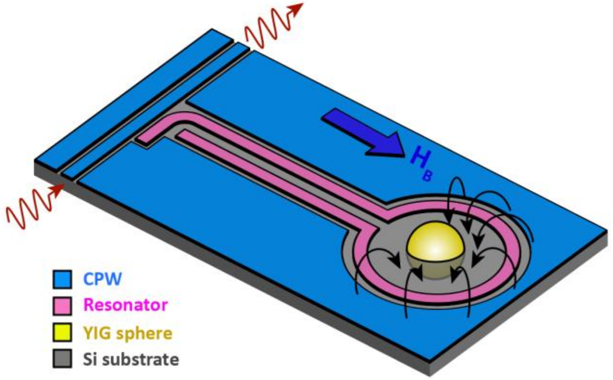
Hybrid Magnonic Devices for Quantum Information Science

Yi Li (assistant scientist)

Superconductivity and Magnetism group

Materials Science Division

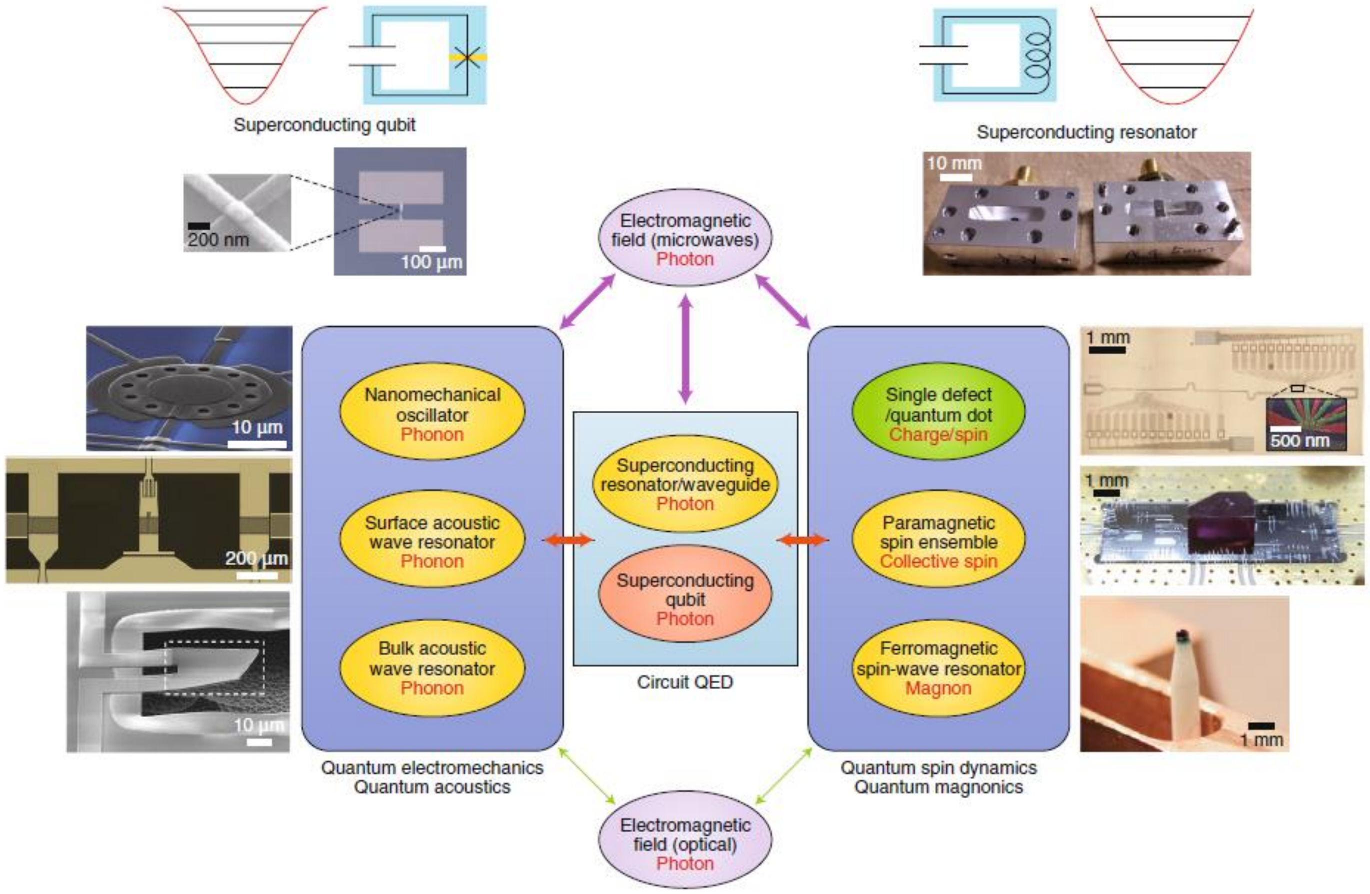
Argonne National Laboratory



U.S. DEPARTMENT OF ENERGY | Office of Science

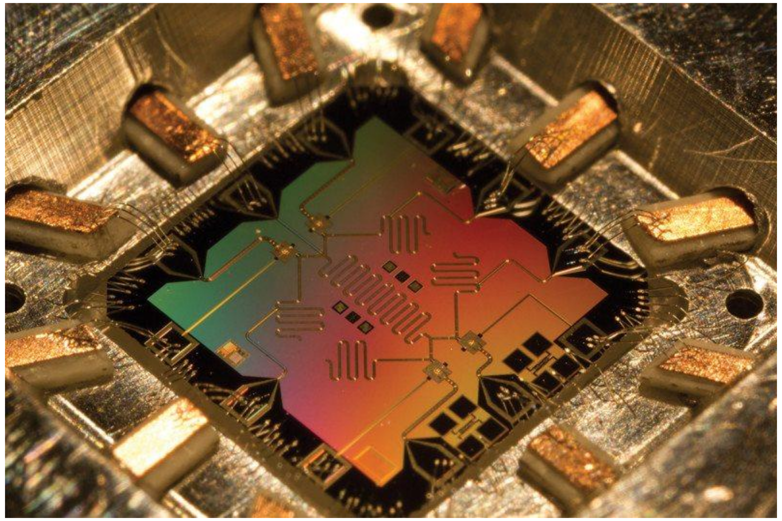
LDRD
Laboratory Directed Research and Development Program Activities

Background: hybrid quantum systems with cQED



AA Clerk, et al. Nature Phys. 16, 257 (2020)

- Microwave quantum systems
- Multi-tasking functionality
- New quantum properties



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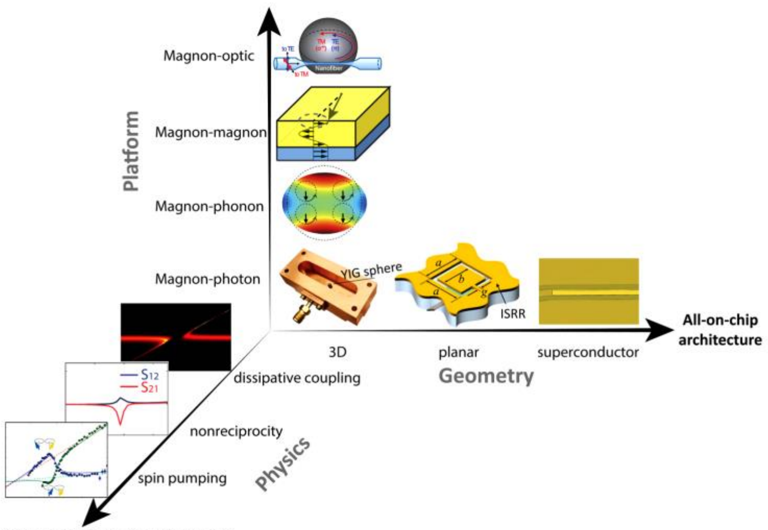
Background: magnon for QIS

- Magnon for QIS
  - Large dipolar coupling to microwave
  - Frequency tunability
  - Transduction (mechanical, microwave, optic)
  - Unique properties (nonreciprocity, small wavelength)
  - Advanced sensing (dark matter detection…)

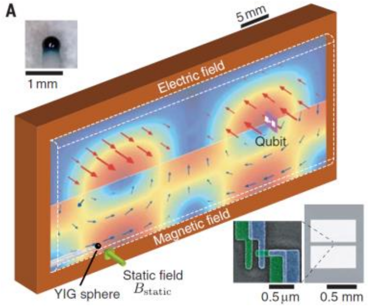


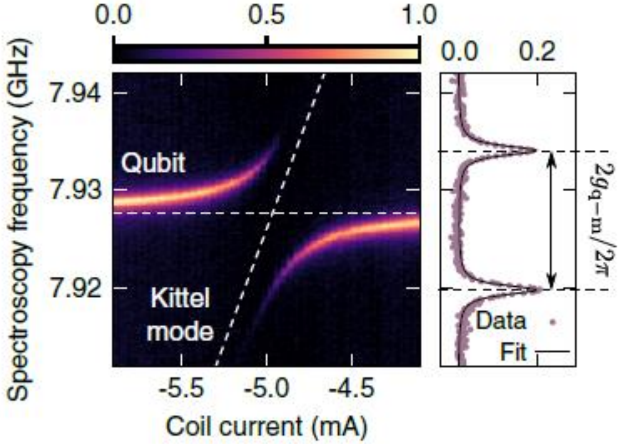
Yi Li et al. J. Appl. Phys. 128, 130902 (2020) [perspective]

Basic Energy Sciences Roundtable

Opportunities for Basic Research for Next-Generation Quantum Systems

- PRO 1: Advance Artificial Quantum-Coherent Systems with Unprecedented Functionality for QIS
- PRO 3: Discover Novel Approaches for Quantum-to-Quantum Transduction

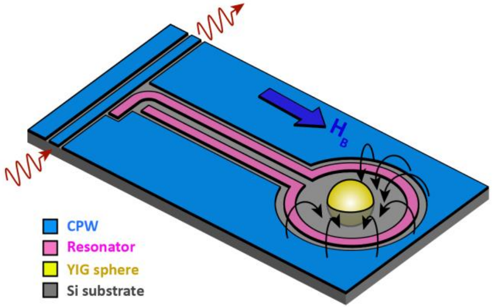


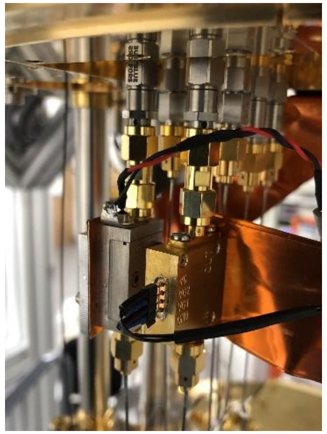


Y. Tabuchi et al. Science 349, 405 (2015)
D. Lachance-Quirion, et al. Science 367, 425 (2020)

Project description

- Overall goal
  - Develop hybrid magnonic circuits & devices for QIS-compatible applications
  - Explore magnon excitations in the single quantum limit
- Approach
  - High T_c NbN superconducting coplanar resonators & nanowires
  - YIG thin films and spheres, new low-damping FM thin films
  - Bluefors dilution fridge (10 mK) with HEMT cryogenic low-noise amplifier
  - AMI triple-axis electromagnet (1.4 K)
- Core team members
  - Magnetism and hybrid magnonics [*Yi Li (MSD), Valentine Novosad (MSD)*]
  - Superconductivity [*Wai-Kwong Kwok (MSD), Ulrich Welp (MSD)*]
  - Superconducting nanodevices & engineering [*Tomas Polakovic (PHY), Tom Cecil (HEP), Volodymyr Yefremenko (HEP), Clarence Chang (HEP)*]
- Funding
  - 2 LDRDs (one in collaboration with U Delaware)
  - DOE BES (in collaboration with UIUC)
  - FWP (superconductivity & magnetism group)





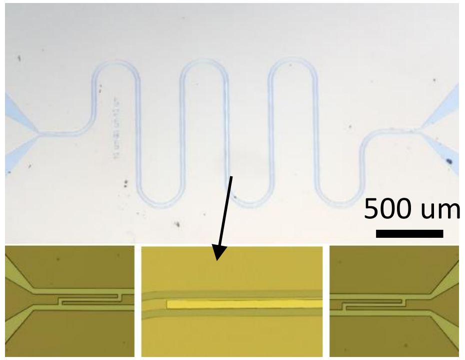
Reference:
Yi Li et al. J. Appl. Phys. 128, 130902 (2020) [perspective]
Yi Li, et al. APL Materials 9, 060902 (2021) [perspective]
DD Awschalom, et al. IEEE Trans. Quantum Eng. 2, 5500836 (2021) [review]

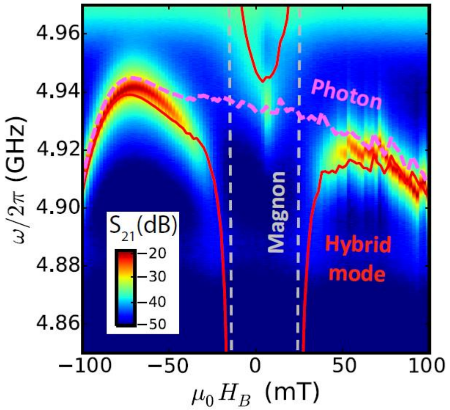
Recent progress 1:
Hybrid magnonics embedded in SC resonators

- Py thin-film device integrated with λ/2 superconducting resonator
- YIG sphere integrated with ring superconducting resonator

	λ/2 + Py	Ring + YIG sphere
g	152 MHz (900 um x 14 um x 30 nm)	130 MHz (2R=250 um)
$g/\sqrt{N}$	27 Hz	0.6 Hz
κ_{photon}	2.0 MHz	1.3 MHz
κ_{magnon}	168 MHz	1.0 MHz
Cooperativity	68	13000

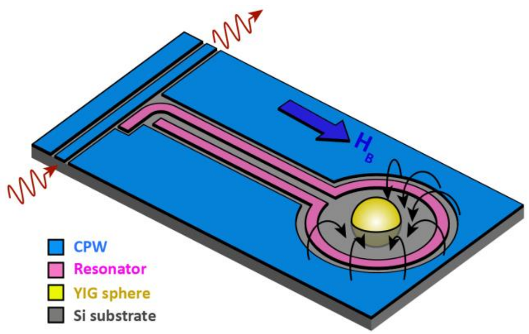
Py thin-film device

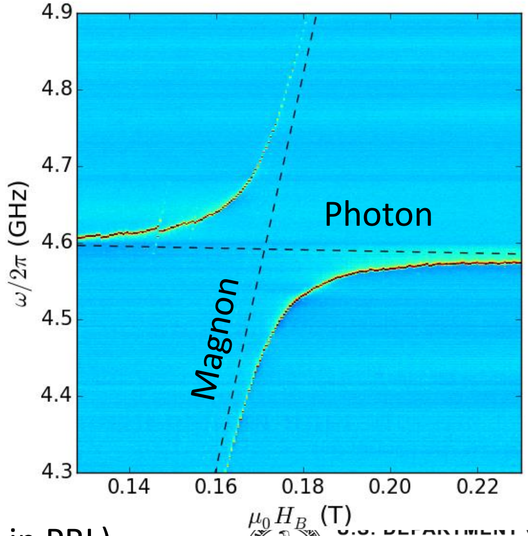




Yi Li, et al. PRL 123, 107701 (2019)

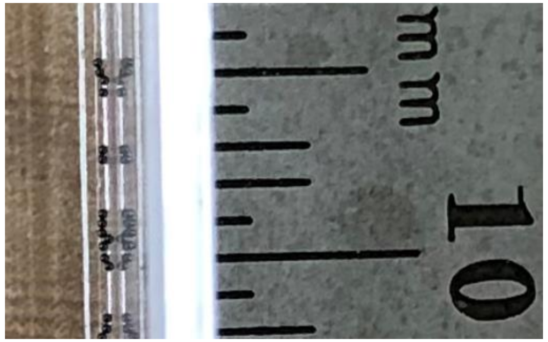
YIG sphere





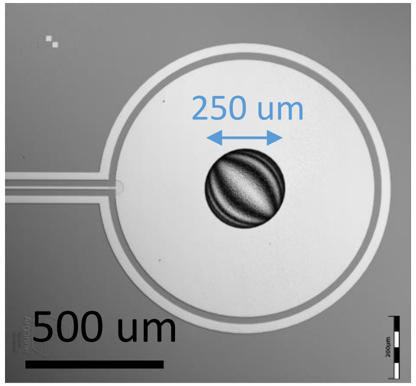
Yi Li, et al. (under review in PRL)

Recent progress 1:
Hybrid magnonics embedded in SC resonators

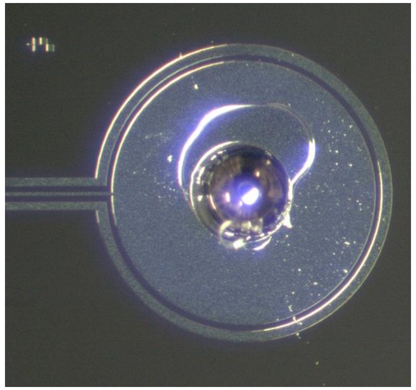


YIG sphere
- D=250 um

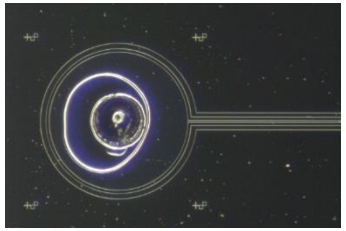
Mounting
- Lithographically defined locations
- RIE etching
- Depth: 125~150 um
- Roughness: <5 um

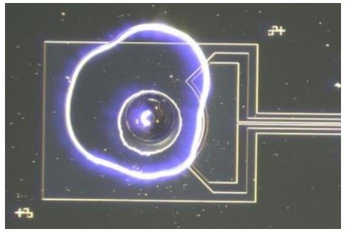


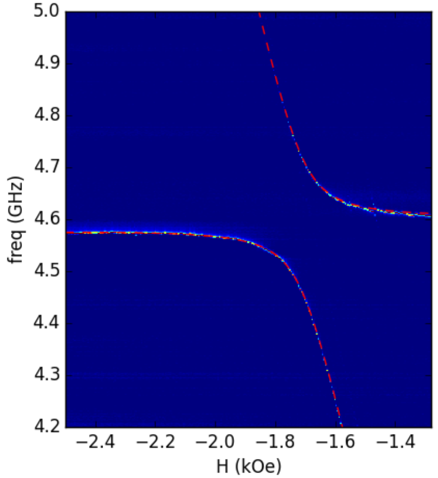
Before mounting

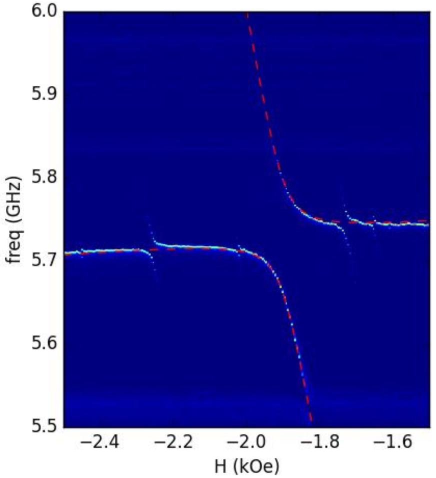


After mounting





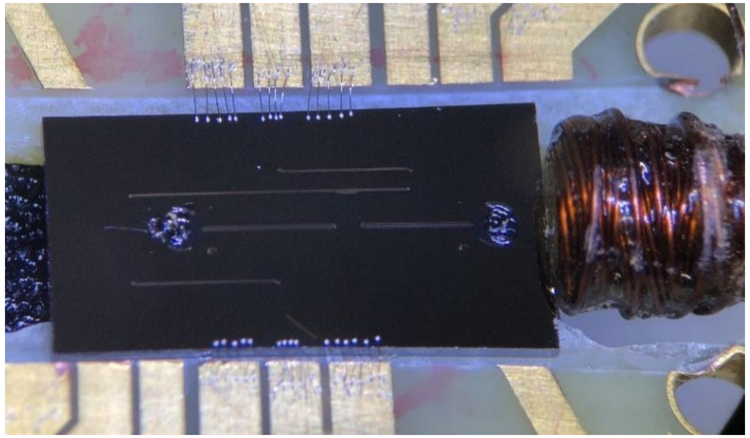


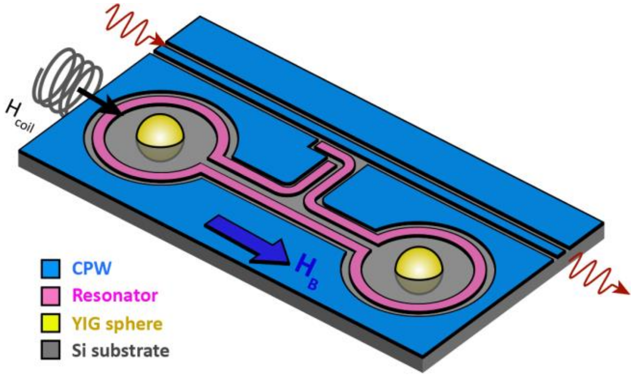


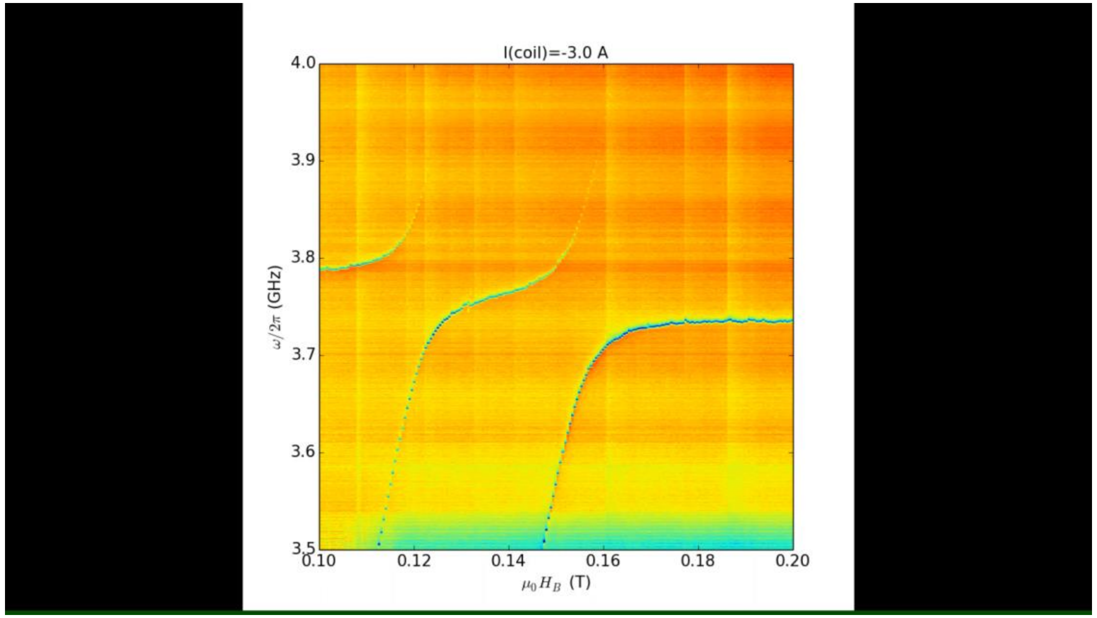
Yi Li, et al. (under review in PRL)

Recent progress 2:
Remote magnon-magnon coupling mediated by SC resonators

- Chip integration of 2 YIG sphere on a SC resonator
- Local SC coil (NbTi) for controlling magnon-magnon frequency detuning



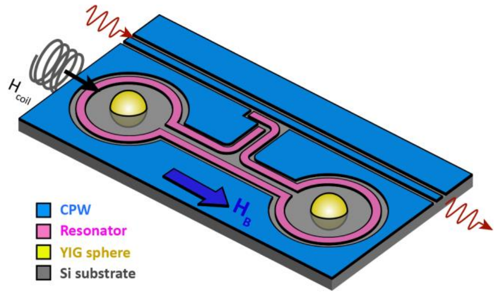




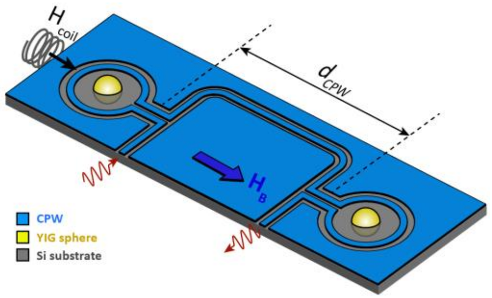
- Wire diameter: 0.1 mm
- Coil diameter: 4 mm
- Field: ~60 Oe/Amp
- Stray field on the 2nd YIG sphere: ~ 1.5 Oe/Amp

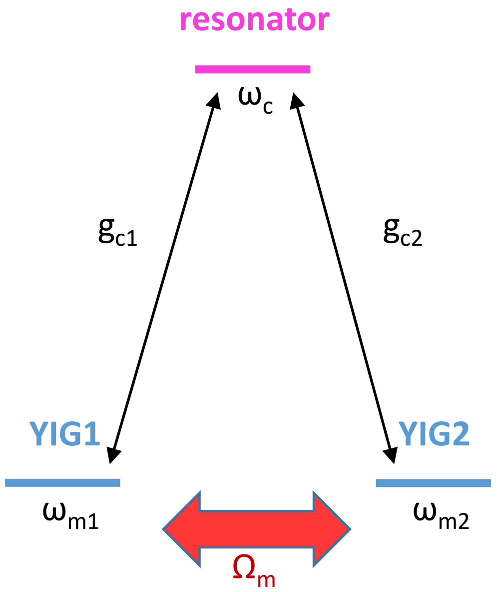
Yi Li, et al. (under review in PRL)

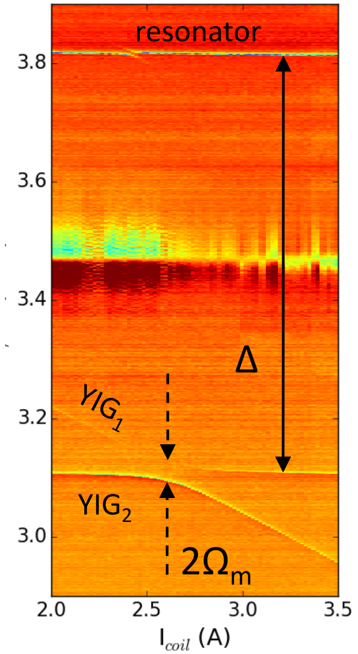
Recent progress 2:
Remote magnon-magnon coupling mediated by SC resonators

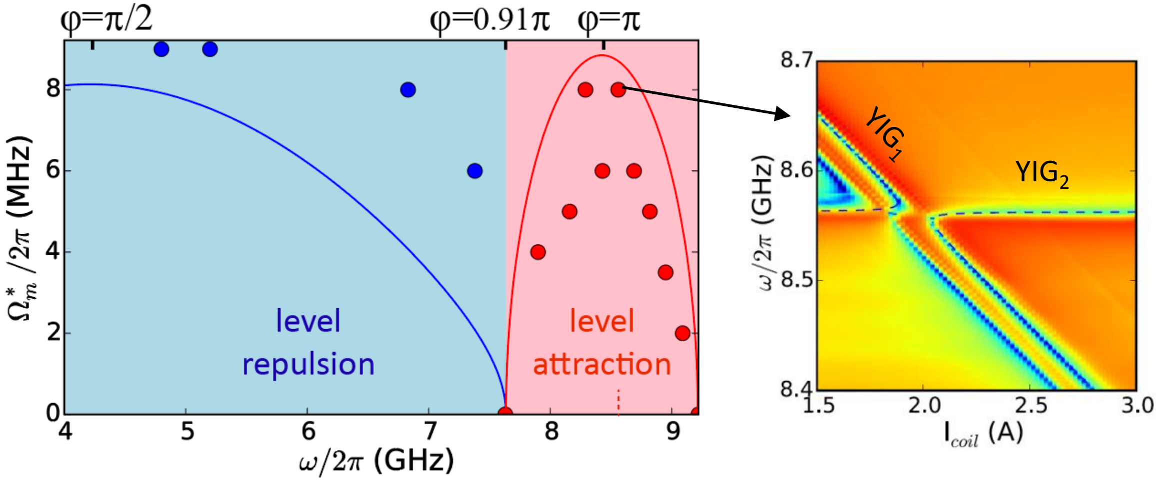


- Coherent magnon-magnon coupling in the dispersive regime
- Dissipative magnon-magnon coupling mediated by propagating microwave







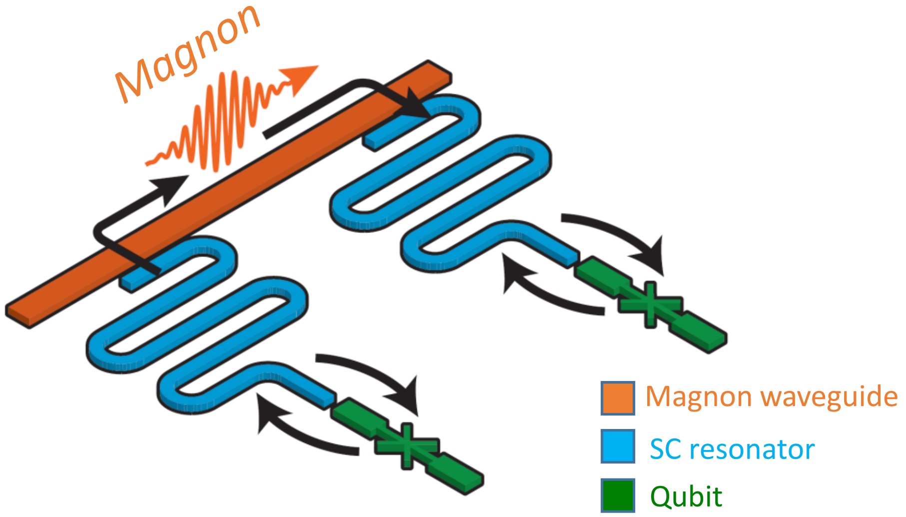


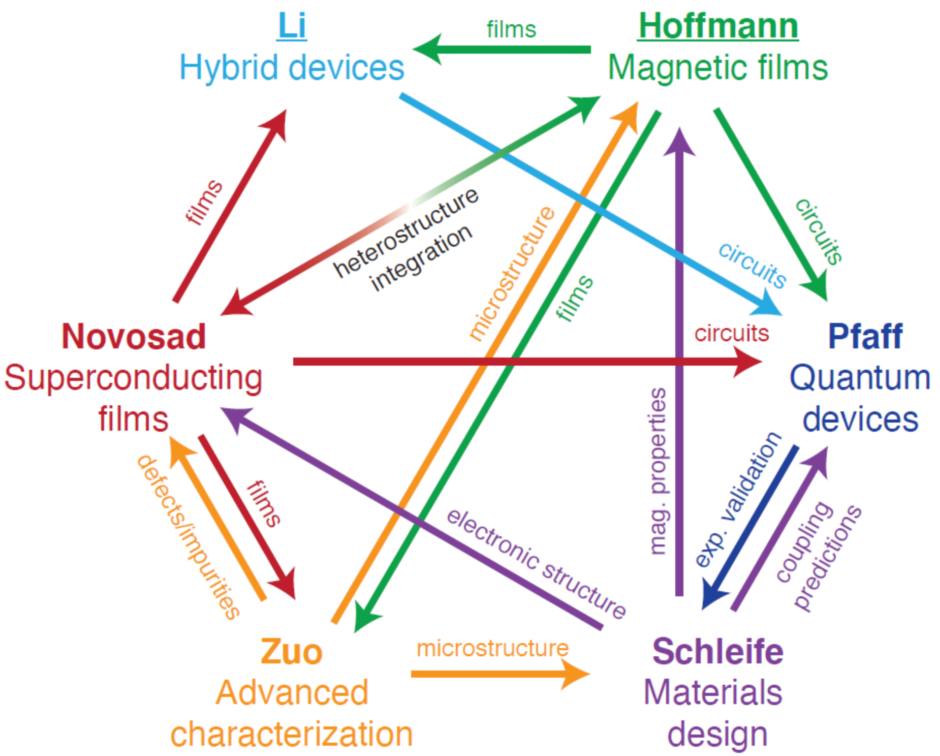
Yi Li, et al. (under review in PRL)

Future work 1: hybrid magnon quantum device

Goal:

- Explore low-damping magnetic thin-film materials for QIS application (YIG, CoFe, Heusler alloy)
- Utilize nonreciprocal magnon propagation in SC-resonator-magnon hybrid circuit
- Develop field-tolerant SC qubit for quantum magnonic application

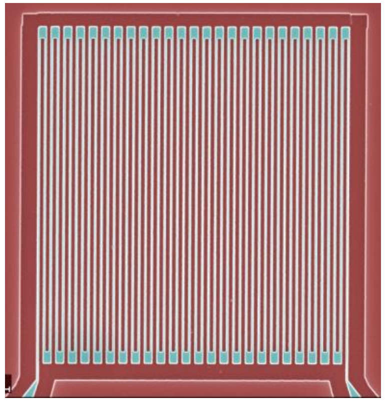




Future work 2: superconducting magnonics

Goal:

- Explore superconducting devices (SC NWs) for nonlinear SC resonators
- Explore high-impedance SC NW resonator for enhanced magnon sensitivity (reduced effective V)
- Cultivate SC vortex lattice for Bragg scattering of magnons in the nanoscale



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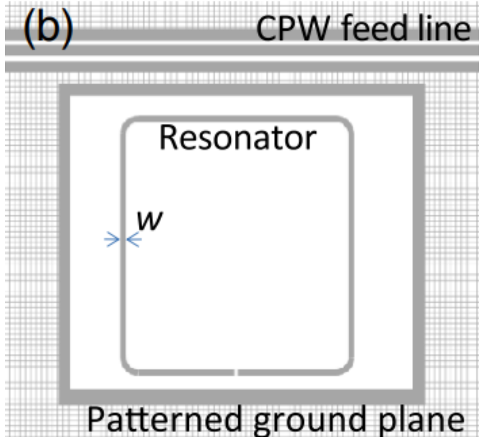
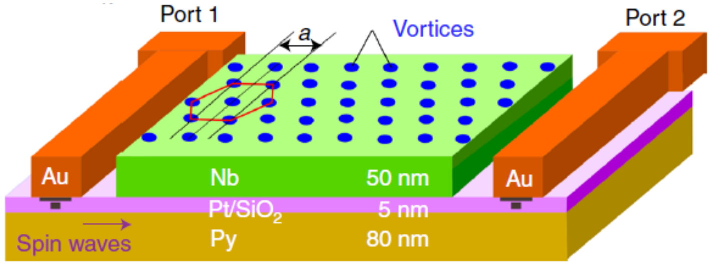
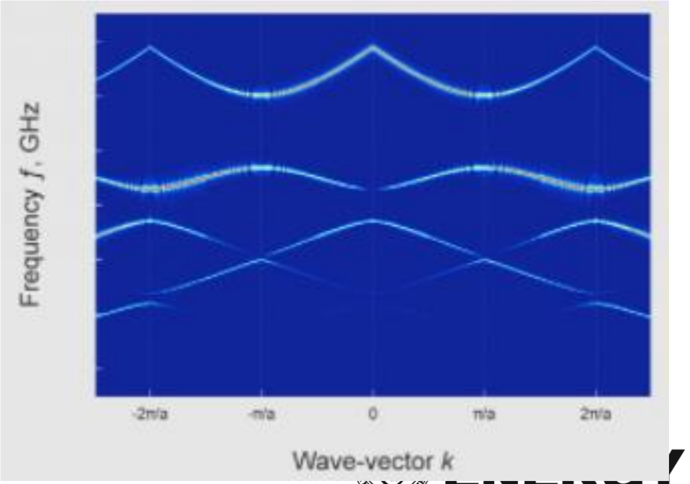


N. Samkharadze, et al. Phys. Rev. Appl. 5, 044004 (2016)

Collaboration & synergy: PHY, HEP, CNM



O. Dobrovolskiy, et al. Nature Phys. 15, 477 (2019)



Thank you!

Q & A?