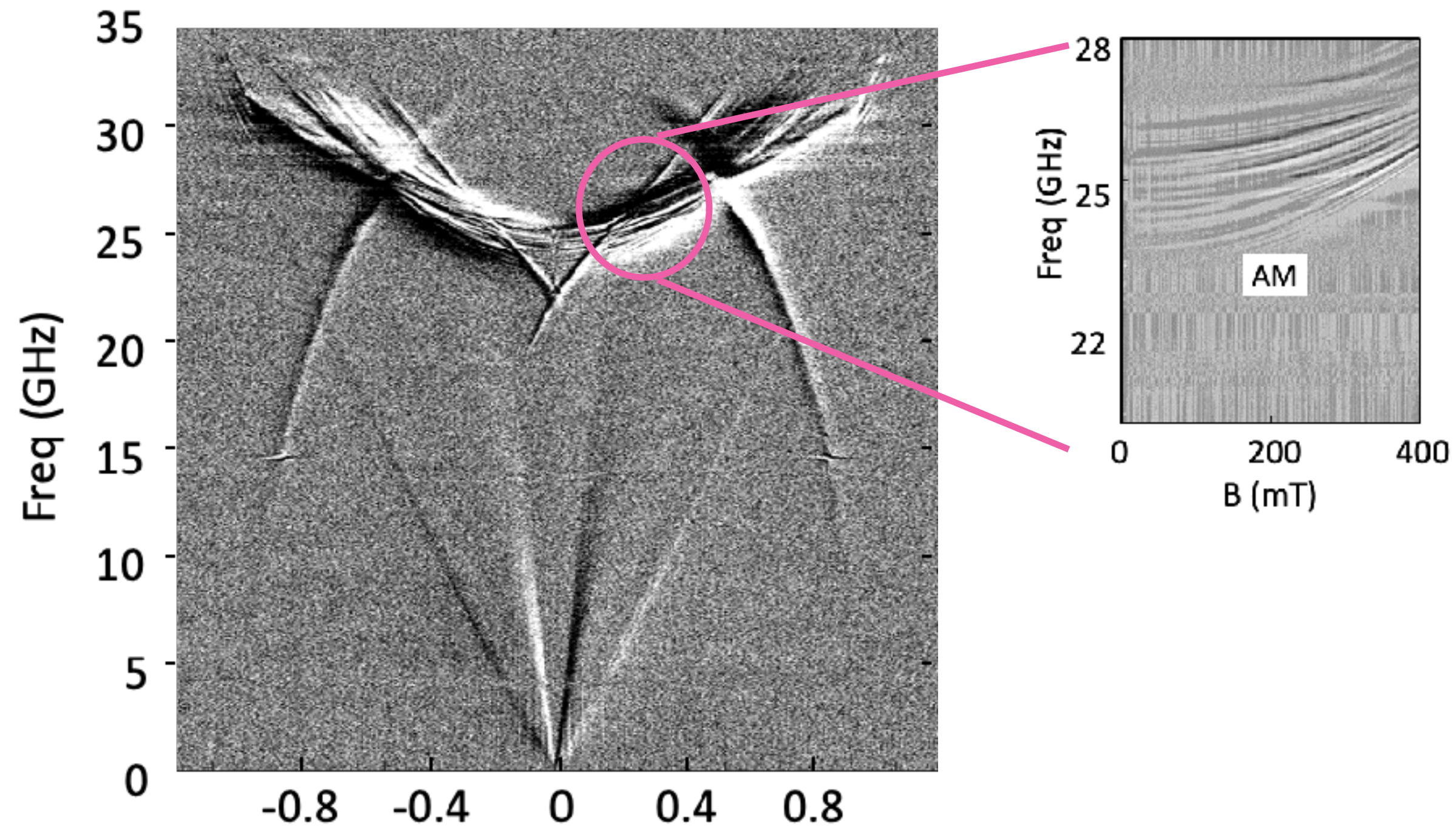


Magnons



Transmission exp.

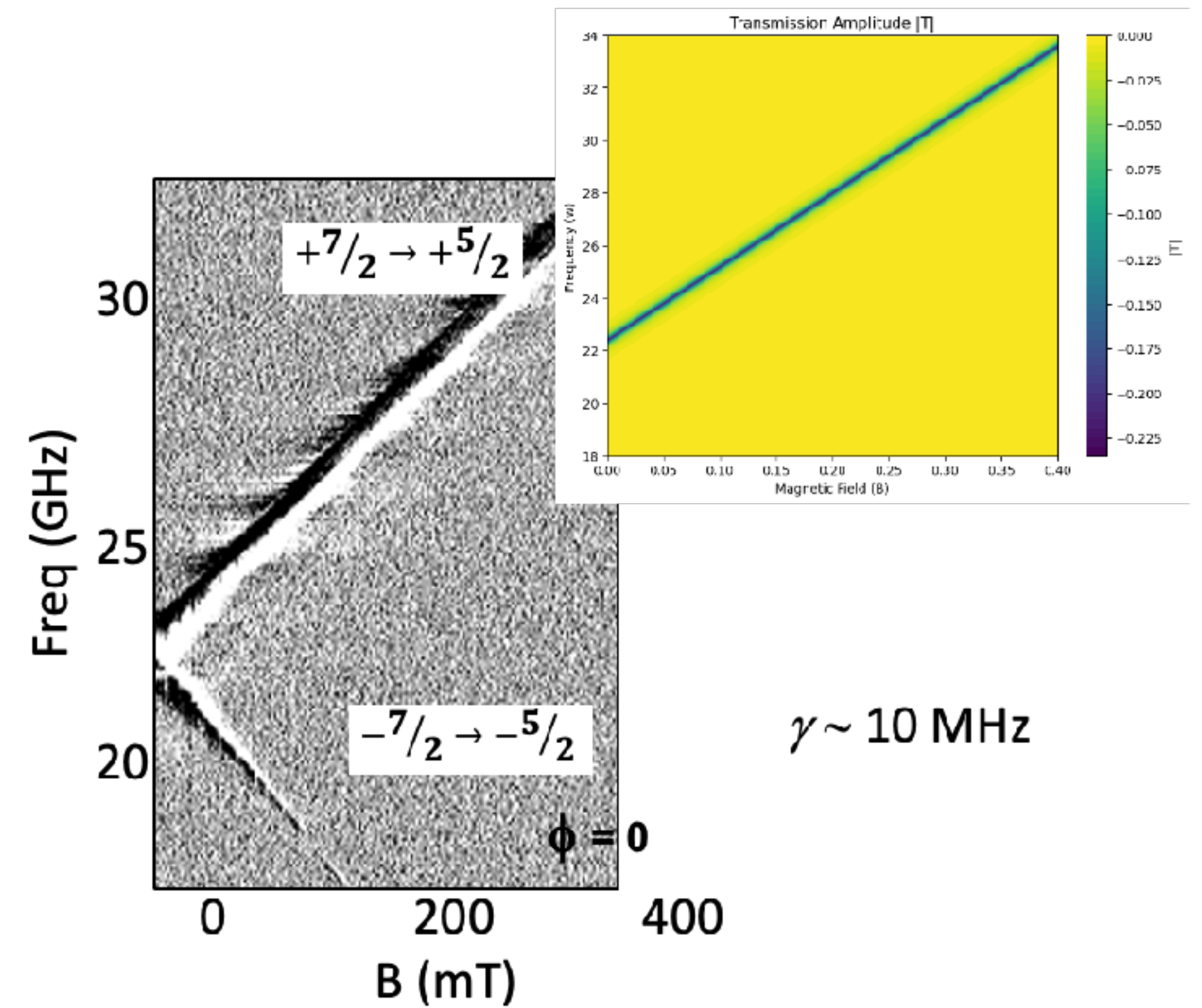
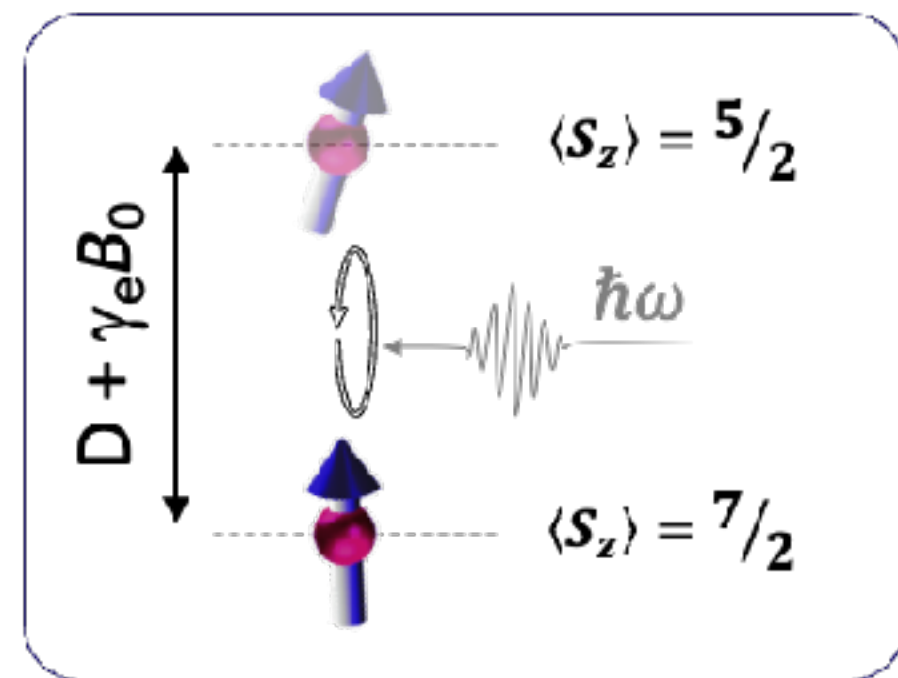
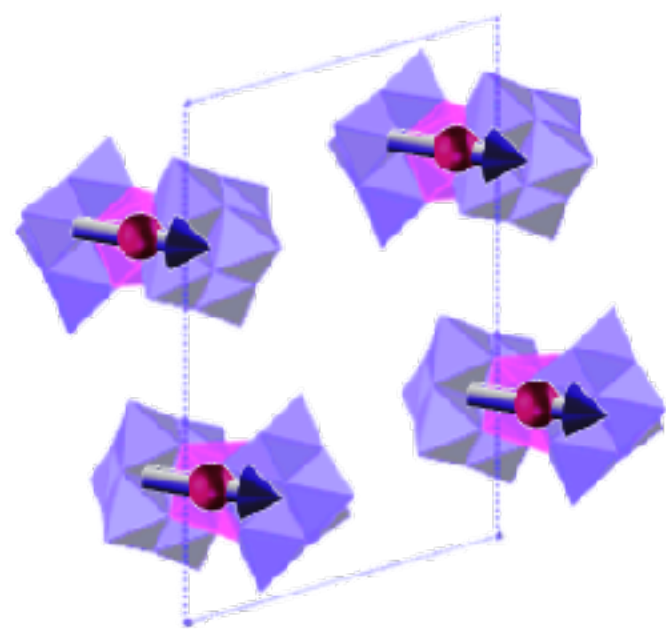
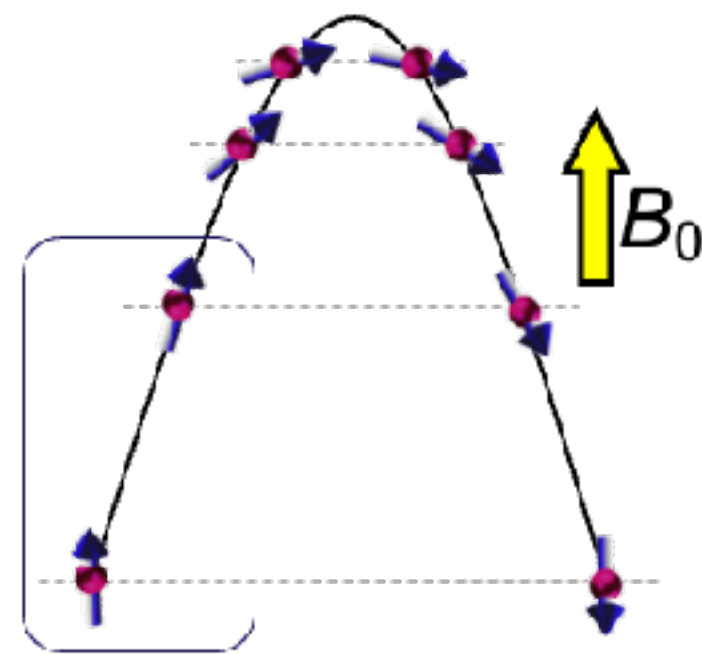
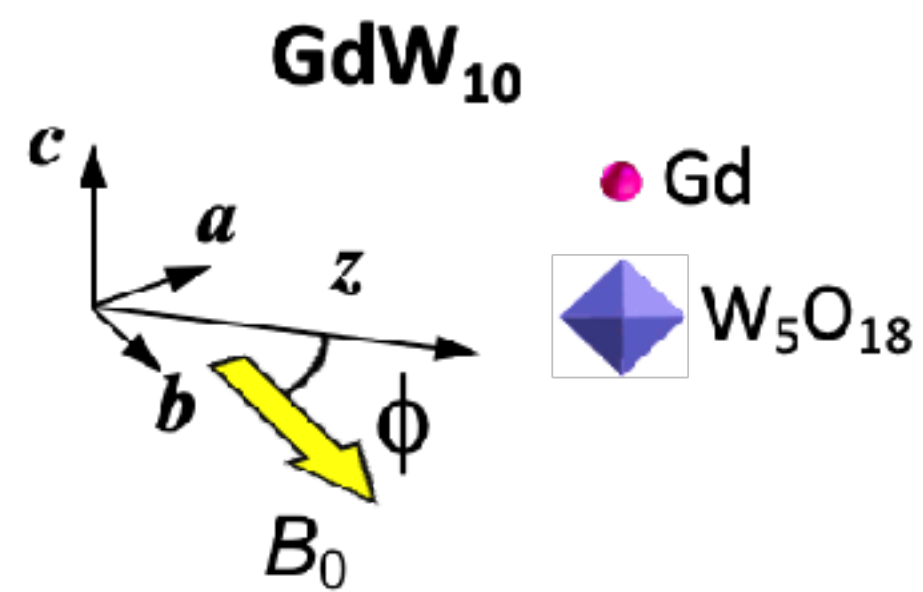
# Random Stacking model



Multiple lines, cannot be different  $k$ -modes

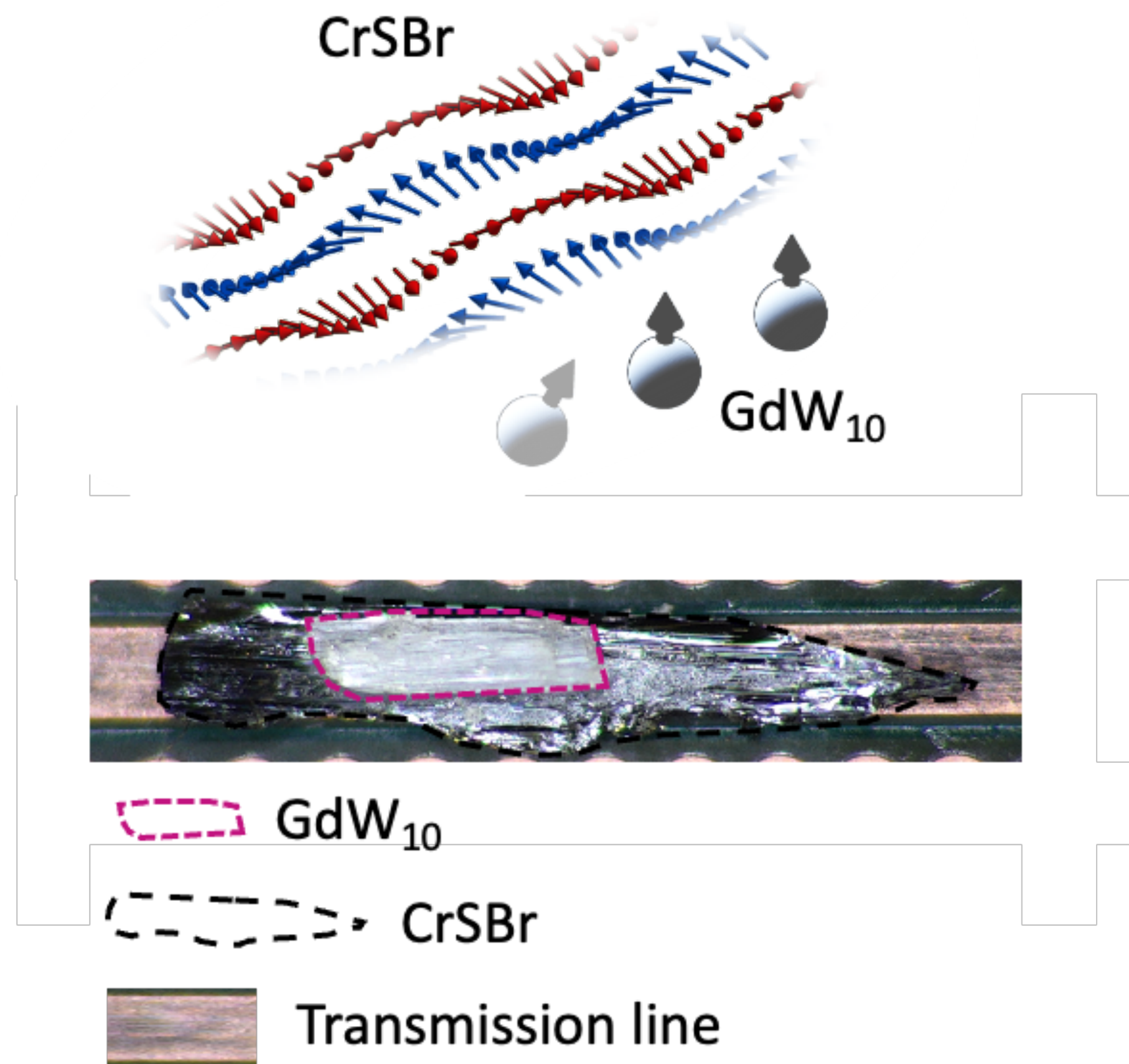
VdW “weak coupling”  $\rightarrow$  random stacking

# Gd, the qub(d)it

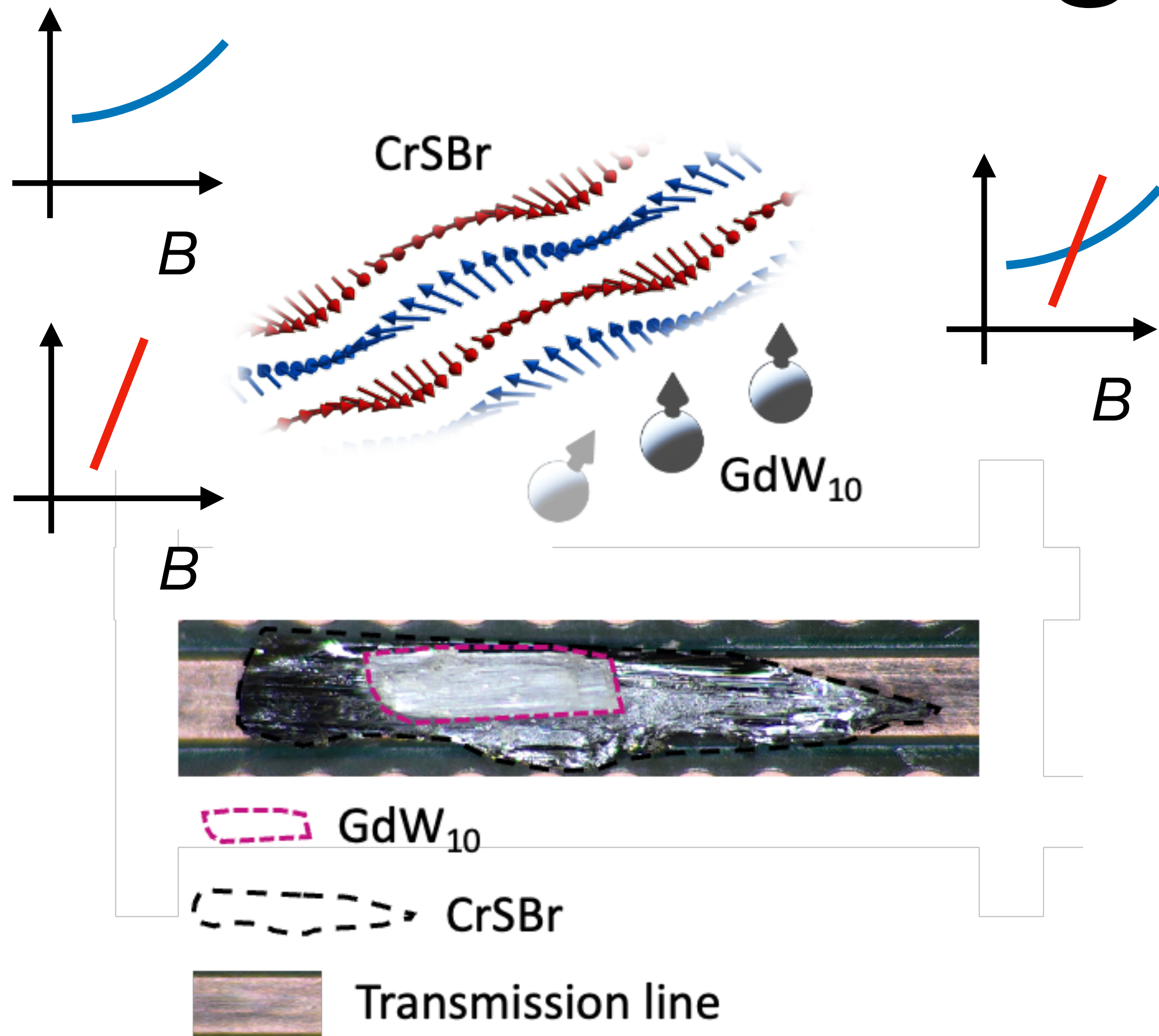


$$H = DO_2^0 + EO_4^4 + \mathbf{B} \cdot \mathbf{S}$$

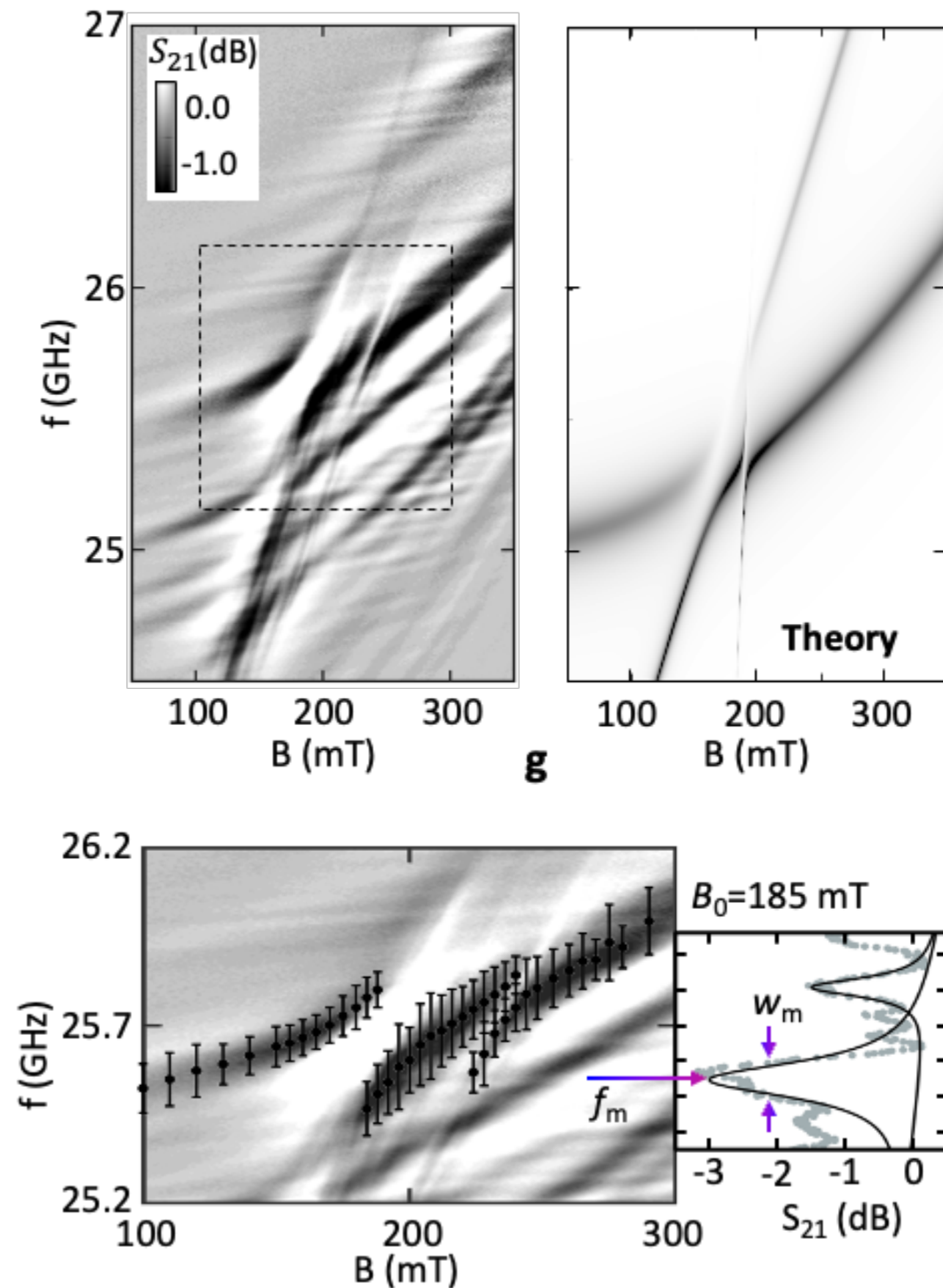
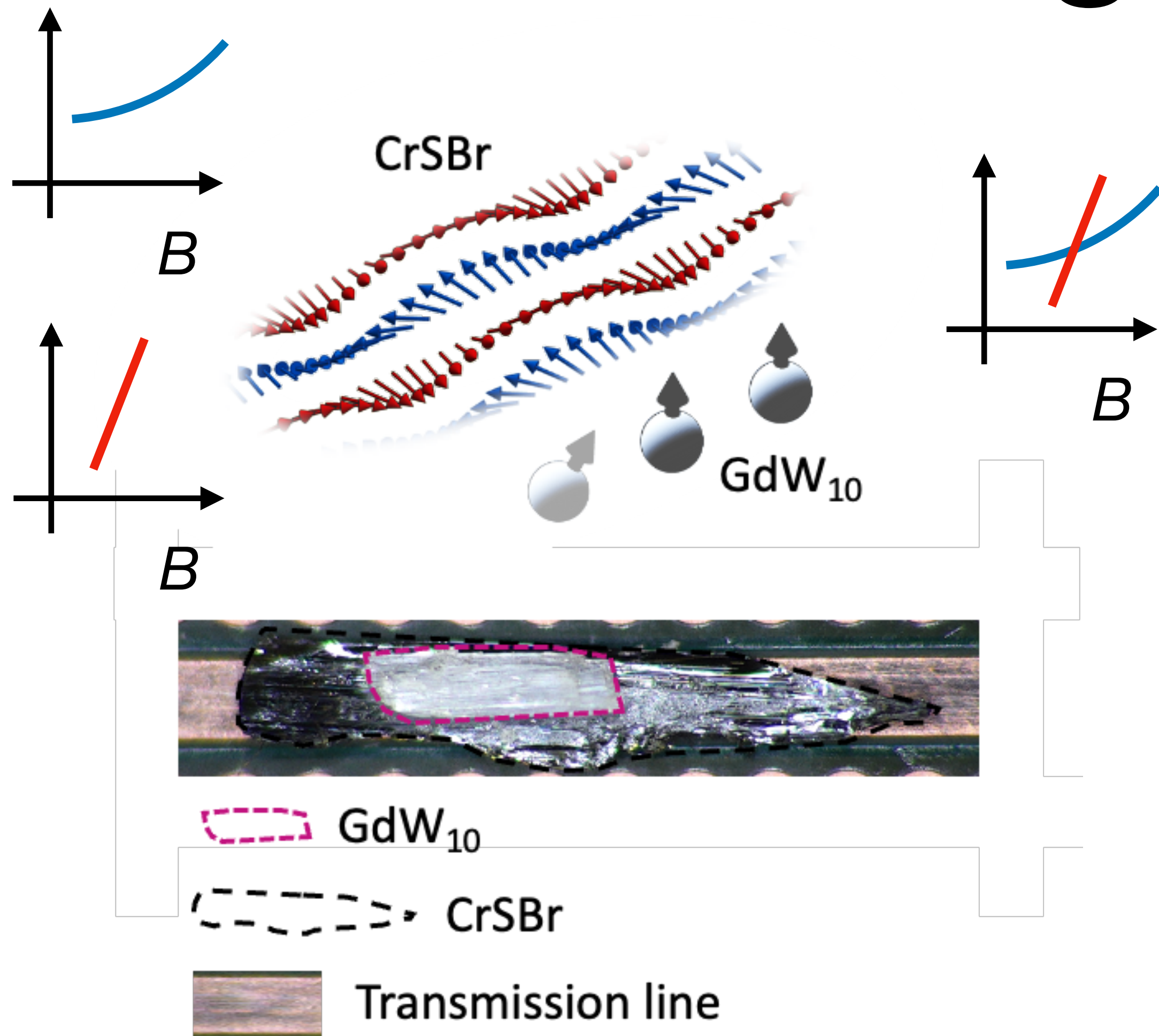
# Strong coupling



# Strong coupling

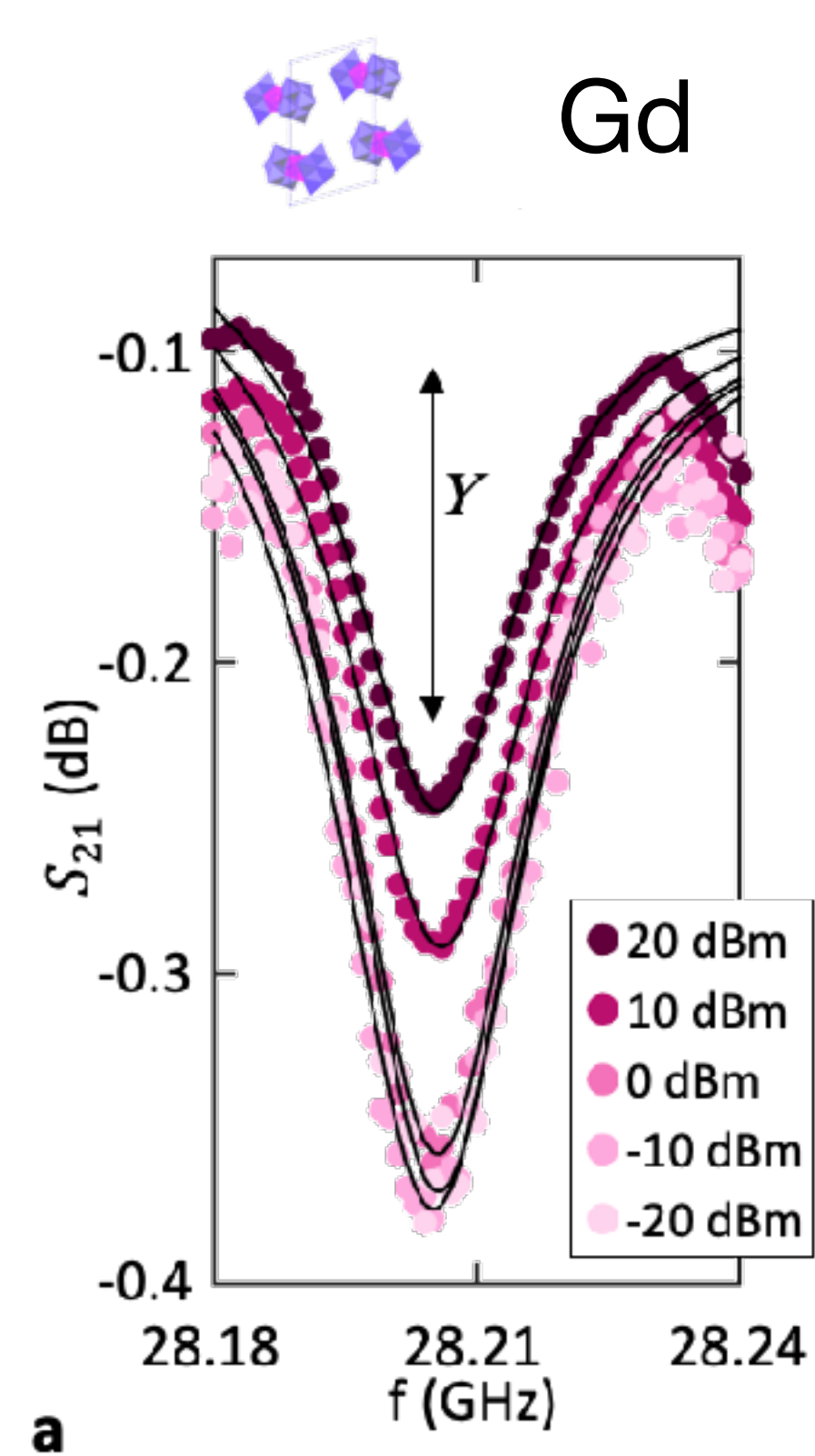


# Strong coupling



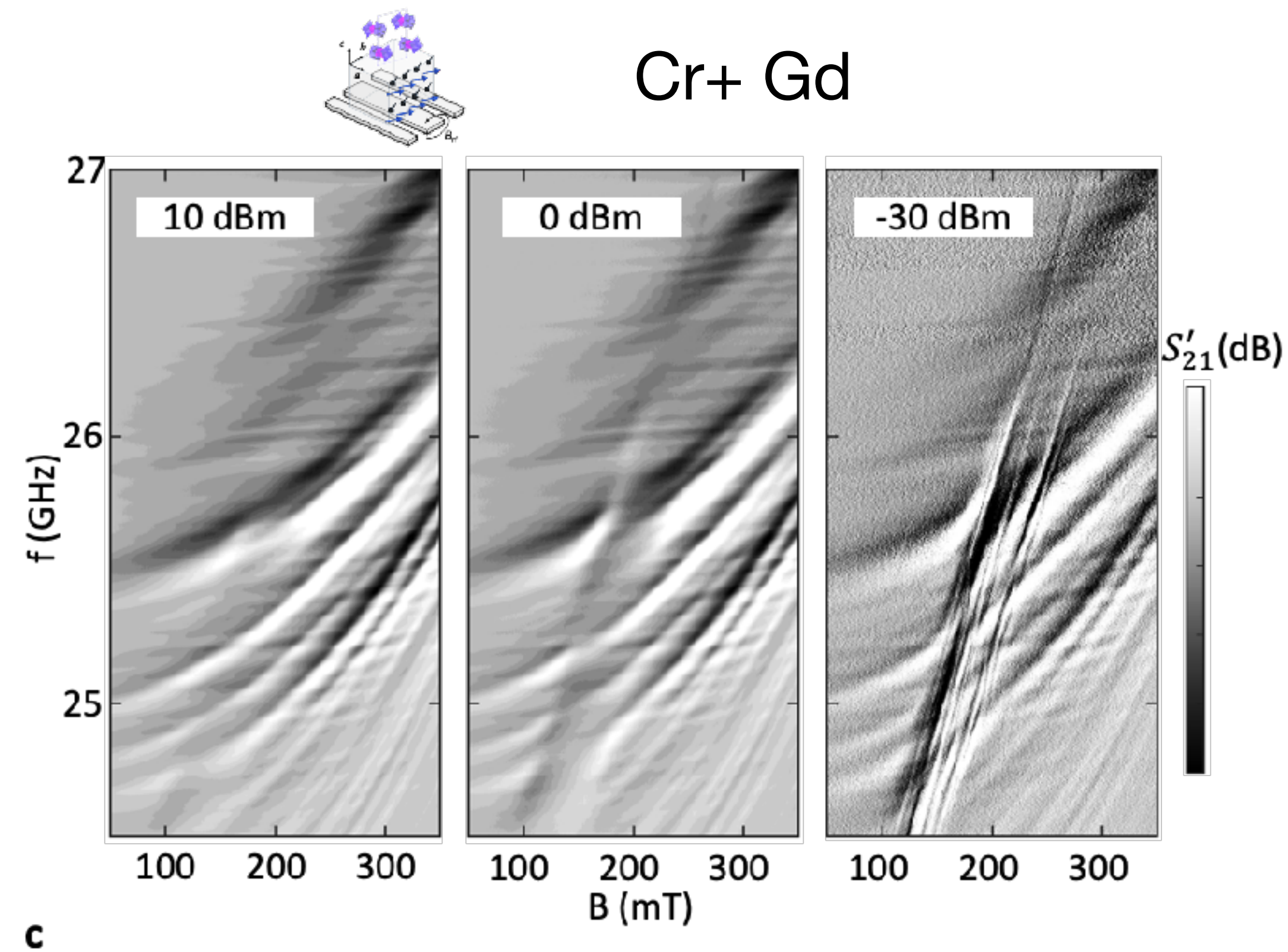
$$G/2\pi = 130 \text{ MHz} \rightarrow G^2/\kappa\gamma = 8$$

# Testing magnons linearity

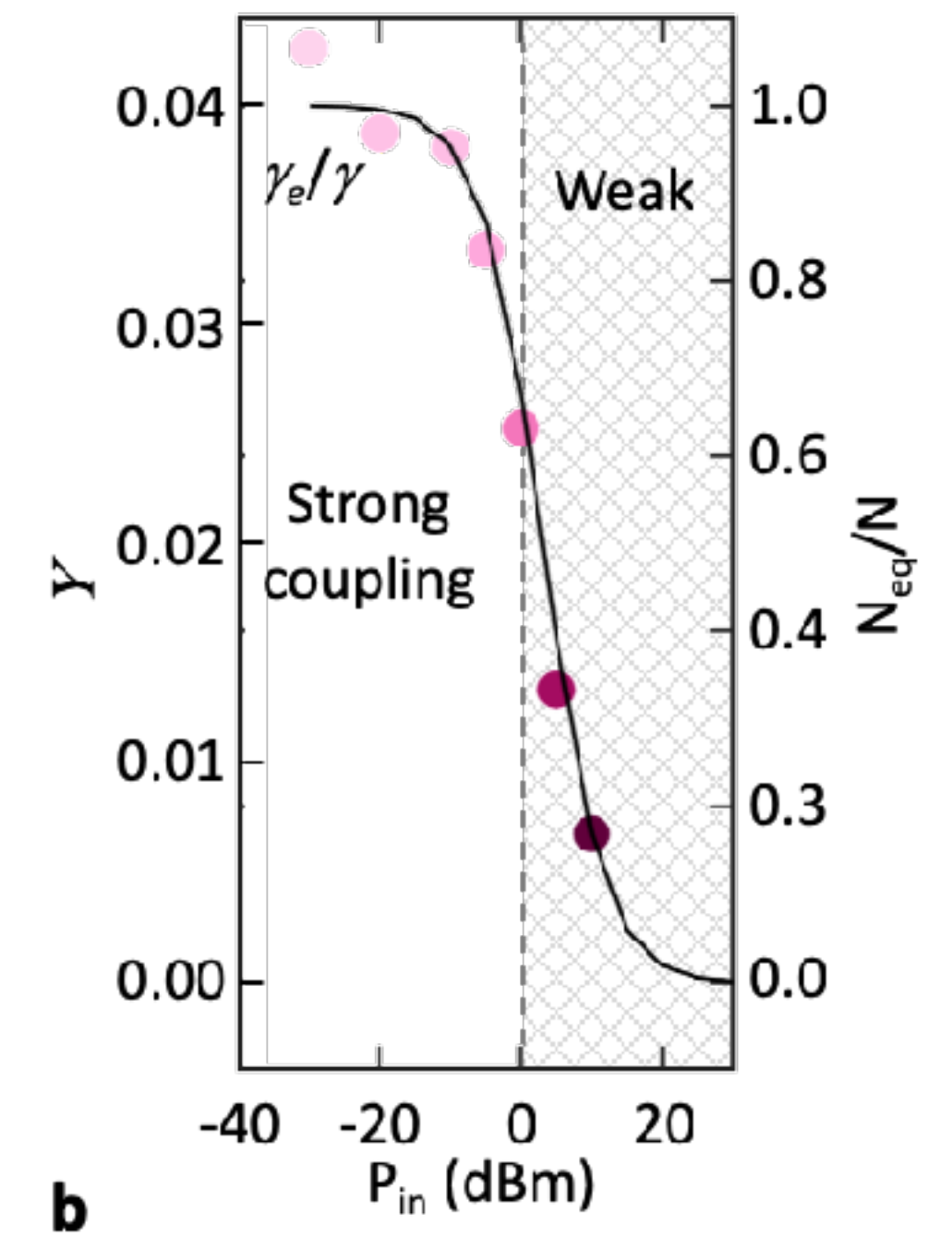


Saturation

$$N_{\text{eff}} = N_0 \frac{1}{1 + 4\lambda^2/\gamma\gamma_{\parallel}}$$



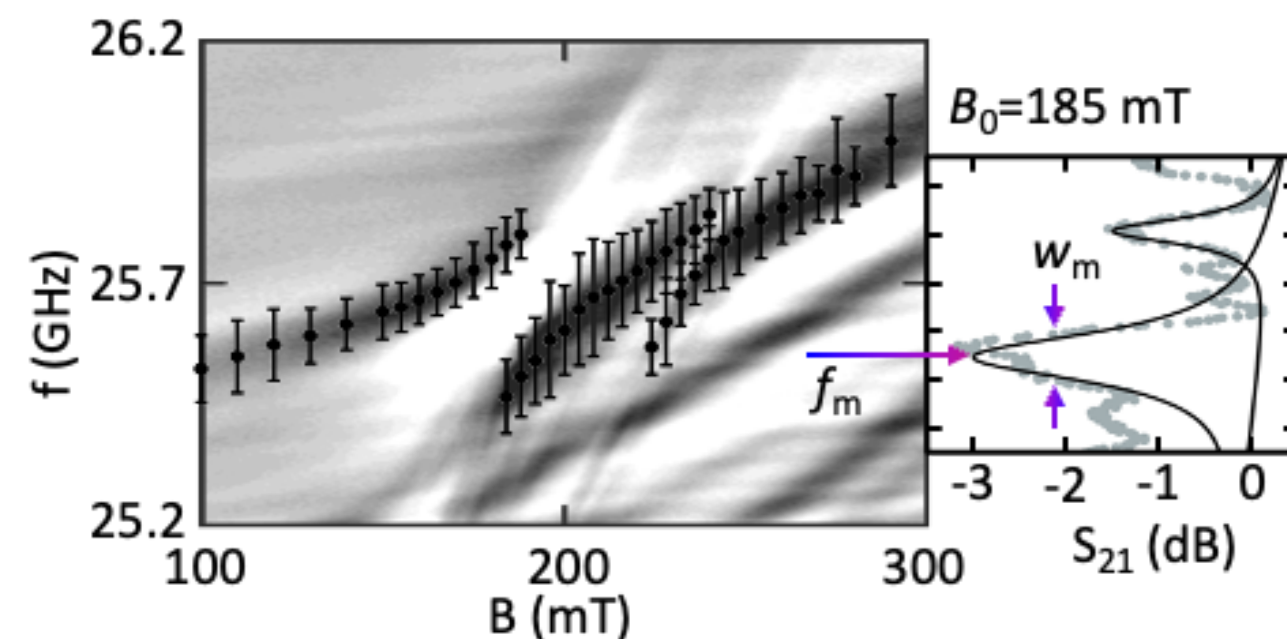
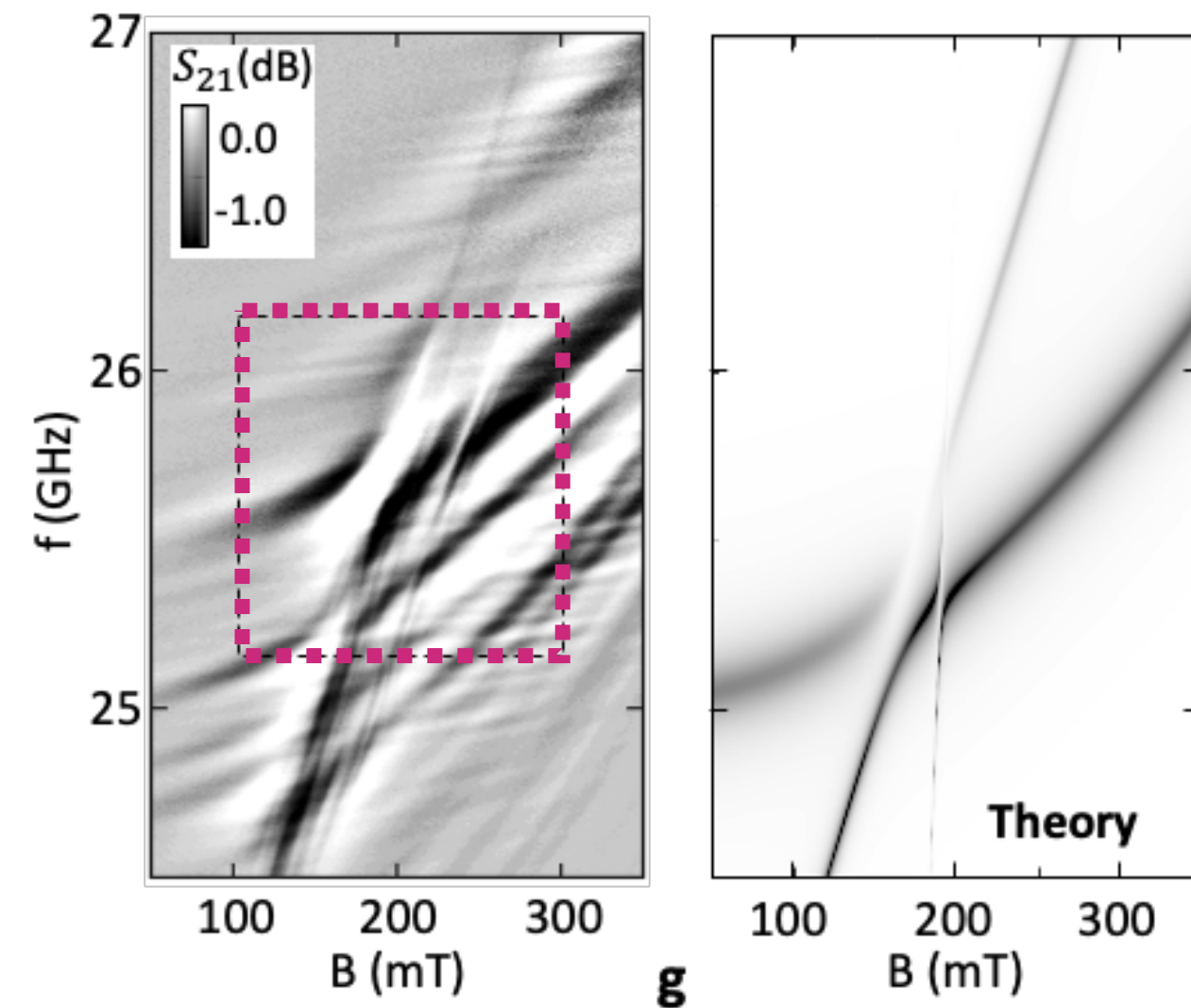
Magnons do not saturate (linear)



Saturation  $\rightarrow$   $G$  reduction

$$G_{\text{eff}} = g\sqrt{N_{\text{eff}}}$$

# Q-optics modeling



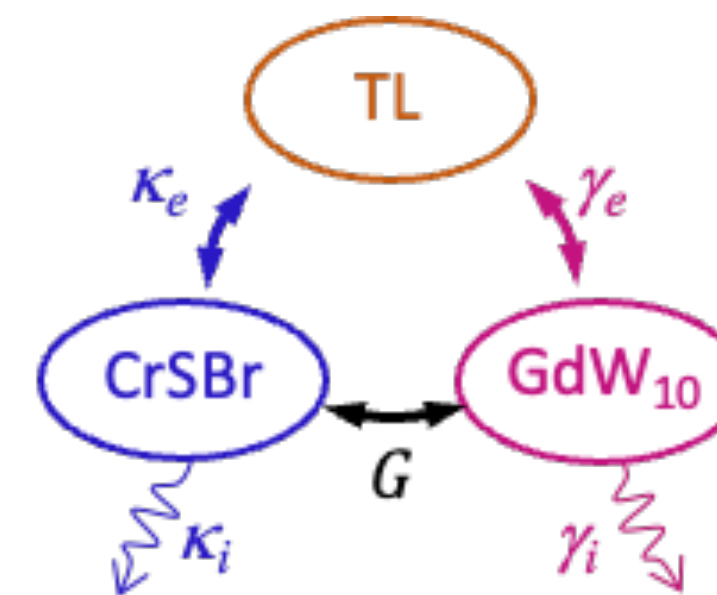
$$\frac{H}{\hbar} = \sum_q \omega_q a_q^\dagger a_q \quad \text{magnons}$$

$$+ \frac{\Delta(B_0)}{2} \sum_j \sigma_j^z \quad \text{Gd (spins)}$$

$$+ \sum_j \sum_q g_j(q) \sigma_j^+ a_q + \text{h.c.} \quad \text{coupling}$$

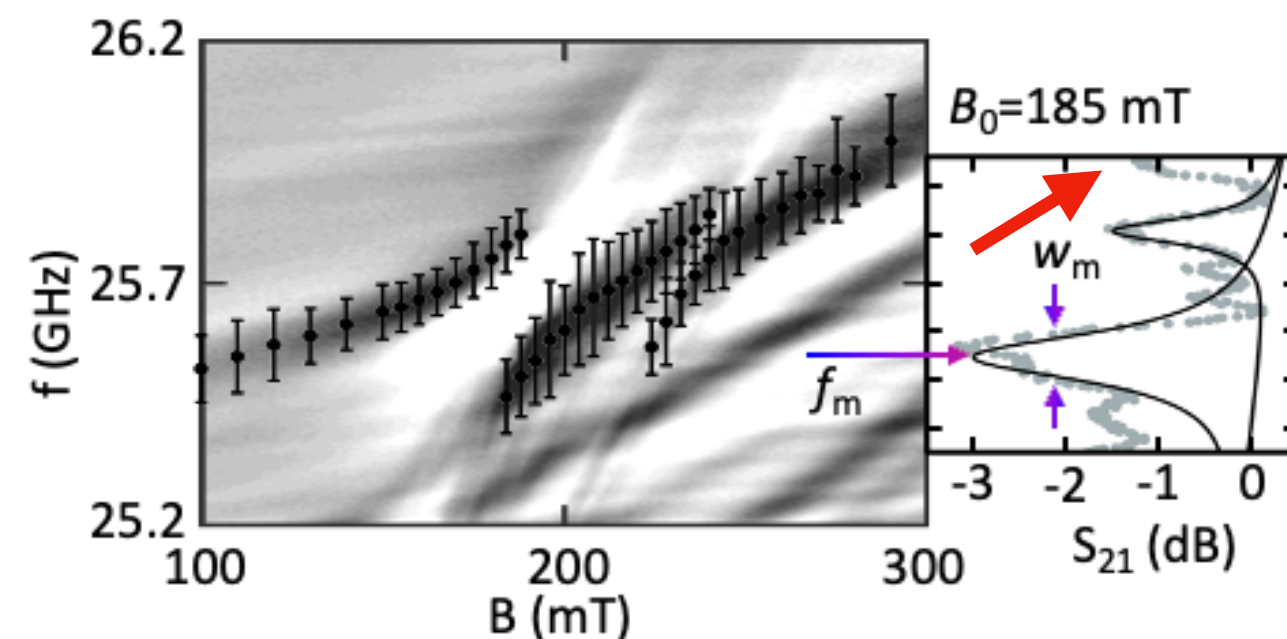
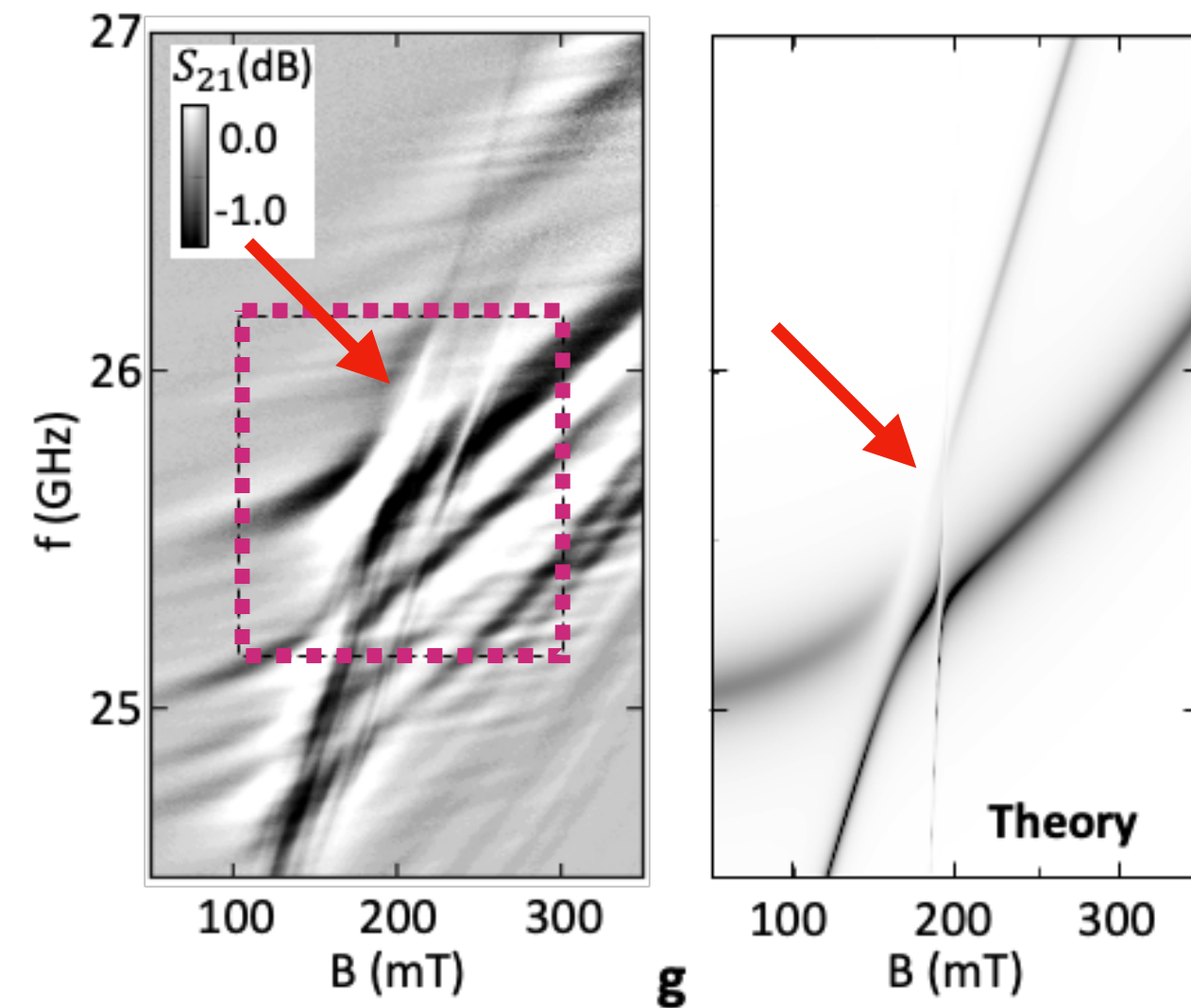
Transmission reveals:

- strong coupling
- dark state (coherent)
- Low Power: Linear cavity



$$G/2\pi = 130 \text{ MHz} \rightarrow G^2/\kappa\gamma = 8$$

# Q-optics modeling



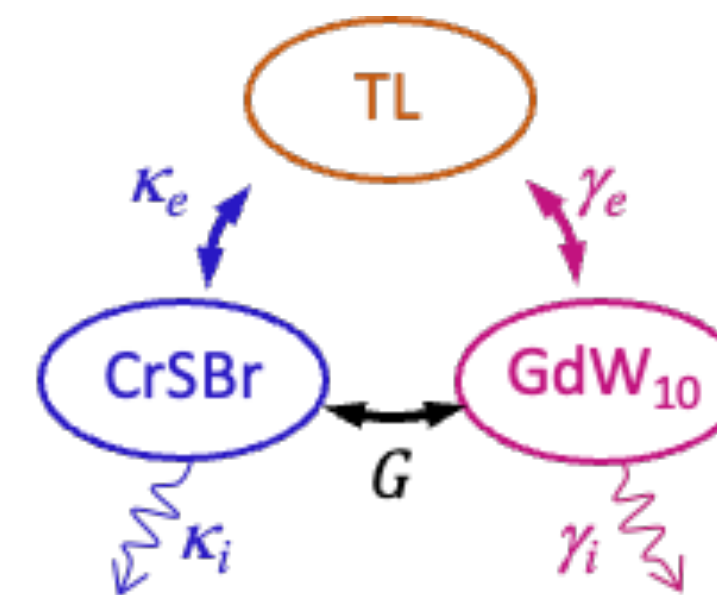
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Transmission reveals:

- strong coupling
- dark state (coherent)
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$$G/2\pi = 130 \text{ MHz} \rightarrow G^2/\kappa\gamma = 8$$

# Chiral Cavities

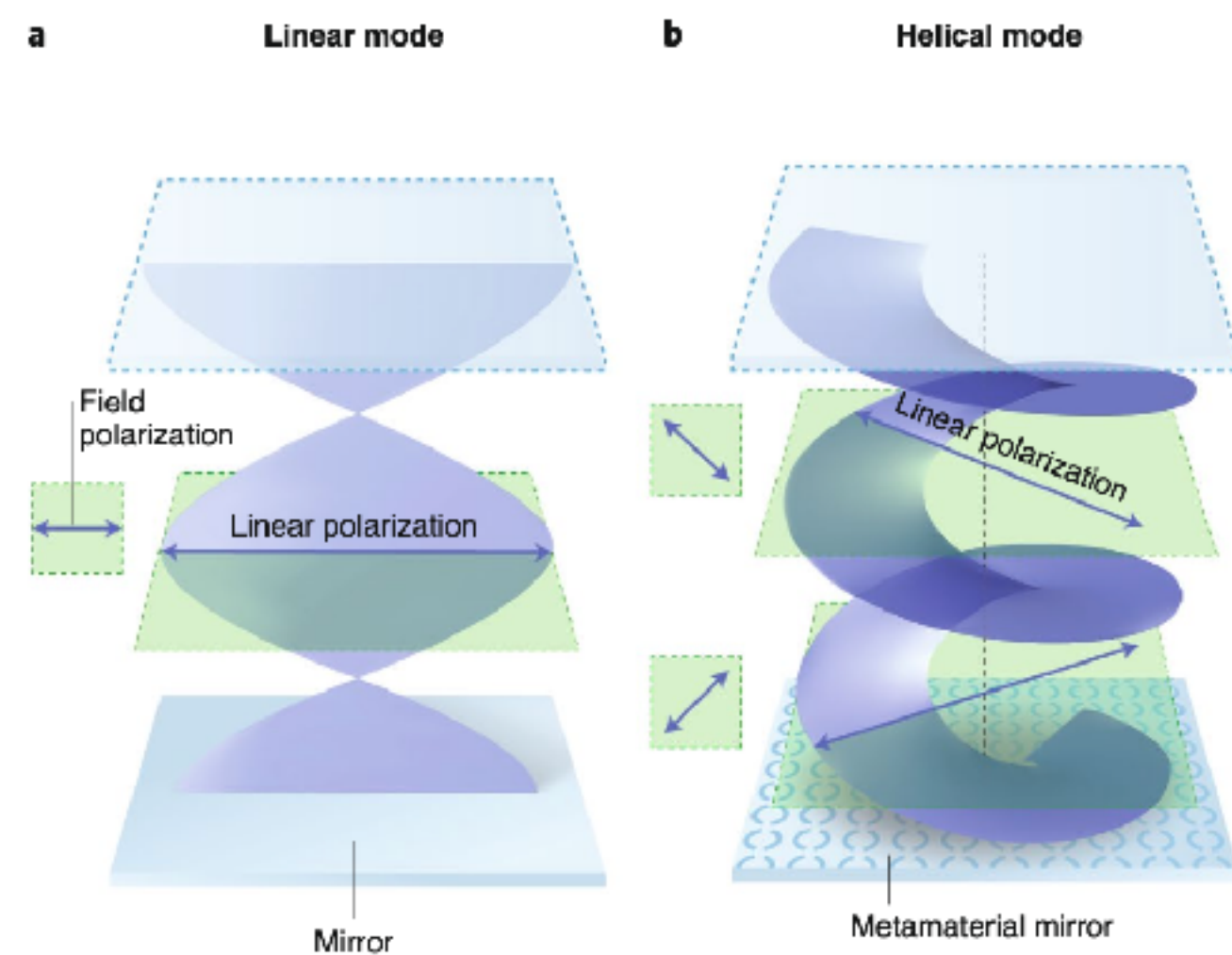


Fig: Hübener et al, Nat. Mat. 2021

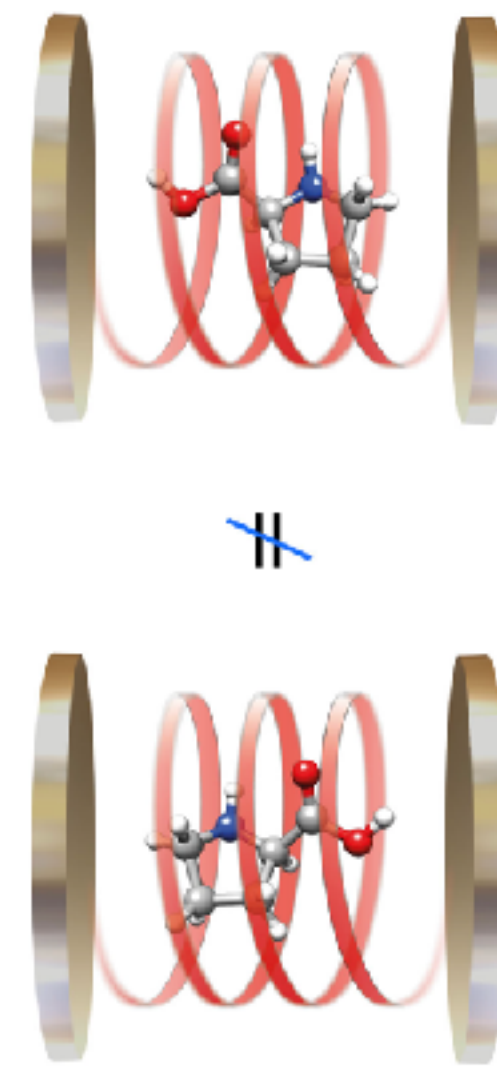


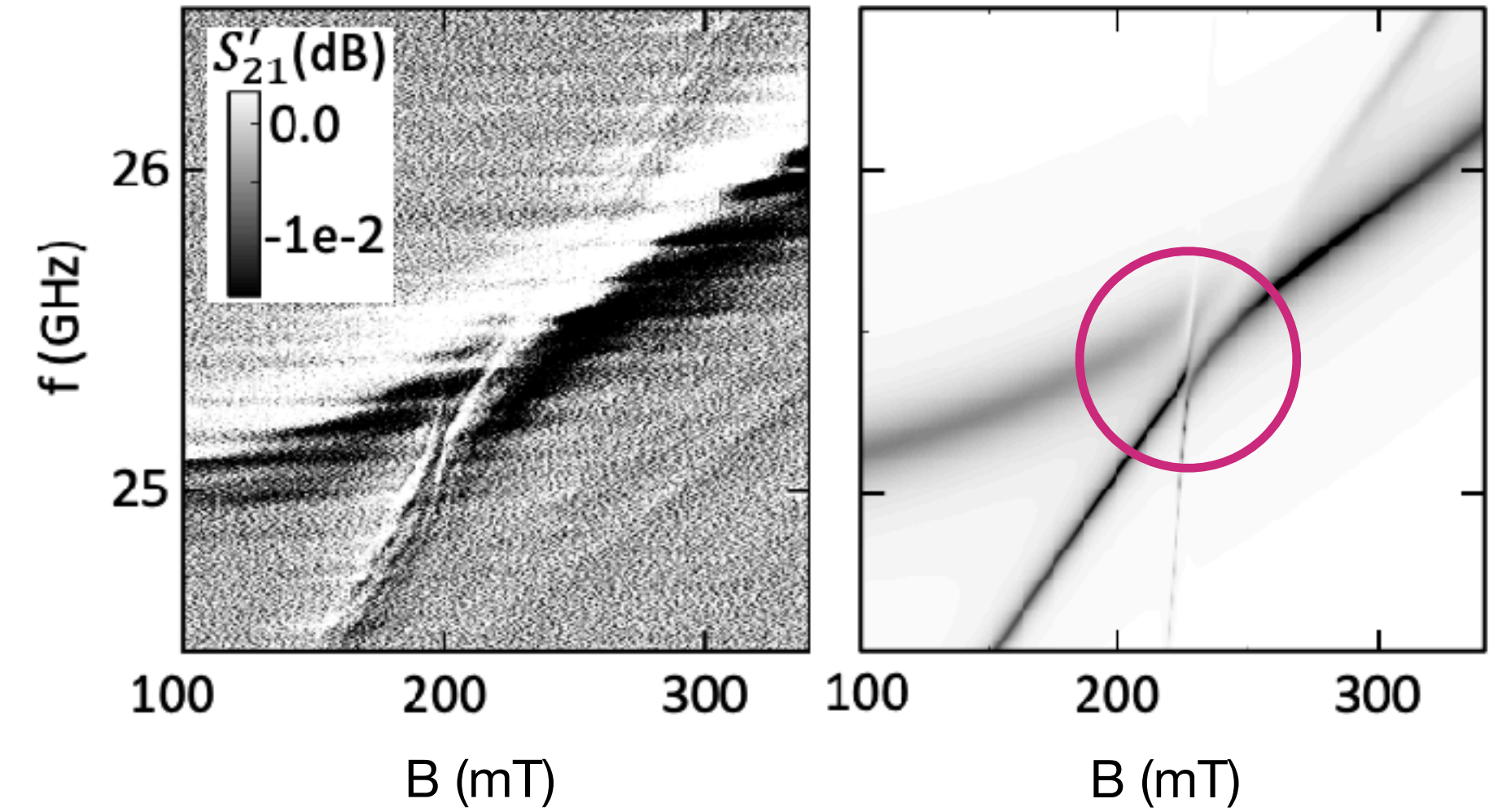
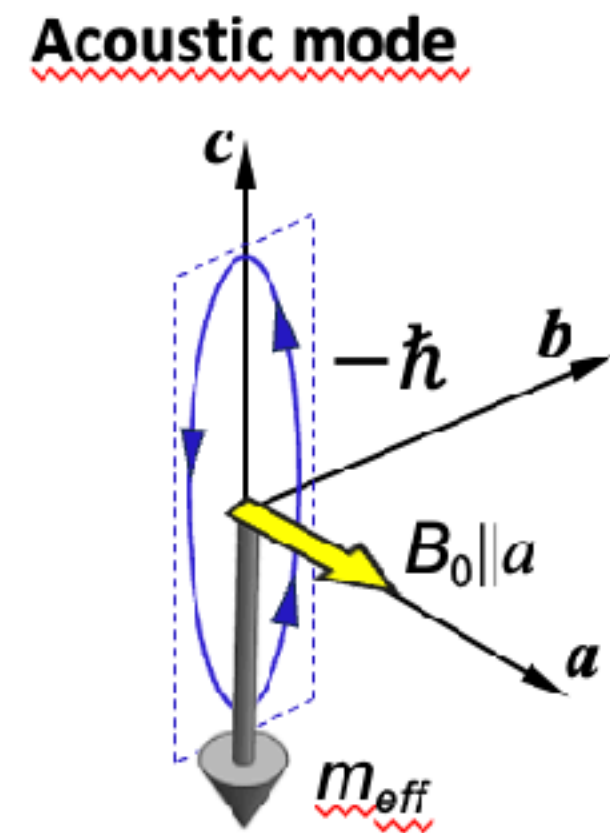
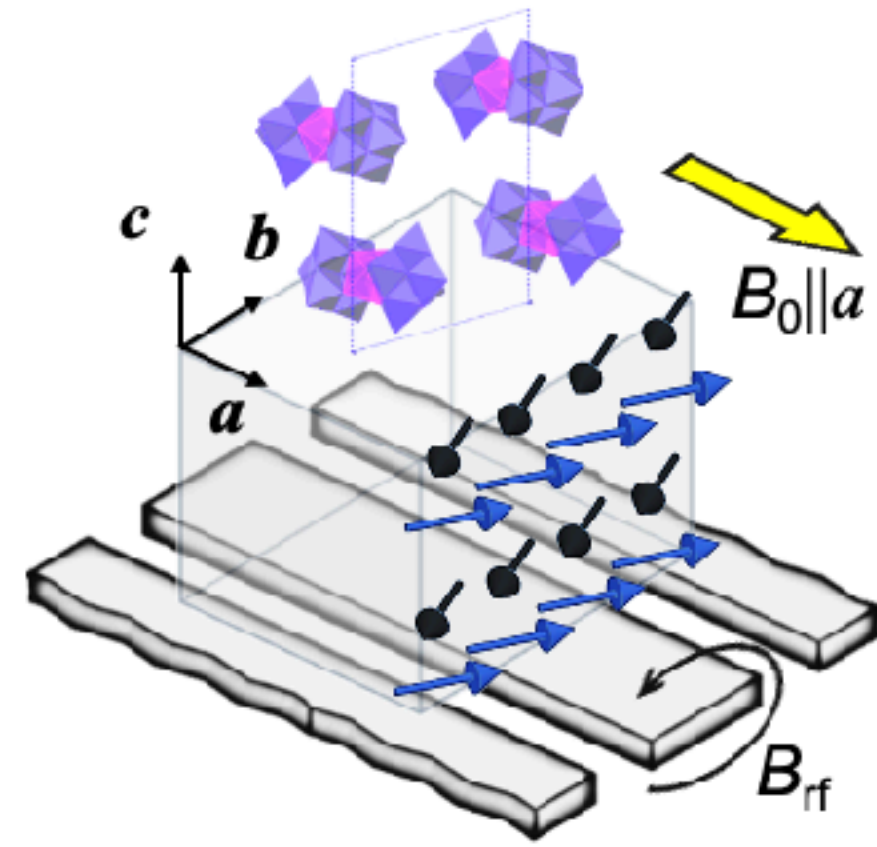
Fig: Riso et al, PRX. 2023

- Polarized light modes
- Selective coupling, e.g. spin momentum locking
- chiral emission → Q. gates, qubit-qubit coupling
- chemistry with q-light
- In our case, the Gd:
  - $7/2 \rightarrow 5/2$
  - Right Handed

# Chiral Cavities

Acoustic mode:  
linear polarization

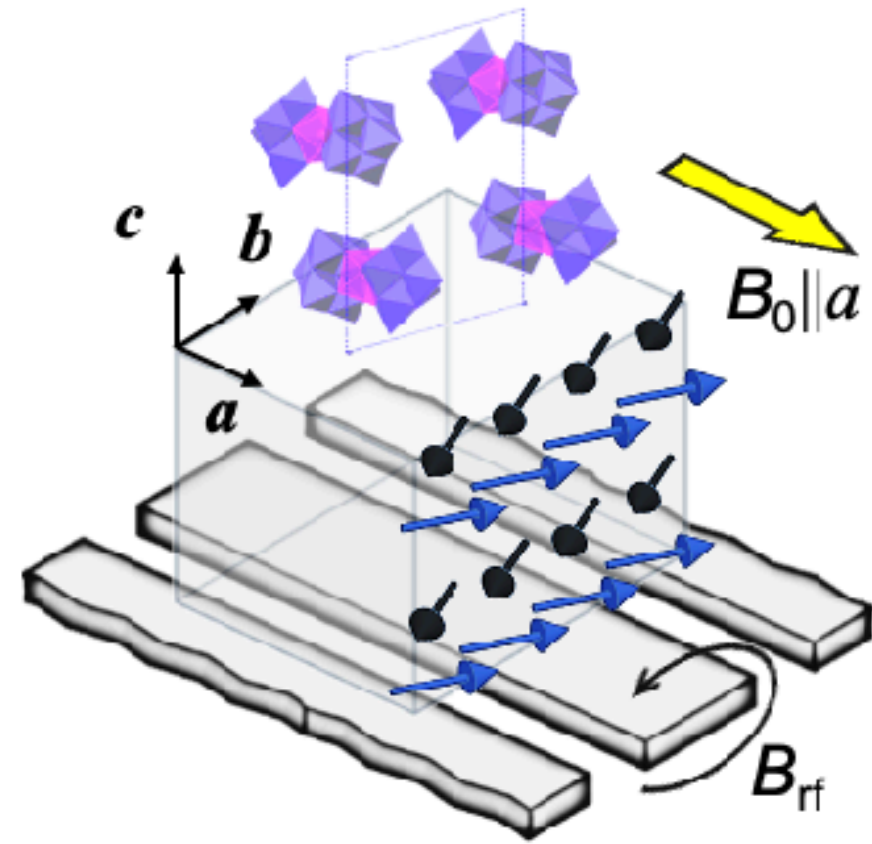
$$G \neq 0$$



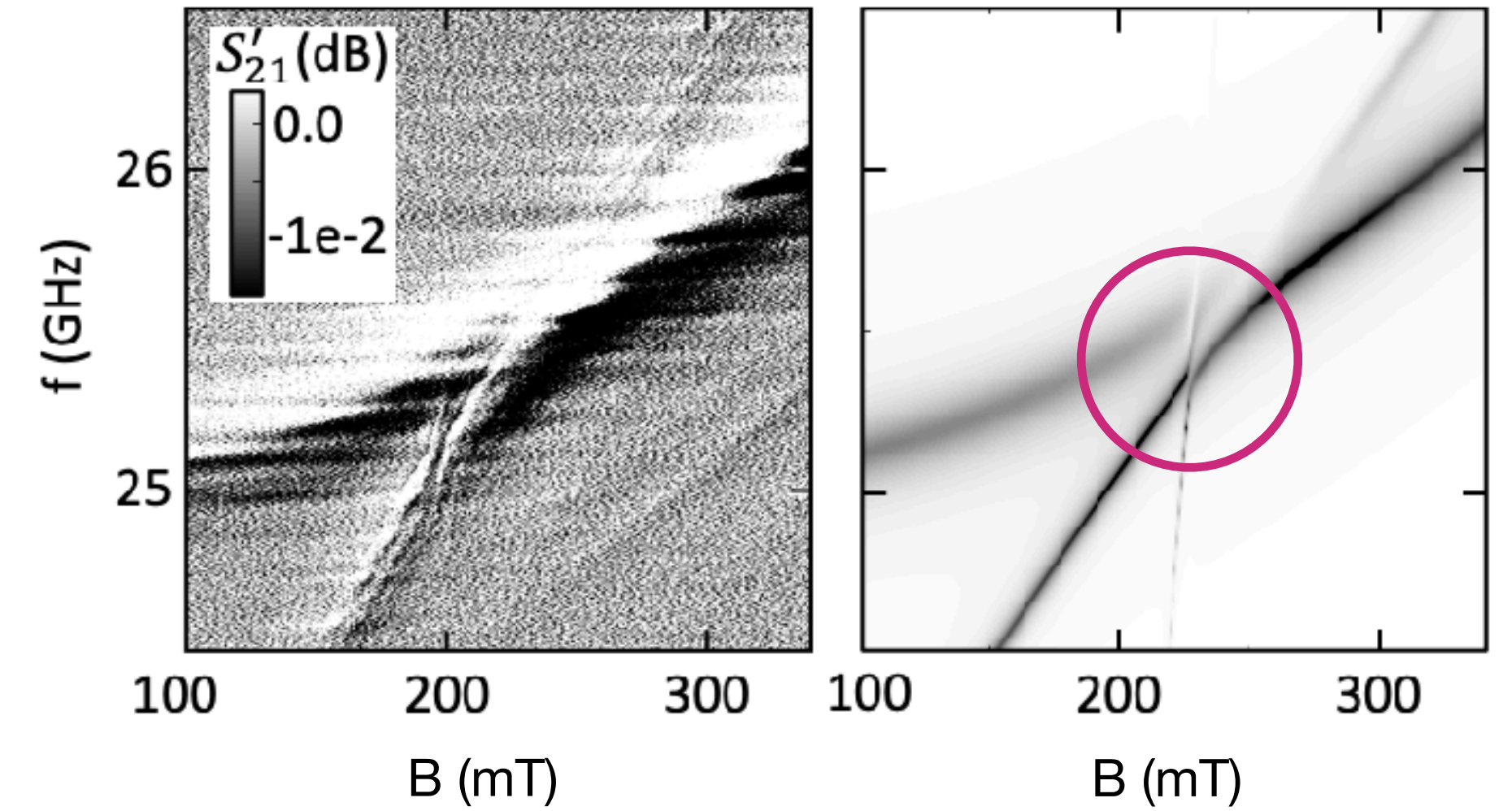
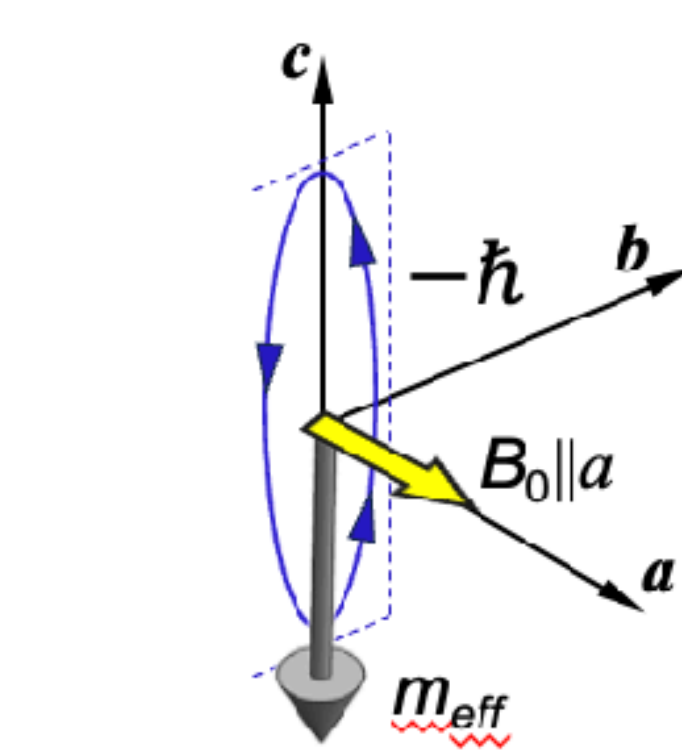
# Chiral Cavities

Acoustic mode:  
linear polarization

$$G \neq 0$$

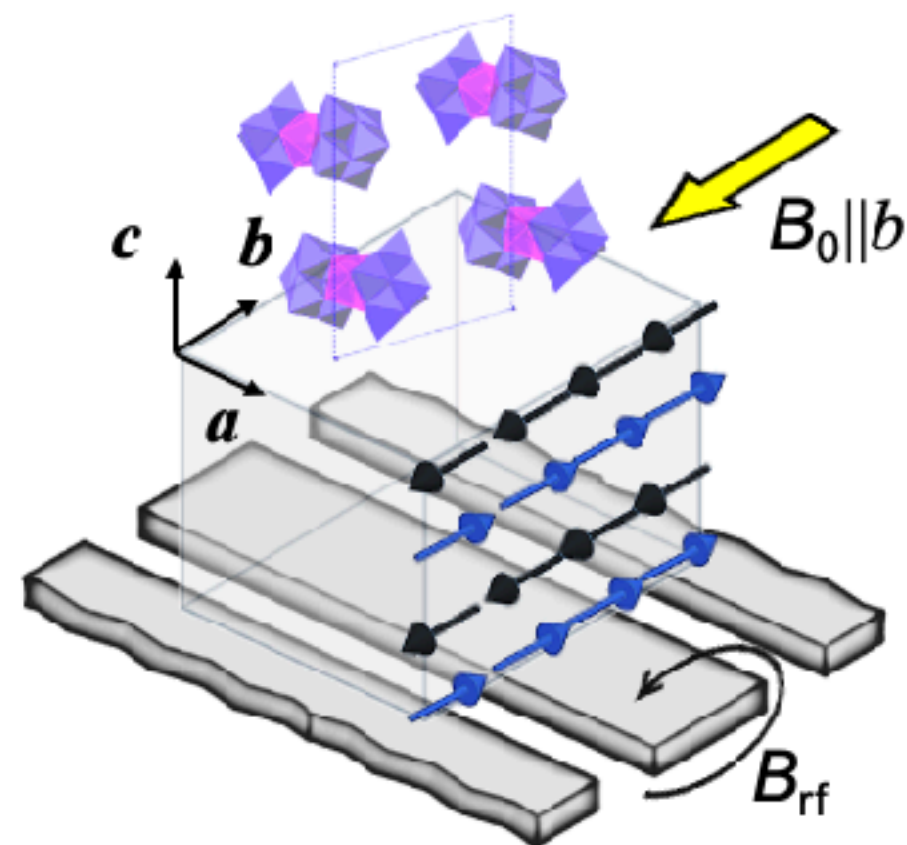


Acoustic mode

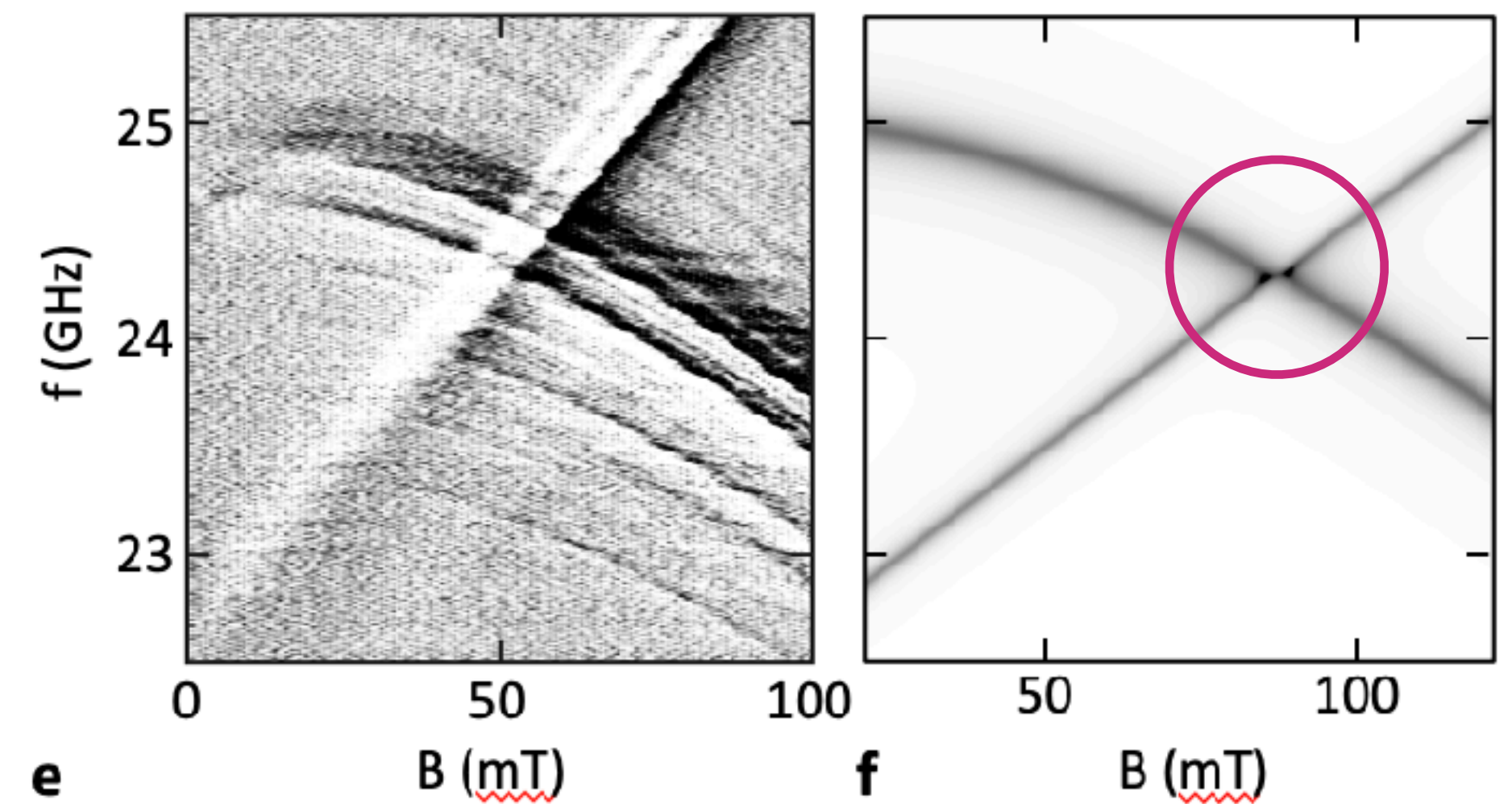
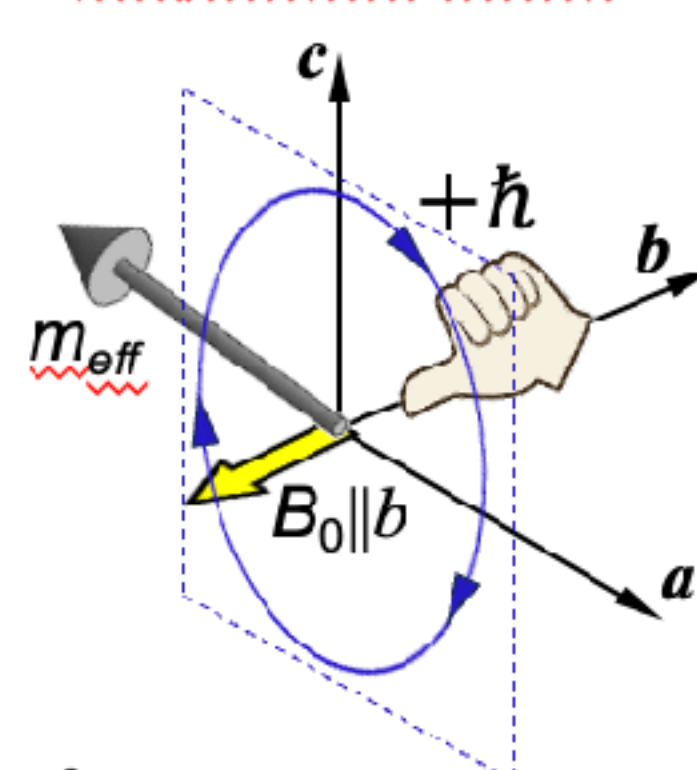


Chiral Mode:  
Left Handed polariz.

$$G \cong 0$$

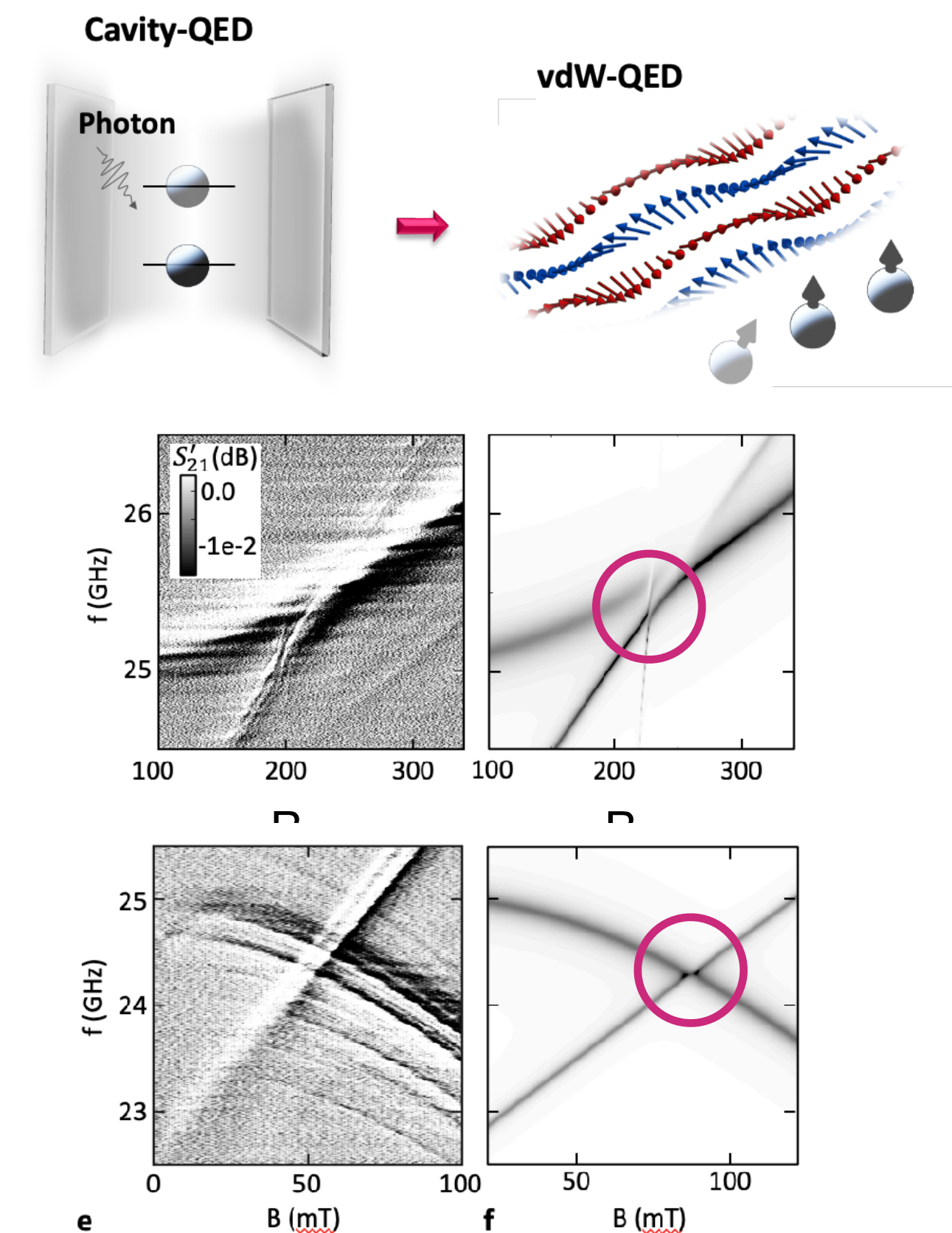


Left-handed mode



# Overview

- Introducing spin-Magnon strong coupling with VdW materials
- Characterization (TL exp) + Theory
- Other materials
- Experiments towards 2D limit
- Reduce mode volume  $G \sim 1/\sqrt{V}$
- Chiral cavity QED first demonstration. Here, coupling control.



# Acknowledgments

Experiments:   
INMA  
INSTITUTO DE NANOCIENCIA  
Y MATERIALES DE ARAGÓN

- María José (Pepa) Martínez-Pérez (group)
  - David García-Pons
  - Jorge Pérez-Bailón

2D Materials:   
ICMOL

- Eugenio Coronado (group)
  - C Boix
  - I Gómez-Muños
  - S Mañas-Valero



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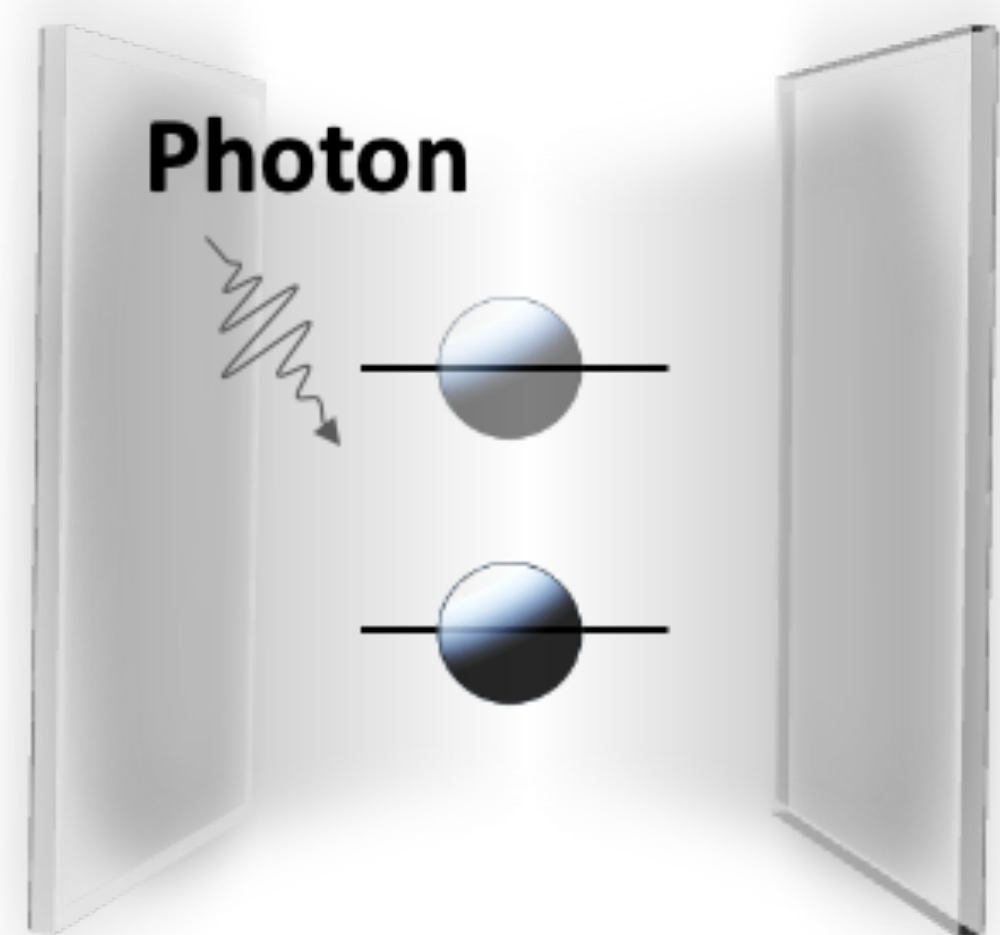
2D Materials:   
ICMOL

- Eugenio Coronado (group)
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  - I Gómez-Muños
  - S Mañas-Valero

# Thank you for your attention!



## Cavity-QED



## vdW-QED

