Analog light-matter interfaces with spin waves

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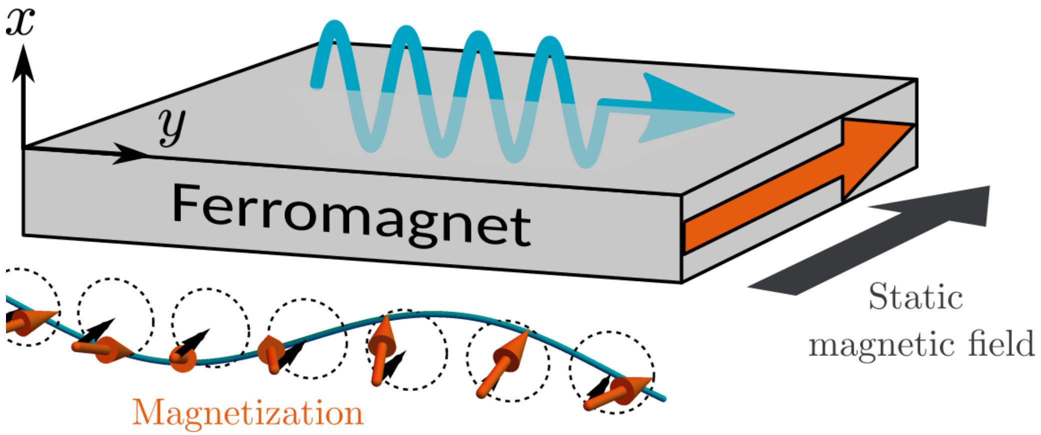
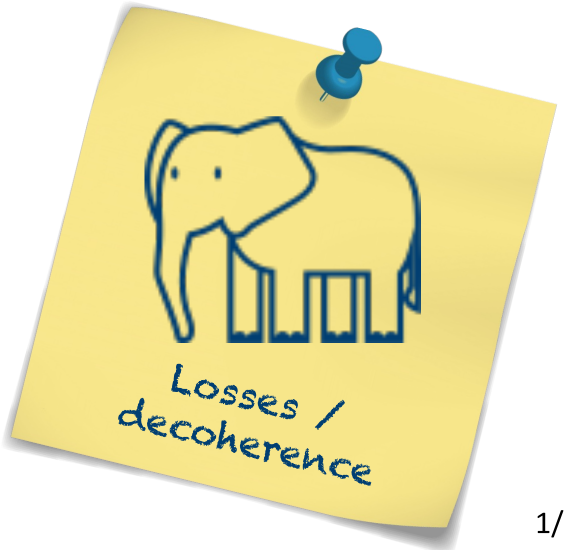
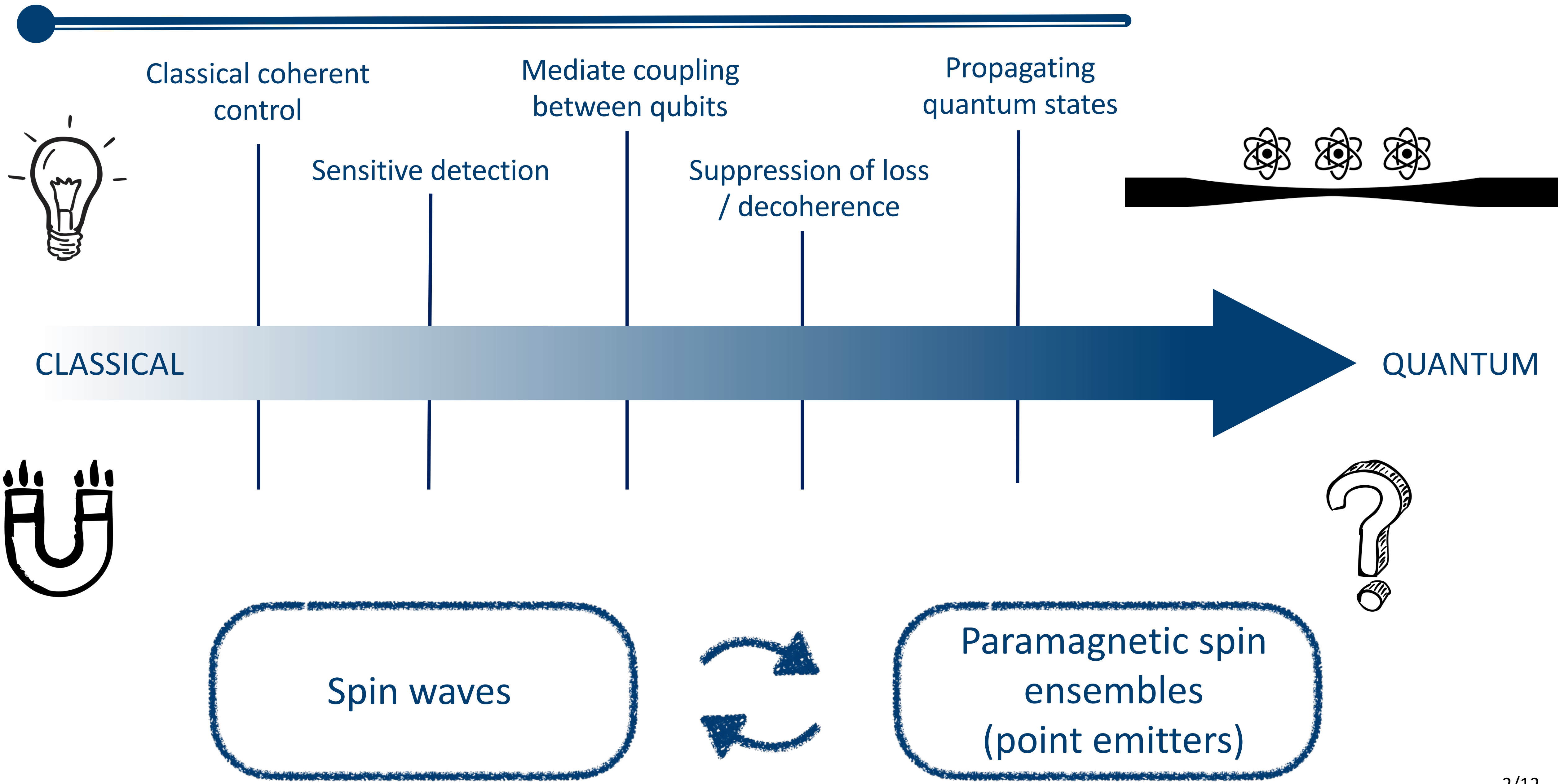
Spin waves for a quantum optician

- Complex & tunable dispersion
- GHz frequencies vs micron wavelengths
- Nonlinearity





How useful can spin waves be?



Classical coherent control

Sensitive detection

Mediate coupling between qubits

Suppression of loss / decoherence

Propagating quantum states

CLASSICAL

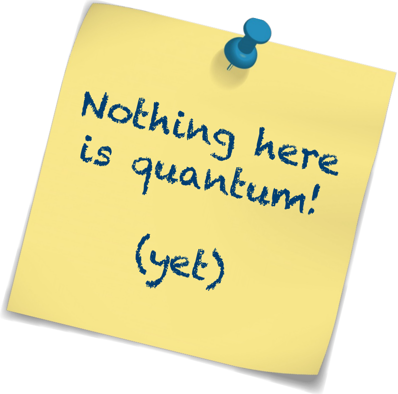
QUANTUM

Spin waves

Paramagnetic spin ensembles (point emitters)

Outline

- System & theory in a nutshell
- Spin wave control: “slow magnons”
- NV-assisted sensing of magnon fluctuations
- Other results: spectral hole burning & chiral spin interaction
- Conclusions & Outlook

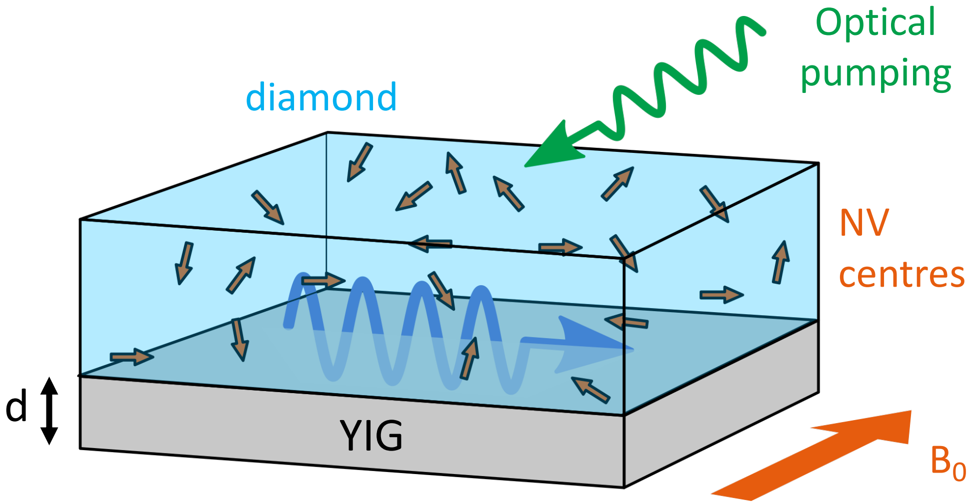


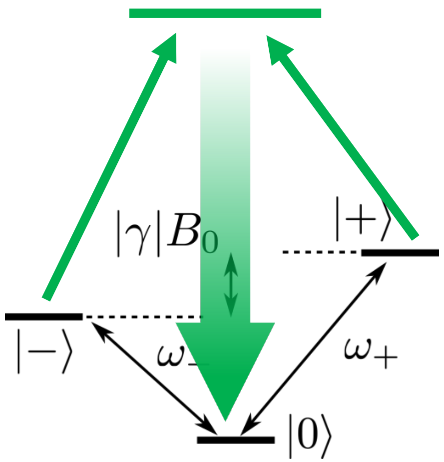
Nothing here is quantum!

(yet)

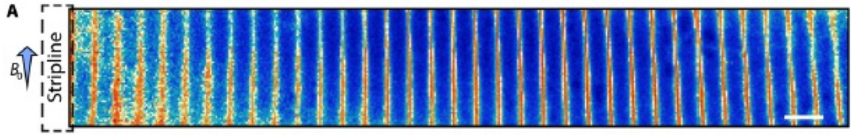
System

- YIG thin film
  - Spin wave mode indices $\{n = 0, \mathbf{k}\}$
- Ensemble of NV centres
  - Independent & randomly positioned
  - Include optical pumping





T. Van der Sar
(TU Delft)



Bertelli et al, Sci Adv 2020

CGB, T. van der Sar, O. Romero-Isart, PRB 105, 075410 (2022)

Theory in a nutshell

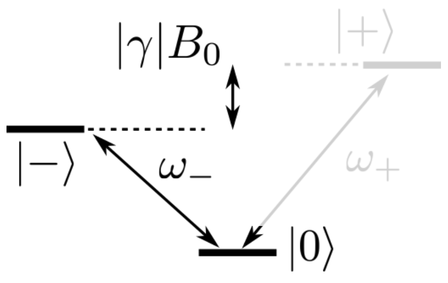
- Solve analytically & quantize magnon dynamical equations (Landau-Lifshitz)

$$\hat{H}_m = \sum_{\mathbf{k}} \omega_{\mathbf{k}} \hat{a}^\dagger_{\mathbf{k}} \hat{a}_{\mathbf{k}}$$

- Compute analytically coupling to NV centres

$$\hat{V} = -\hat{\boldsymbol{\mu}}_{\rm nv} \cdot \hat{\mathbf{B}}(\mathbf{r}_{\rm nv})$$

~ Jaynes-Cummings



- Write master equation

$$\dot{\rho} = -i\left[\hat{H}_{\rm NV} + \hat{H}_m + \hat{V}, \rho\right] + \sum_{\mathbf{k}} \gamma_{\mathbf{k}} \mathcal{D}_{\rm th}[\rho] + \mathcal{D}_{T_1}[\rho] + \mathcal{D}_{T_2}[\rho] + \mathcal{L}_{\rm pumping}[\rho]$$

Magnon damping NV Decay NV Dephasing Optical pumping

- Compute effective dynamics of magnons / NVs

arXiv:2305.19704 (quant-ph)

[Submitted on 31 May 2023 (v1), last revised 1 Jun 2023 (this version, v2)]

Tutorial: projector approach to open quantum systems

C. Gonzalez-Ballestero

CGB, T. van der Sar, O. Romero-Isart, PRB 105, 075410 (2022)

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Spin wave control: ``slow magnons”

- Collective back-action of the NV ensemble:
  - Frequency shift $\omega_{\mathbf{k}} \to \omega_{\mathbf{k}} + \delta_{\mathbf{k}}$
  - Modified damping $\gamma_{\mathbf{k}} \to \gamma_{\mathbf{k}} + \Gamma_{\mathbf{k}}$
  - Shifts calculated analytically:

Decoherence rate
~ 1/T$_2$*

$$\Gamma_{\mathbf{k}} \propto -\langle\hat{\sigma}_z\rangle \rho_{\mathrm{nv}} \frac{\kappa_{\mathrm{nv}}}{\kappa_{\mathrm{nv}}^2 + (\omega_{\mathbf{k}} - \omega_{\mathrm{nv}})^2}$$

NV density

NV-magnon detuning

  - Tunable through optical pumping, spin density, and external field

Damping can be fully suppressed by μw driving

K. Kustura, O. Romero-Isart, CGB, PRA 103, 053709 (2021)

P. Heidler, C. MF Schneider, K. Kustura, CGB, O. Romero-Isart, G. Kirchmair, PRA 103, 053709 (2021)

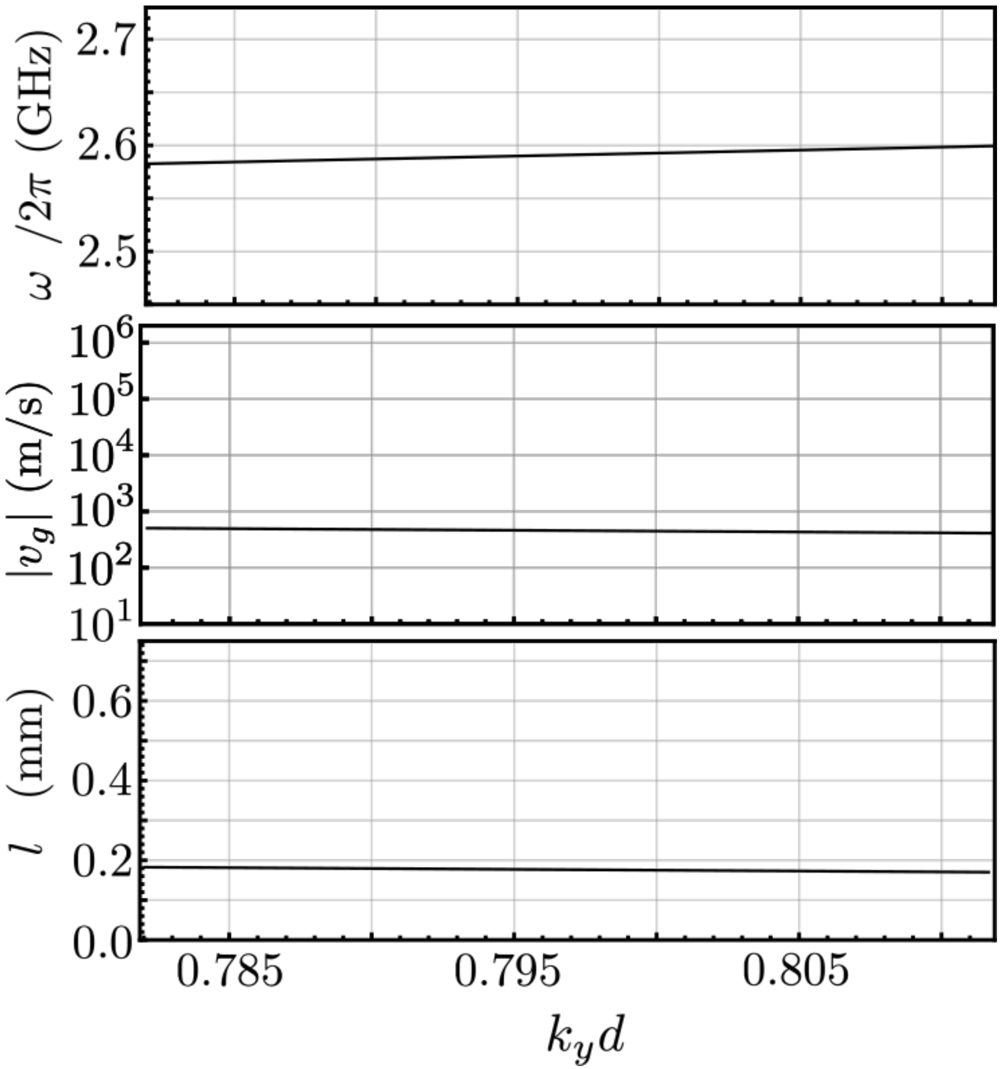
CGB, T. van der Sar, O. Romero-Isart, PRB 105, 075410 (2022)

Spin wave control: ``slow magnons”

- Propagation properties along Y

(density $\rho_{\mathrm{NV}} = 10^5 \mu\mathrm{m}^{-3}$)

NVs at room T, no pumping



CGB, T. van der Sar, O. Romero-Isart, PRB 105, 075410 (2022)

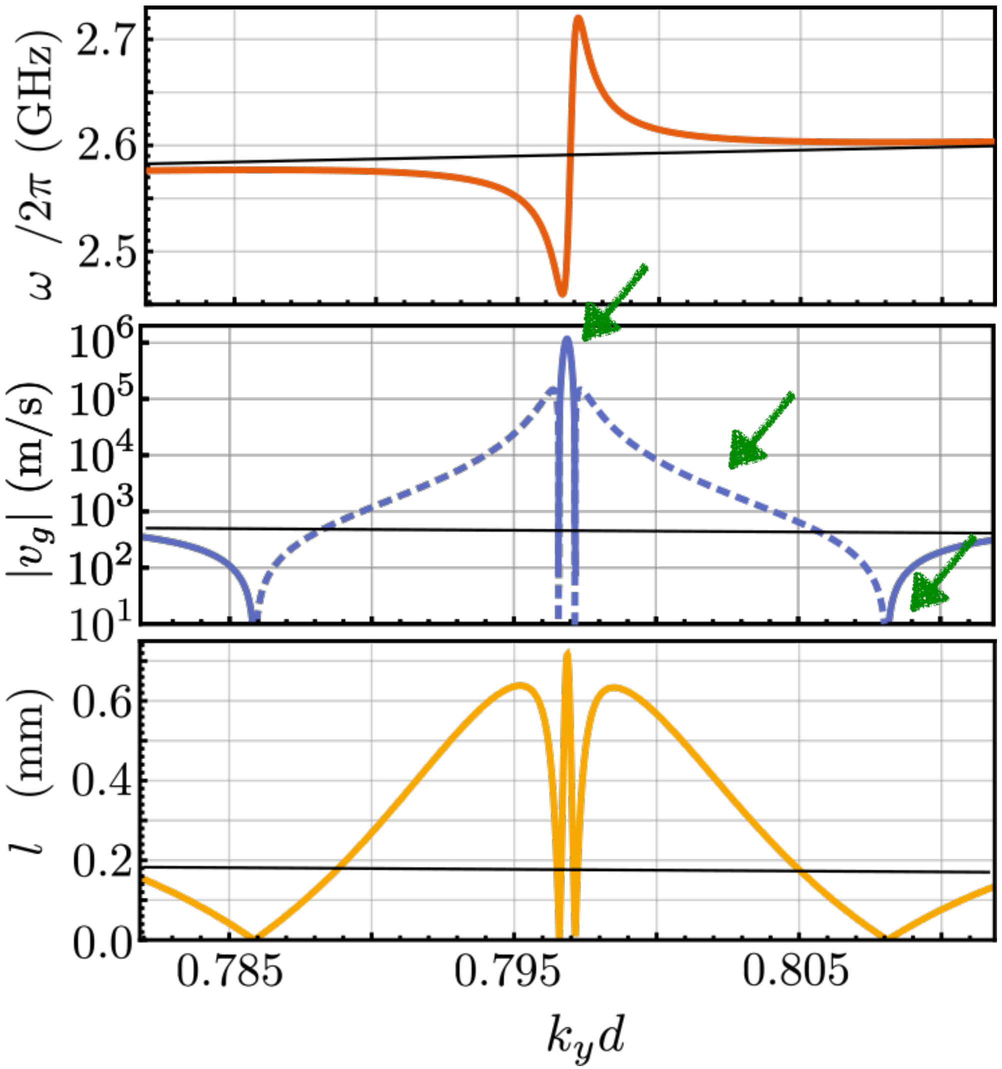
Spin wave control: ``slow magnons”

- Propagation properties along Y
(density $\rho_{\rm NV} = 10^5 \mu{\rm m}^{-3}$)
    - 1000x velocity enhancement @ resonance
    - Backward waves
    - Full suppression of velocity (``slow magnons”)
    - 3x increase in propagation length

- Spin wave propagation can be modified in multiple ways

- Tunable!

NVs at room T, optimal pumping



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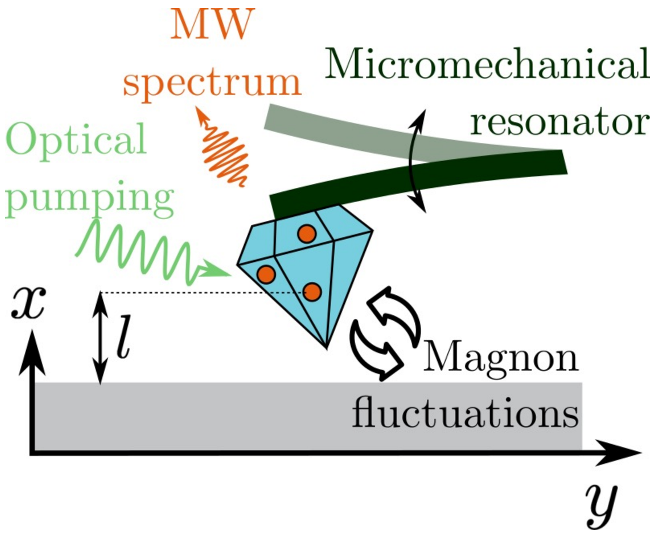
Spin wave sensing

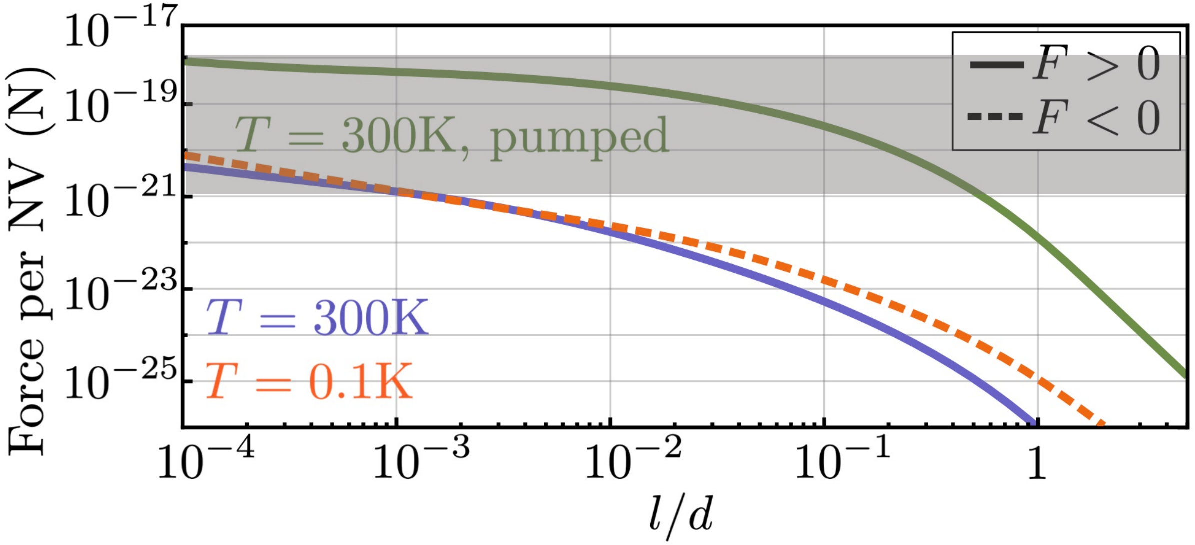
- Spin-wave back-action on a single NV centre:
  - Modifications of T_1 and T_2*
  - Frequency shift

NV – film distance

$$\delta(l) = \sum_{\mathbf{k}} |g_{\mathbf{k}}(l)|^2 \frac{\omega_{\text{nv}} - \omega_{\mathbf{k}}}{(\omega_{\text{nv}} - \omega_{\mathbf{k}})^2 + (\gamma_{\mathbf{k}}/2)^2}(1 + 2\bar{n}_{\mathbf{k}})$$

- Optical measurement of frequency shift
- Mechanical measurement of force





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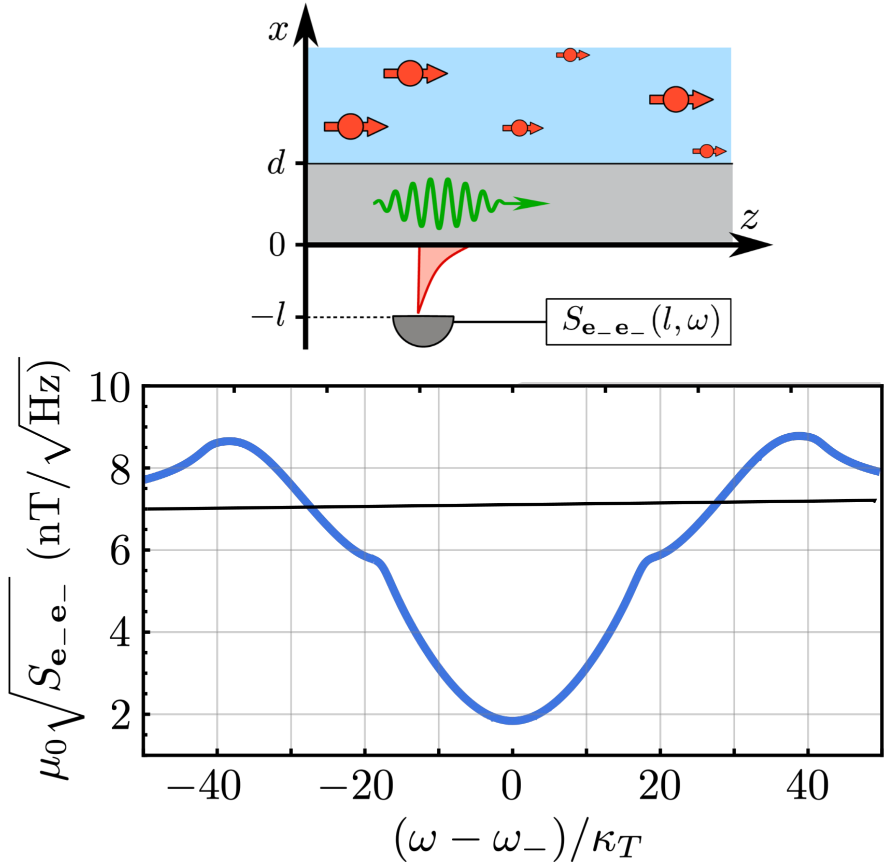
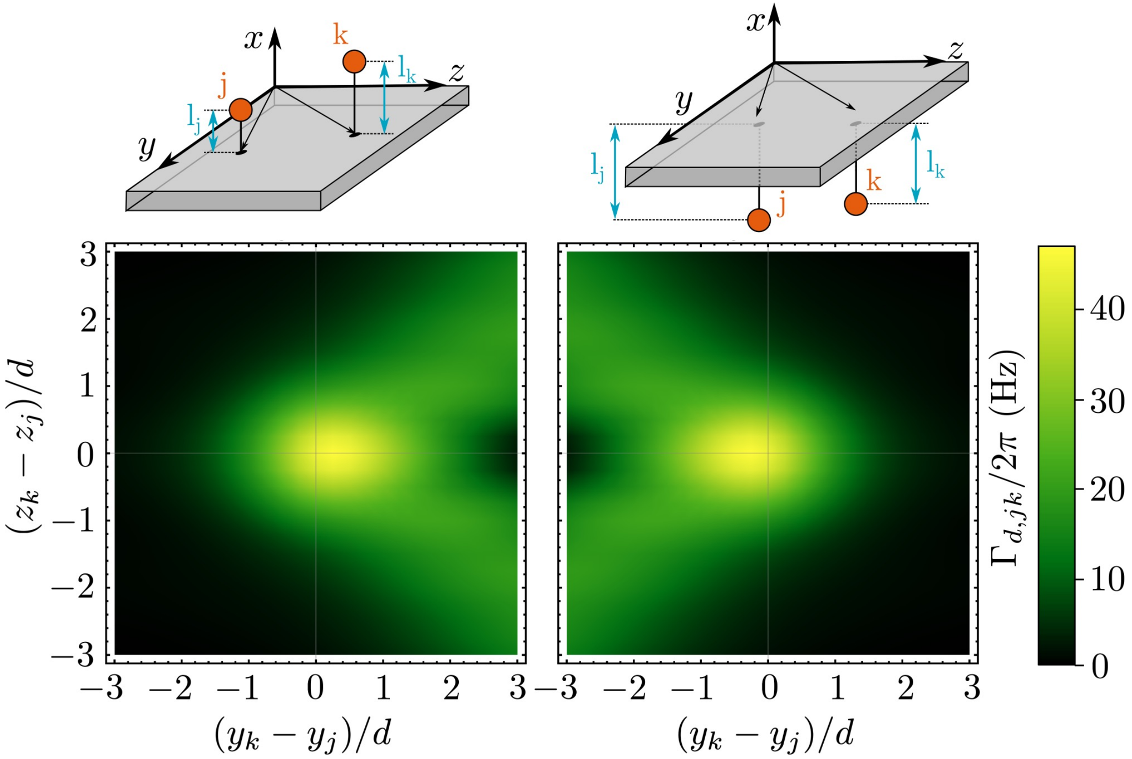
Other results: spectral hole burning & chiral spin interaction

- NVs can suppress magnon fluctuations



  - ‣ Enhanced SNR @ few-magnon level?

- Magnon-mediated coupling between NVs



  - ‣ Tunable cascaded systems?

CGB, T. van der Sar, O. Romero-Isart, PRB 105, 075410 (2022)

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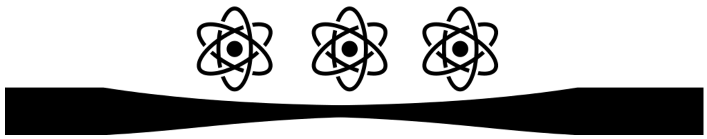


Classical coherent control ✓

Sensitive detection ✓

Mediate coupling between qubits ✓

Suppression of loss / decoherence ?

Propagating quantum states ?

CLASSICAL → QUANTUM

Plenty of room @ the bottom:

- Design & optimization
- Other platforms & degrees of freedom

Understanding magnon decoherence

- What we're doing now:

Classical dynamical equation (phenomenological)

Quantization

$$\dot{\rho}_m = -i\left[\hat{H}_m, \rho\right] + \sum_{\mathbf{k}} \gamma_{\mathbf{k}} \mathcal{D}_{\text{th}}[\rho]$$

Classical limit

- What we want to do:

(More) microscopic picture of decay channels

- Phonons
- Spin impurities
- Magnon-magnon coupling
- …

$$\dot{\rho}_m = -i\left[\hat{H}_m, \rho\right] + \sum_{\mathbf{k}} \gamma_{\mathbf{k}} \mathcal{D}_{\text{th}}[\rho]$$

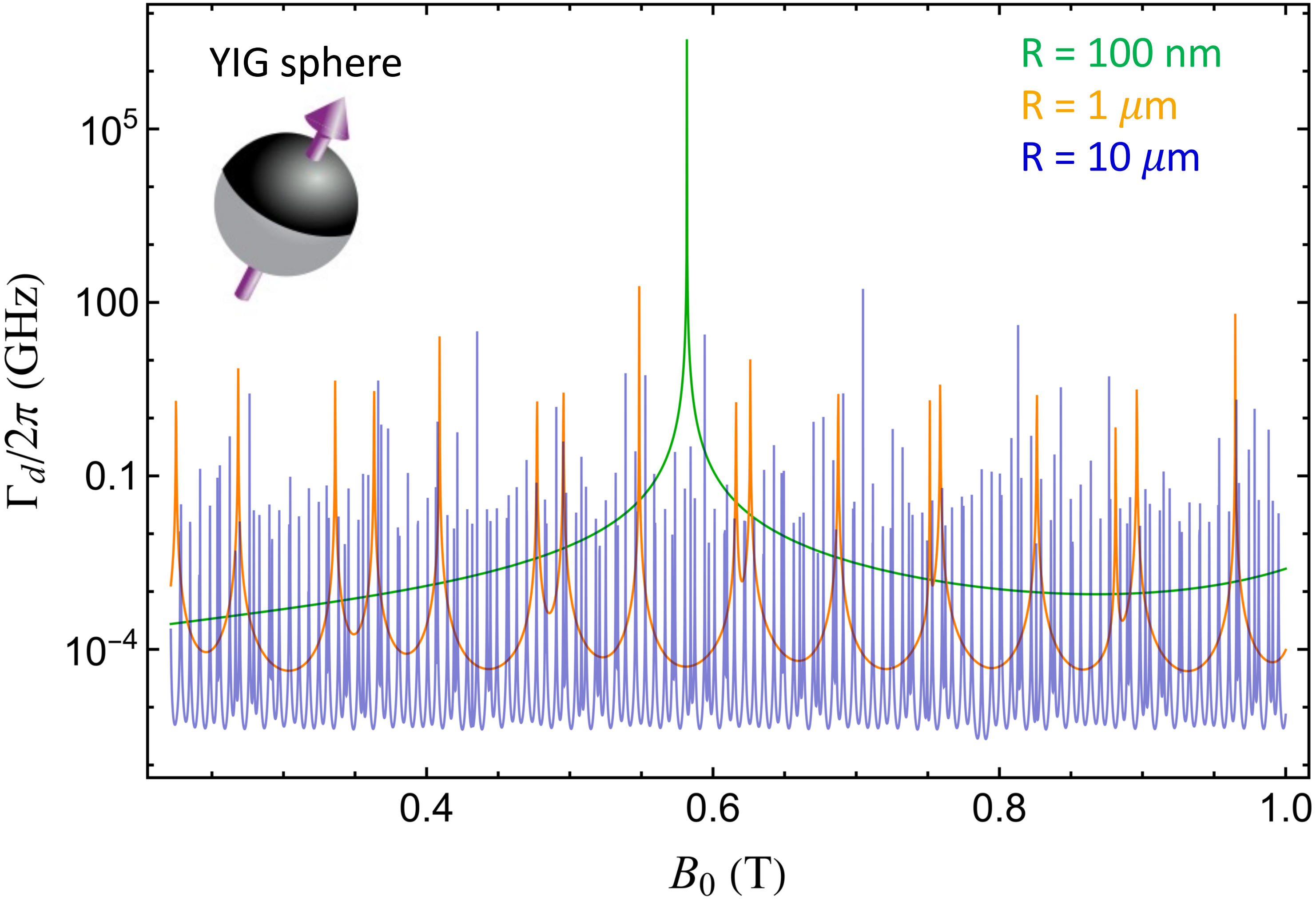
+ others!! (e.g. dephasing)

Expression for decoherence rate

Decoherence suppression

Understanding magnon decoherence

- Magnon-phonon linewidth (magnetoelastic theory)



WORK
IN
PROGRESS

- Purcell suppression / enhancement

Marco Brühlmann

Thank you

PRB 105, 075410 (2022)

O. Romero-Isart

T. van der Sar

https://www.gonzalezballesterogroup.com

IQI

TU Delft

universität innsbruck

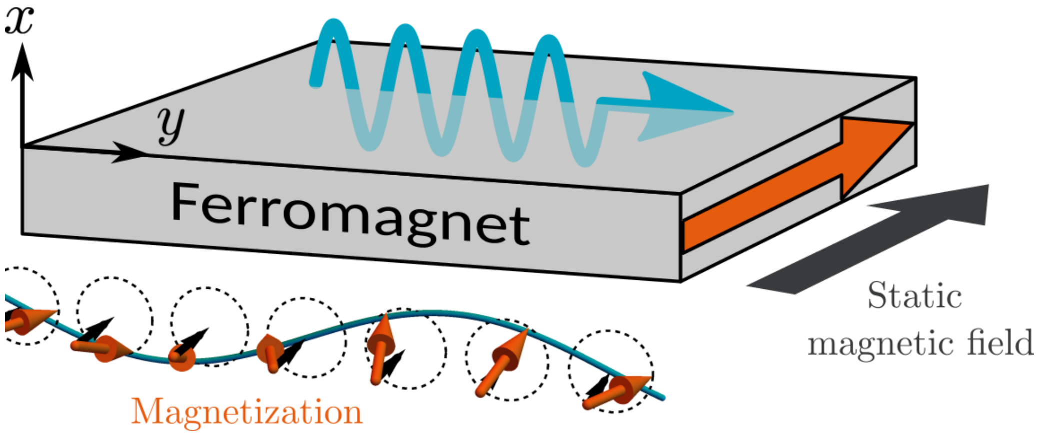
In a nutshell

- We propose an analog to light-matter interfaces

Coupling light to ensembles of electric dipole emitters

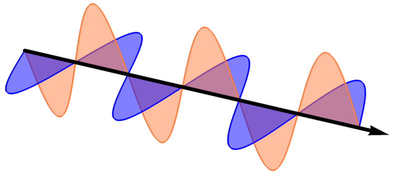
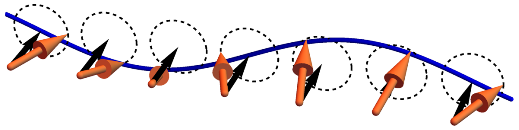
⇩

Coupling spin waves to ensembles of magnetic dipole emitters



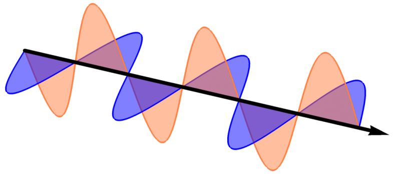
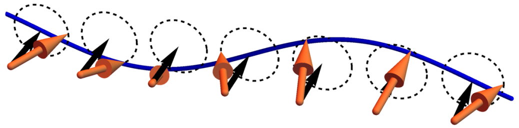
Hybrid electromagnetic + magnetization waves propagating in magnetized ferromagnetic materials

Why spin waves?

		
✓	‣ Simple dispersion relations ‣ Very linear (easy to treat) ‣ Easy to route & coherently control ‣ Low loss (coherent propagation)	‣ Complex and tunable dispersion relations ‣ Nonlinear ‣ CMOS-compatible
✗	‣ Complexity requires nanostructuring ‣ Dispersion tunability is very limited ‣ Nonlinear gates difficult	

- “Beyond-CMOS” computing
  - Cascaded devices/repeaters (2015)
  - Holographic memories (2016)
  - Transistors, MAJ gates, full adder chips (2014-2021)
  - Prime factorization (2016)

Why spin waves?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✗	‣ Complexity requires nanostructuring ‣ Dispersion tunability is very limited ‣ Nonlinear gates difficult	‣ Difficult to route & coherently control ‣ Higher losses

Couple to emitter ensembles (spoiler: solid-state spins)

- "Beyond-CMOS" computing
  - Cascaded devices/repeaters (2015)
  - Holographic memories (2016)
  - Transistors, MAJ gates, full adder chips (2014-2021)
  - Prime factorization (2016)
- Quantum magnonics
  - Great components for hybrid platforms
  - First observation of "quantumness"

Lachance-Quirion et al, *Hybrid Quantum Systems based on Magnonics*, Appl Phys Exp 12, 070101 (2019)

Lachance-Quirion et al, Science 367, aaz9236 (2020)

- Others (sensing, BEC physics…)

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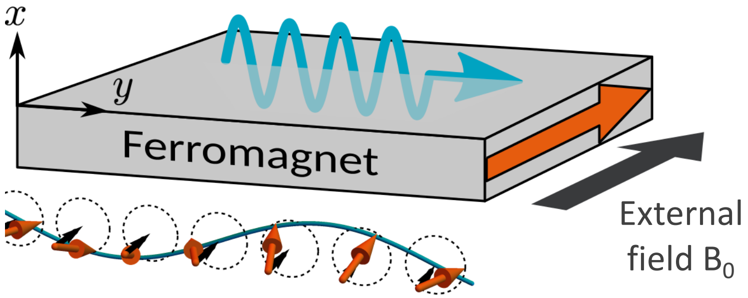
Spin waves

- Magnetization in a ferromagnet is described by Landau-Lifshitz equation (+ Maxwell)



$$\dot{\mathbf{M}}(\mathbf{r},t) = -\gamma\mu_0\mathbf{M}(\mathbf{r},t) \times [\mathbf{H}(\mathbf{r},t) + \mathbf{H}_{\text{eff}}(\mathbf{M};\mathbf{r},t)]$$

Effective field

- Linearization (~ Holstein-Primakoff):

$$\mathbf{M}(\mathbf{r},t) = M_S\mathbf{e}_z + \mathbf{m}(\mathbf{r},t)$$

- Diagonalization (eigenmode index β)

- Quantization $\mathbf{m}(\mathbf{r},t) \rightarrow \hat{\mathbf{m}}(\mathbf{r})$

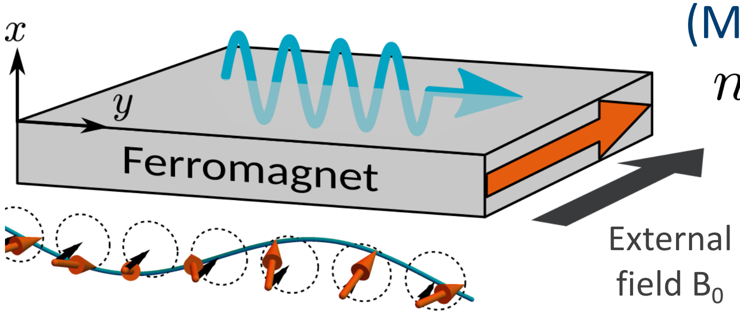
- Adding losses consistent with classical decay

$$\Longrightarrow \quad \dot{\rho} = -\frac{i}{\hbar}\left[\hbar\sum_{\beta}\omega_\beta \hat{s}_\beta^\dagger \hat{s}_\beta, \rho\right] + \gamma_\beta \mathcal{D}_{\text{th}}[\rho]$$

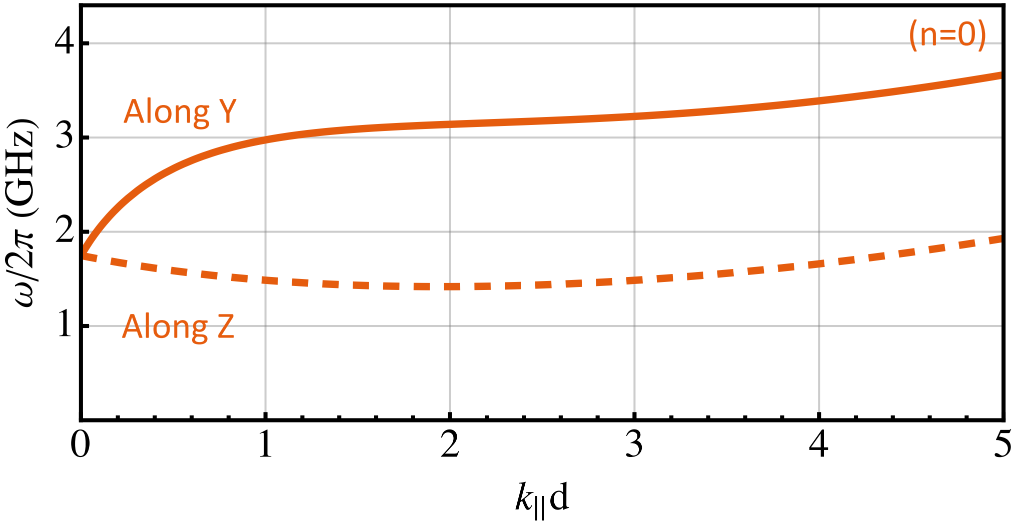
CGB, J. Gieseler, O. Romero-Isart, PRL 124, 093602 (2019)
CGB, D. Hümmer, J. Gieseler, O. romero-Isart, PRB 101, 125404 (2019)
CGB, T. van der Sar, O. Romero-Isart, PRB 105, 075410 (2022)

Spin waves

- Thin-film configuration, thickness d



(Mode indices n and $\mathbf{k}_{\parallel}$)

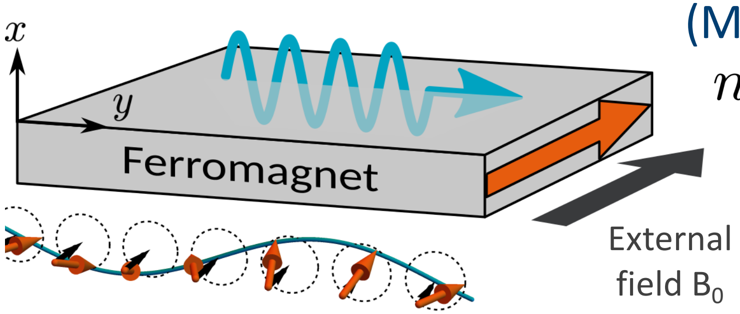


- ‣ Dispersion is highly anisotropic

- ‣ Different bands have different shapes (minima, maxima, degeneracies…)

Spin waves

- Thin-film configuration, thickness d



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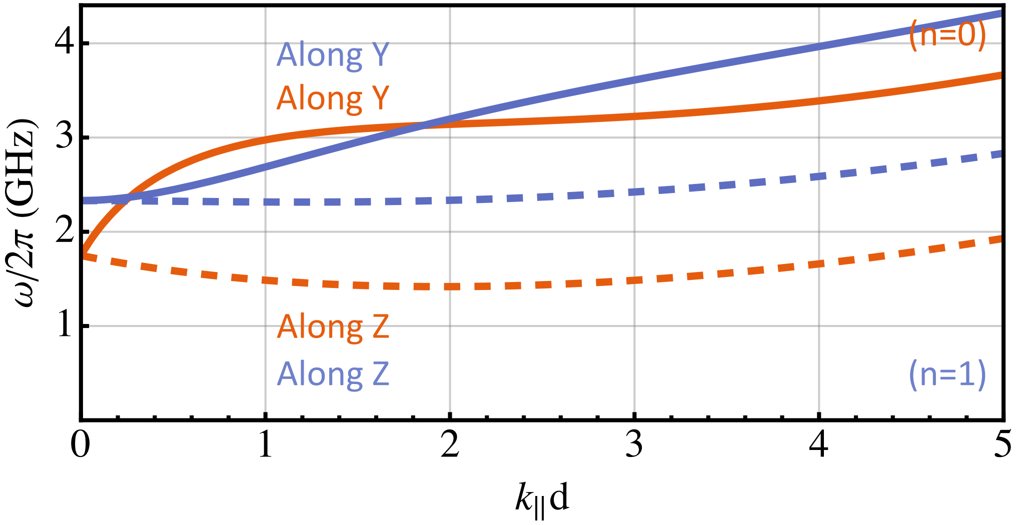

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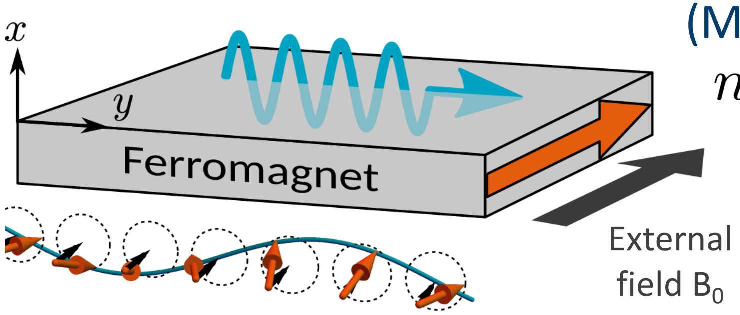

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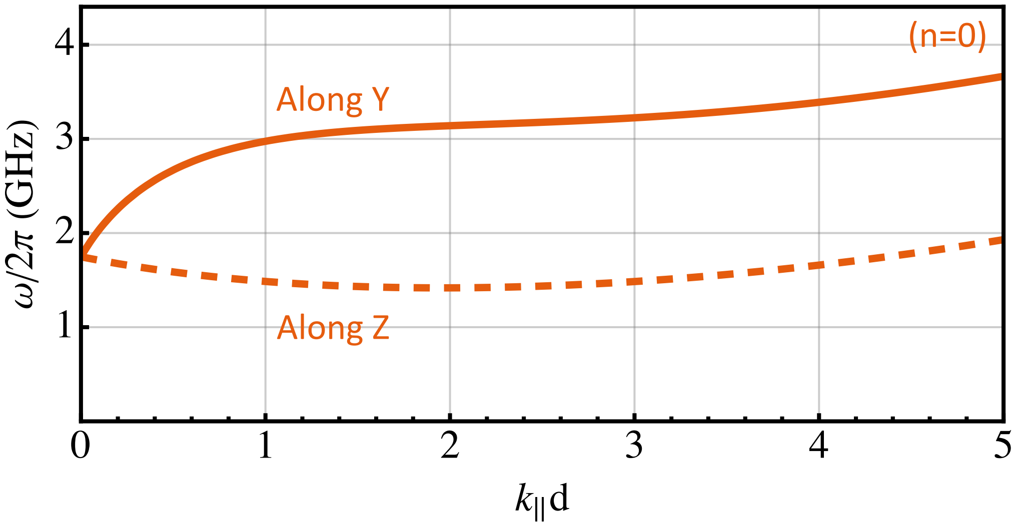
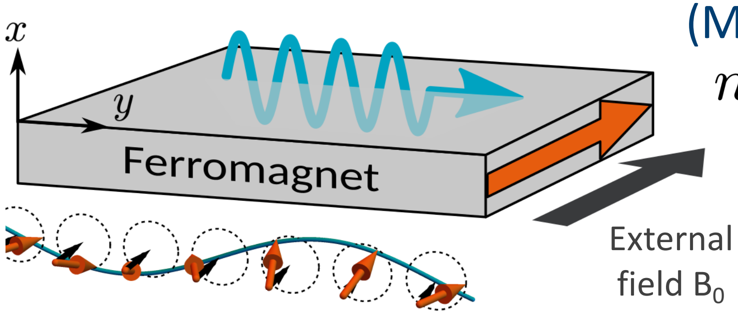


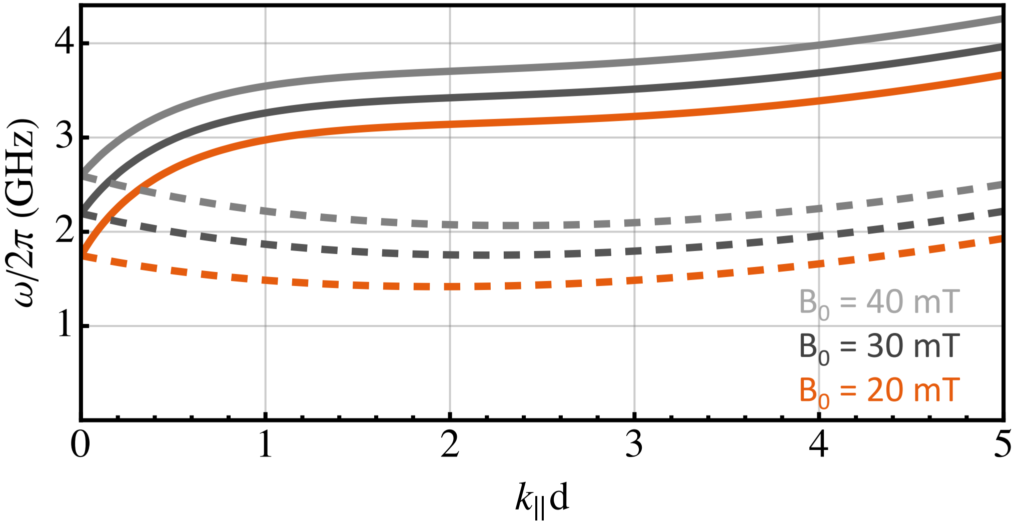
- Dispersion is highly anisotropic
- Different bands have different shapes (minima, maxima, degeneracies…)
- Bands tuneable via external field and geometry

Spin waves

- Thin-film configuration, thickness d



(Mode indices n and $\mathbf{k}_{||}$)



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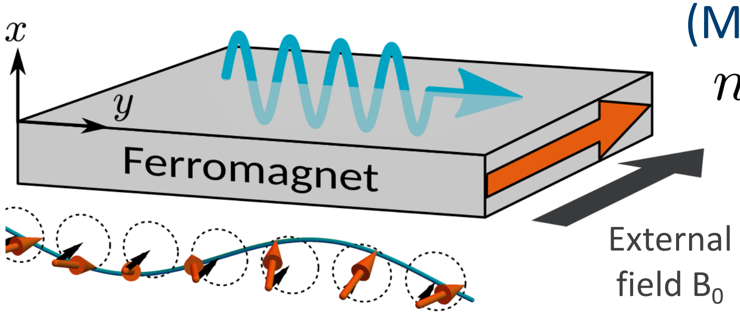

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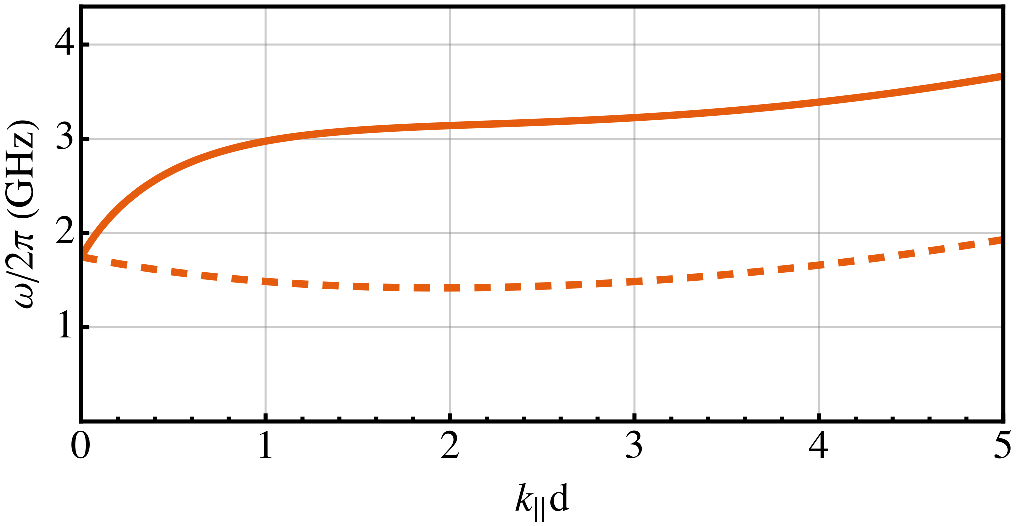

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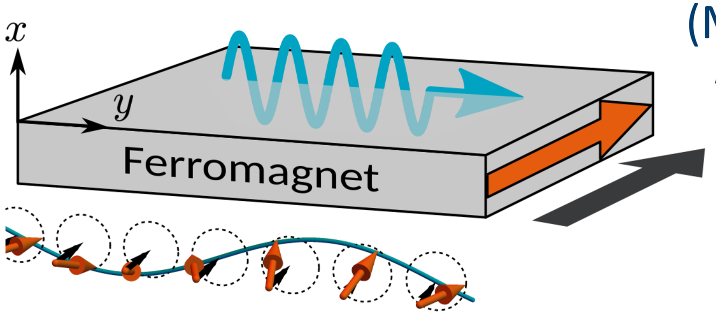

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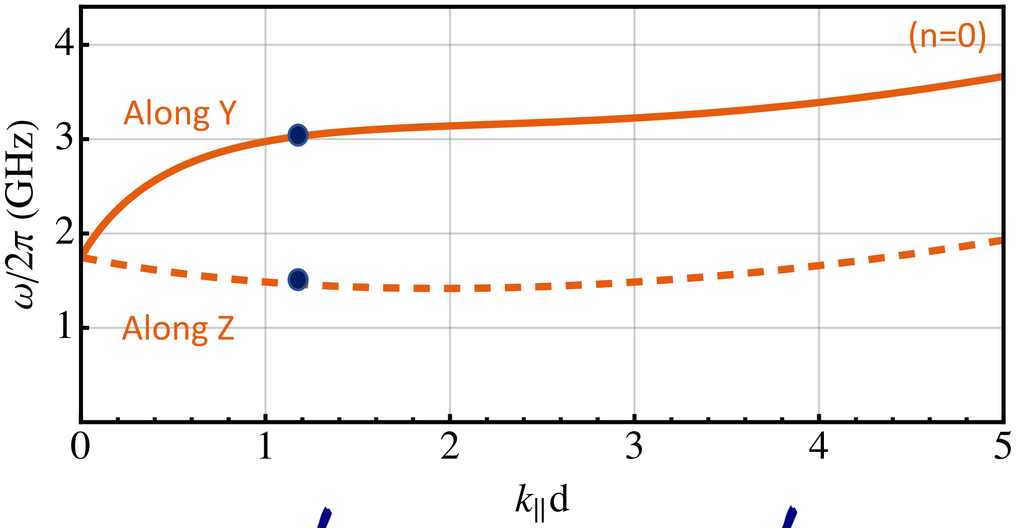
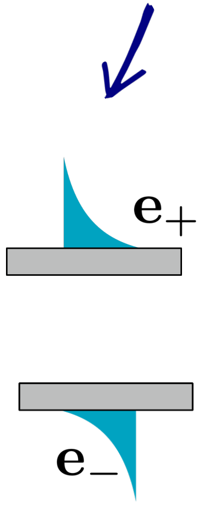


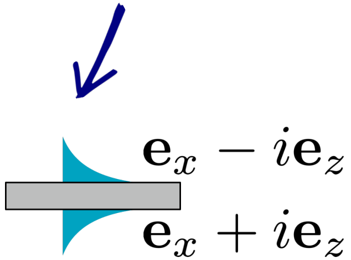
- Dispersion is highly anisotropic

- Different bands have different shapes (minima, maxima, degeneracies...)

- Bands tuneable via external field and geometry

- Polarization + modal field nonreciprocity





Much richer phenomenology than photonic analogues

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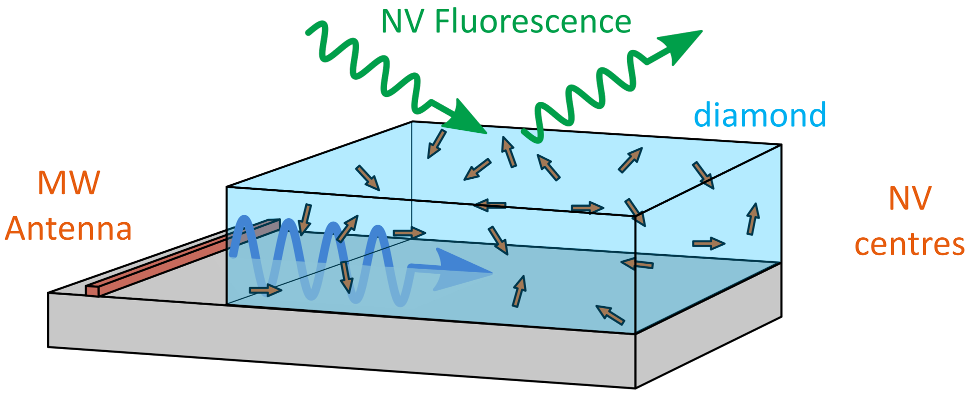
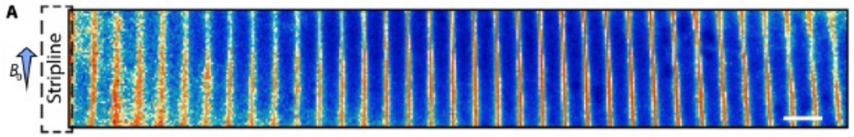
Coupling spin waves to spin ensembles

- Solid-state paramagnetic spins (e.g. NV centres)
  - Can be initialized via optical pumping
  - Ground-state has magnetic dipole transitions
  - Already used for spin-wave detection





Bertelli et al, Sci Adv 2020

- Description as 3 level system + higher levels:

$$\dot{\rho} = -\frac{i}{\hbar}\left[\frac{D_0}{\hbar}\hat{S}_z^2 + |\gamma|B_0\hat{S}_z, \rho\right] + \mathcal{D}_{T_1}[\rho] + \mathcal{D}_{T_2}[\rho] + \mathcal{L}_{\text{pumping}}\rho$$

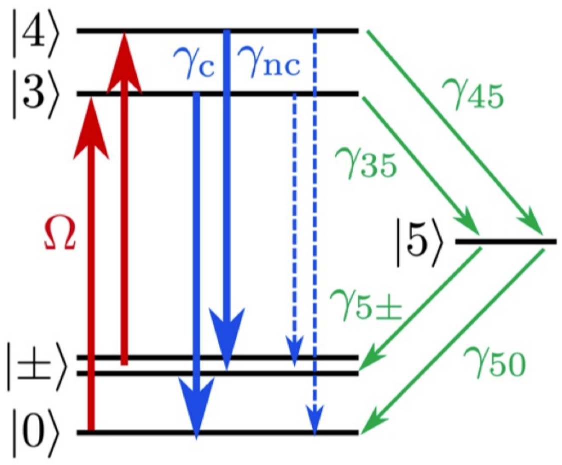
Zero-field splitting

Zeeman

Decay

Dephasing

Optical pumping (multiple terms)



Coupling spin waves to spin ensembles

- Coupling via magnetic dipole interaction $\hat{V} = -\hat{\boldsymbol{\mu}}_{\mathrm{nv}} \cdot \hat{\mathbf{B}}(\mathbf{r}_{\mathrm{nv}})$

$$\Big\Downarrow \ \text{RWA}$$

$$\hat{V} = \hat{V}_1 + \hat{V}_2 = \hbar \sum_{\beta} \left(g_\beta \hat{s}_\beta |-\rangle\langle 0| + \mathrm{H.c.} \right) + \hat{S}_z \sum_{\beta\beta'} G_{\beta\beta'} \hat{s}^\dagger_\beta \hat{s}_{\beta'}$$

Jaynes-Cummings

Effective dephasing

- Extend to N spins by summing over each spin in the ensemble
    - Spins assumed independent, randomly positioned, and parallel to B_0

CGB, T. van der Sar, O. Romero-Isart, PRB 105, 075410 (2022)

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Molding spin wave flow: ``slow magnons”

- Collective back-action of the NV ensemble obtained by tracing out (Born-Markov)

$$\dot{\rho} \sim -\frac{i}{\hbar}\left[\hbar \sum_{\beta} (\omega_\beta + \delta_\beta) \hat{s}_\beta^\dagger \hat{s}_\beta , \rho\right] + (\gamma_\beta + \Gamma_\beta)\mathcal{D}_{\rm th}[\rho]$$

  - Shifts calculated analytically:

Decoherene rate ~ T_2*

$$\Gamma_{n,\mathbf{k}_\parallel} \propto \varrho_{\rm nv} \frac{\kappa_{\rm NV}}{\kappa_{\rm NV}^2 + (\omega_{n,\mathbf{k}_\parallel} - \omega_{\rm NV})^2} \langle \hat{\sigma}_z \rangle$$

Spin wave frequency

NV frequency

  - Tunable through spin density, external field, and optical pumping

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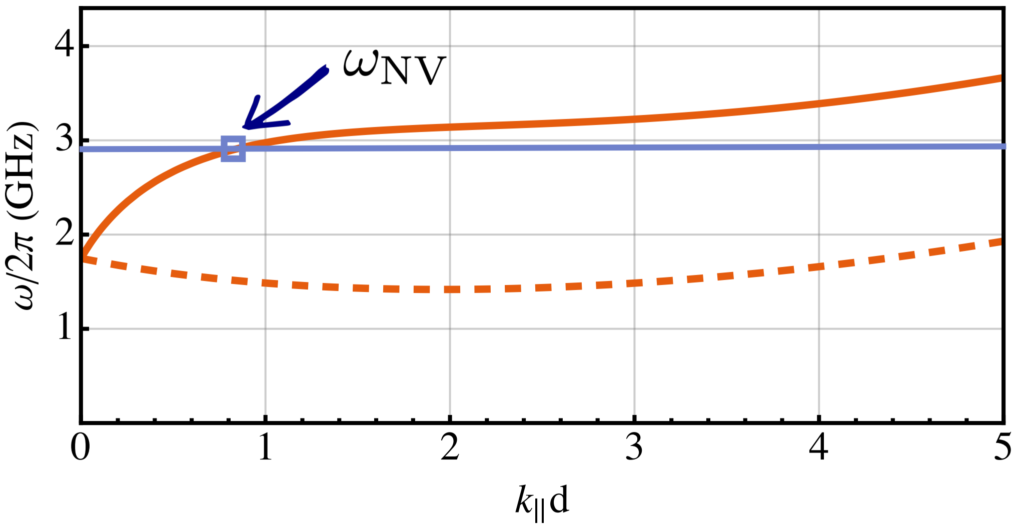
Molding spin wave flow: ``slow magnons"

- Propagation properties

(density $\rho_{\rm NV} = 10^5 \mu{\rm m}^{-3}$)



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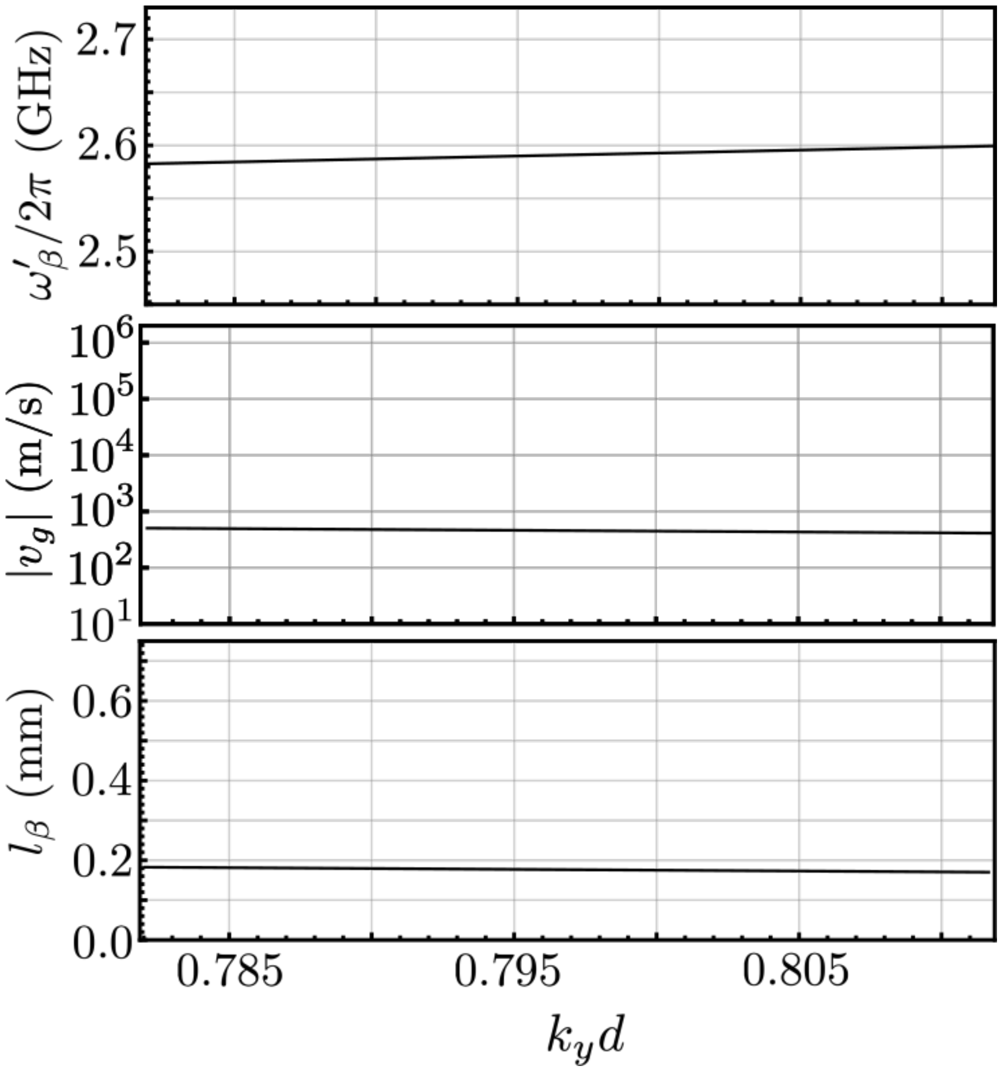
Molding spin wave flow: ``slow magnons”

- Propagation properties

(density $\rho_{\mathrm{NV}} = 10^5 \mu\mathrm{m}^{-3}$)

NVs at room T, no pumping



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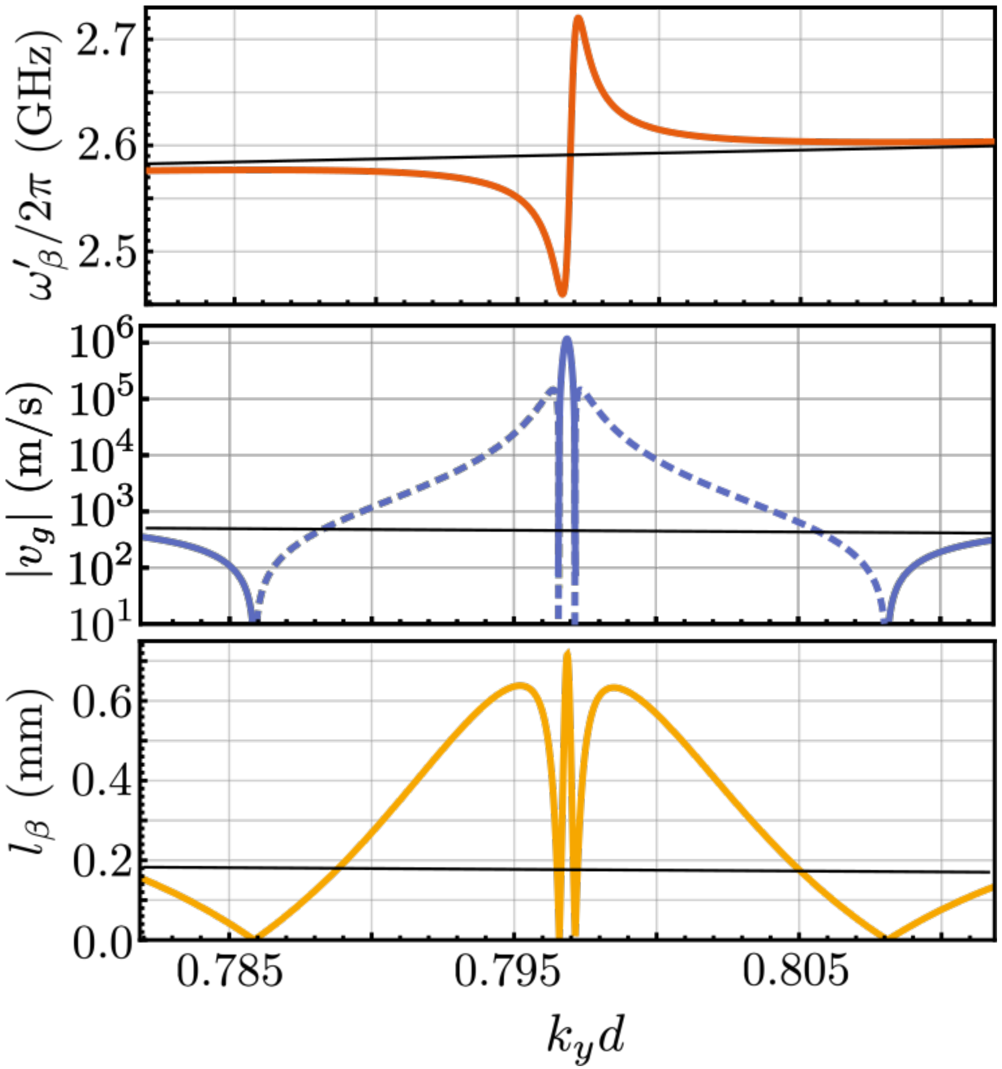
Molding spin wave flow: ``slow magnons”

- Propagation properties
(density $\rho_{\mathrm{NV}} = 10^5 \mu\mathrm{m}^{-3}$)
  - 1000x velocity enhancement @ resonance
  - Backward waves
  - Full suppression of velocity (``slow magnons”)
  - 3x increase in propagation length
- Spin wave propagation can be modified in multiple ways
- Tunable:
  - Frequency selective via B_0
  - Turned on/off by optical pumping

NVs at room T, optimal pumping



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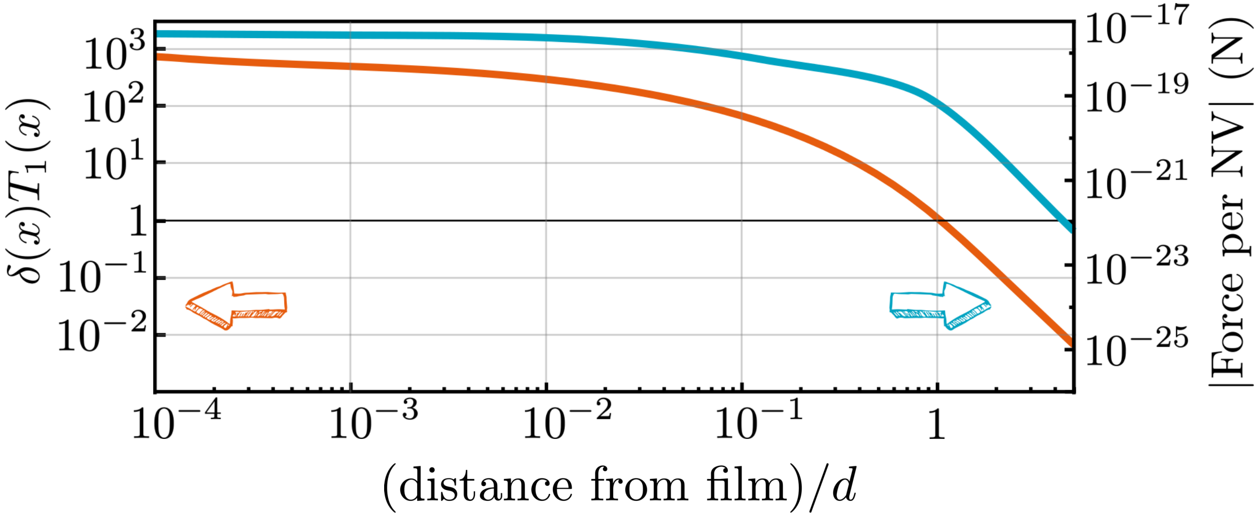
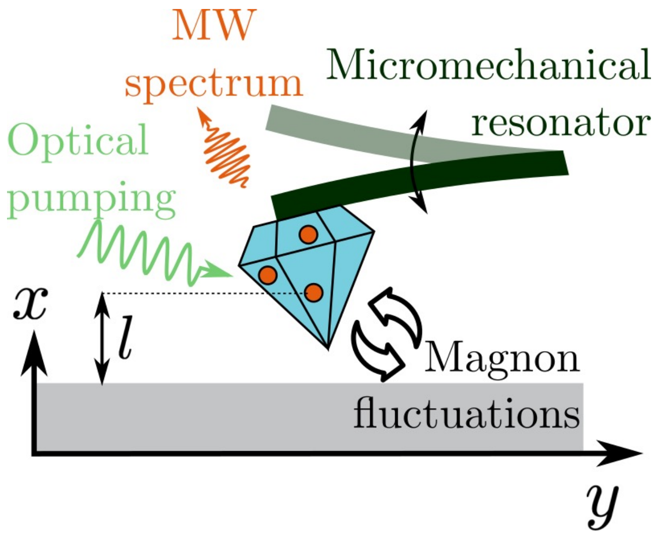
Spin wave sensing

- Trace out spin waves to determine back-action on single NV centre:
  - Modifications of T_1 and T_2*
  - Frequency shift

$$\delta(x) = \sum_{n\mathbf{k}_\parallel} |g_{n\mathbf{k}_\parallel}(x)|^2 \frac{(\omega_{\mathrm{NV}} - \omega_{n\mathbf{k}_\parallel})}{(\omega_{\mathrm{NV}} - \omega_{n\mathbf{k}_\parallel})^2 + (\gamma_{n\mathbf{k}_\parallel}/2)^2} (1 + 2\bar{n}_{n\mathbf{k}_\parallel})$$

- Optical measurement of frequency shift
- Mechanical measurement of force





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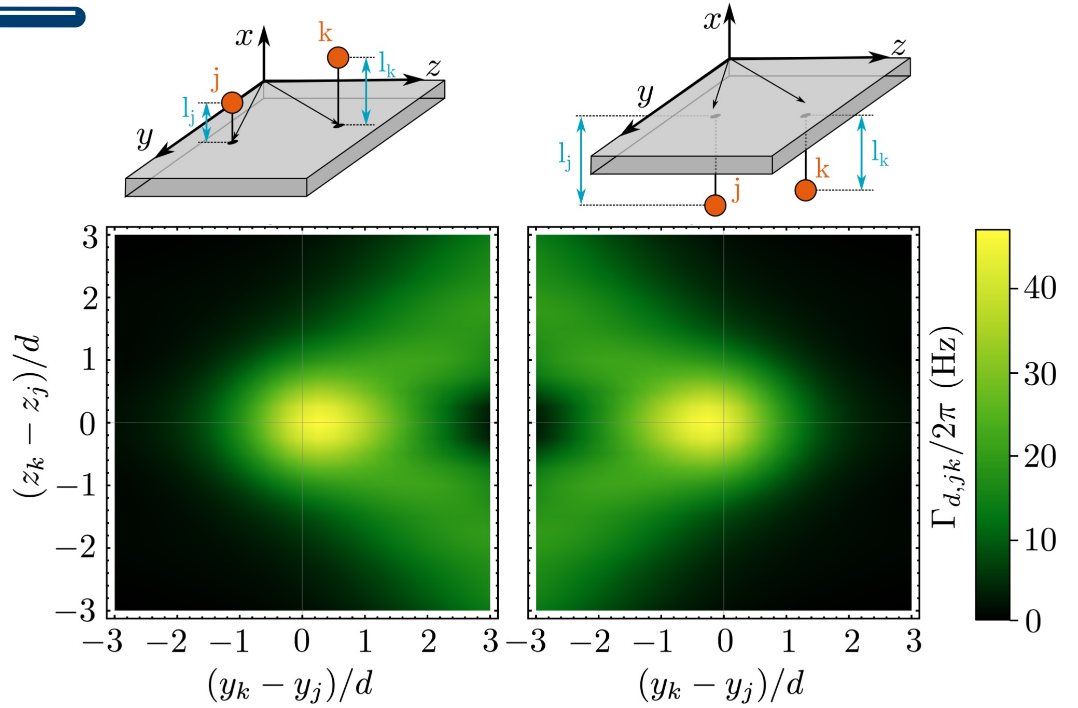
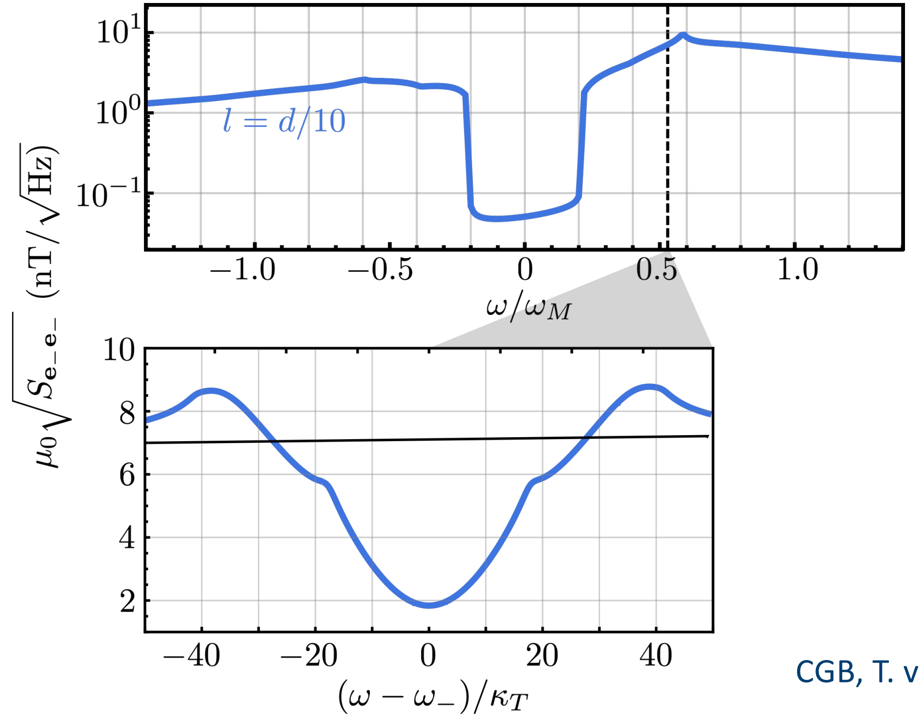
Other results: spin-spin couplings and magnetic noise suppression

- Spin wave bath generates complex coupling landscapes across the NV ensemble
  - Engineering Hamiltonians?
  - Cascaded systems?





- NV ensemble can be used to tune spin wave fluctuations
  - Noise suppression in magnonic circuits?
  - Toward single-magnon sensing?

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Outline

- In a nutshell
- Physics and description of spin waves
- Description of spin wave-paramagnetic spin interfaces
- Potential: slow magnons, magnon sensing, and more
- Conclusions & Outlook

Conclusions

- Spin wave – spin ensemble platforms are analog light-matter interfaces with great flexibility
    - Tunable by magnetic field, microwave drive, optical drive…
- Mutual back-action can be used to mold the flow of spin waves, modify/detect their fluctuations at the quantum level, and tailor spin-spin couplings
    - Classical magnonic information processing
    - Quantum magnonics (single-magnon detector, Hamiltonian engineering…)

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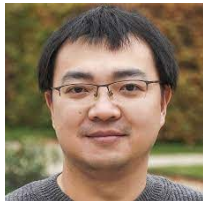
Outlook

- Classical information processing
  - Reconfigurable spin-wave devices
  - Pulse engineering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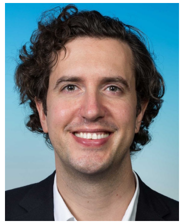
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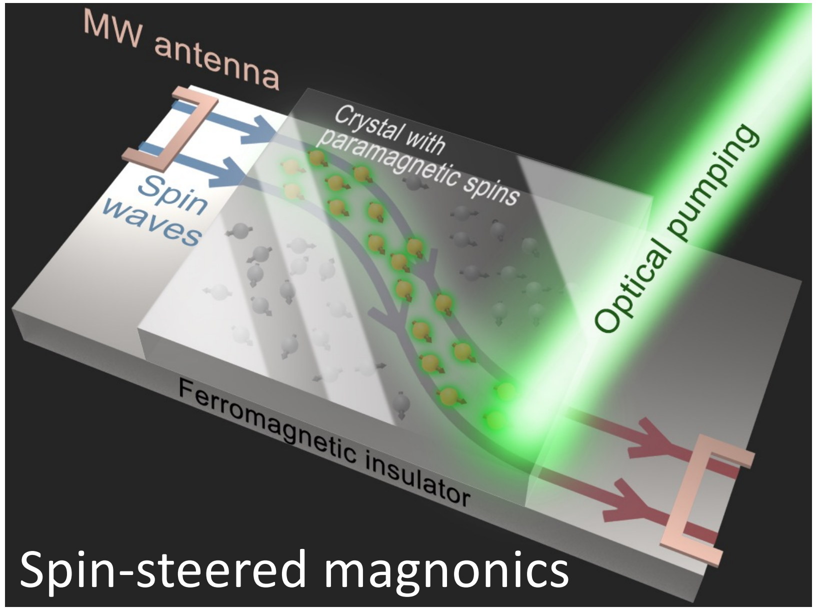

Spin-steered magnonics

- Quantum magnonics
  - Sensing (local magnetometry)
  - Magnonic squeezing

Thank you

C. Gonzalez-Ballestero, T. van der Sar, O. Romero-Isart, *Towards a quantum interface between spin waves and paramagnetic spin baths,*

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O. Romero-Isart

T. van der Sar