Probing magnetic phenomena using Nitrogen Vacancy (NV) Center in Diamond

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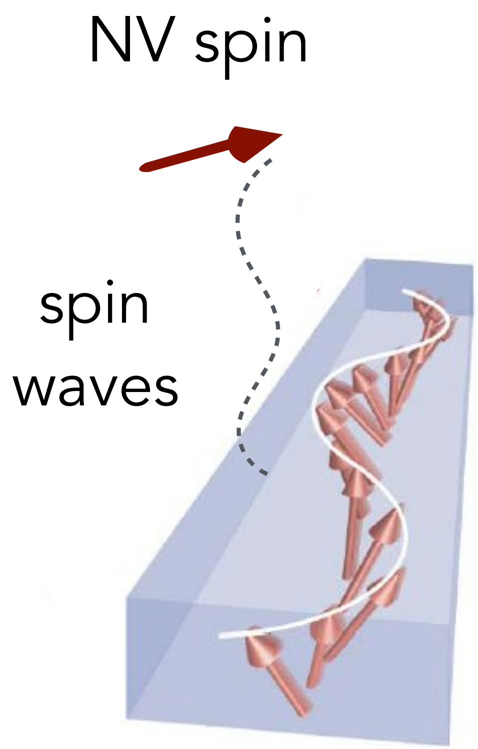


B.F. *et al.*, PRB Rapids (2018)

B.F. *et al.*, PRL (2018)

B.F. *et al.*, PRB Rapids (2019)

B.F., PRB (2019)

Outline

interaction of QI spins with magnetization dynamics

- NV centers as a non-intrusive spectroscopic probe of
  - → bulk spin-wave transport properties
  - → magnon statistics (chemical potential)
  - → magnetic defects

- Magnetic modes as a waveguide mediating coherent coupling between distant NV centers
  - → two-qubit gate mediated by the spin-superfluid mode hosted by an antiferromagnetic domain wall

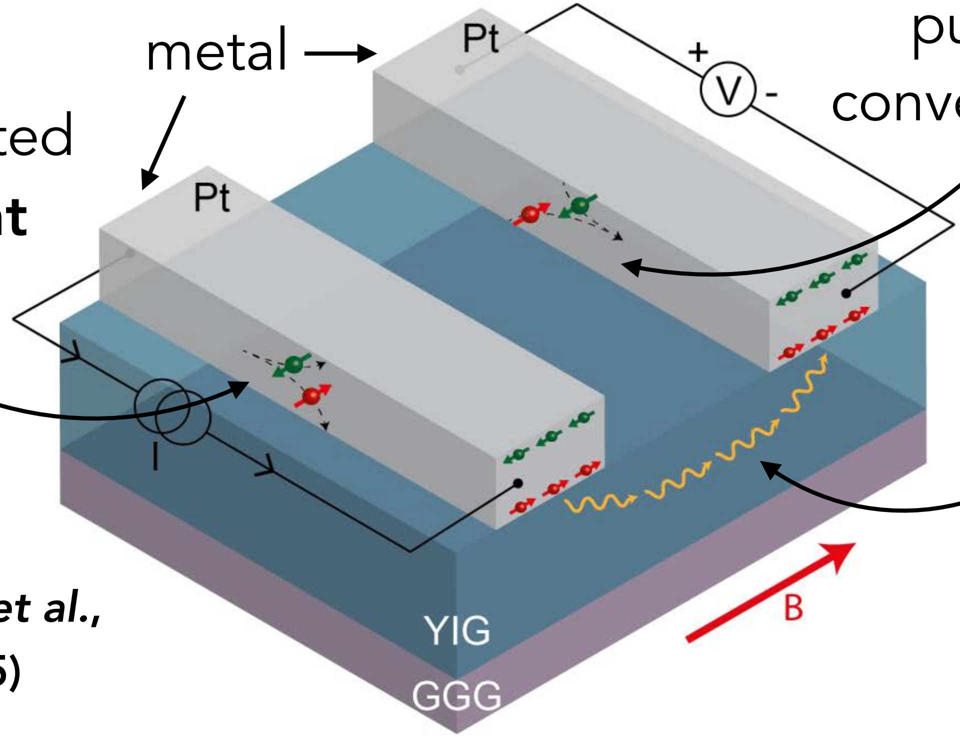
Transport in magnetic insulators

- Long-range transport with no Joule heating

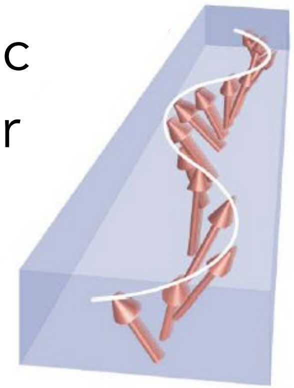
metal →

charge current converted into **pure spin current**

pure spin current converted into **voltage**



magnetic insulator



L.J. Cornelissen *et al.*, Nature (2015)

L.J. Cornelissen *et al.*, PRB (2016)

- hard to extract bulk properties due to interfacial charge-spin interconversion

direct bulk probe needed

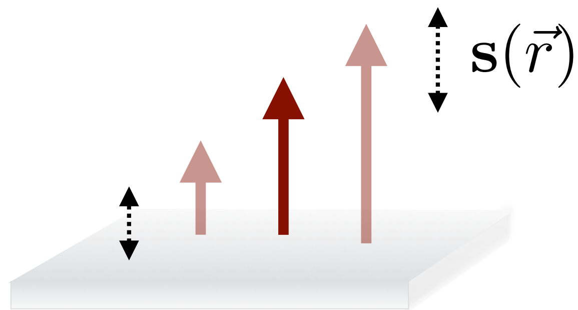
Transport and statistics in magnetic insulators

magnetic system with a symmetry axis (e.g., $\hat{z}$ axis)

→ Hamiltonian invariant under rotations in spin space

→ s_z conserved?

equilibrium || $\hat{z}$



Spin non-conserving interactions with the lattice (i.e., magnon-phonon coupling) always present

$$s_z(\vec{r}) = s - \boxed{a^\dagger(\vec{r})a(\vec{r})}$$

magnon number operator

$$\langle a^\dagger(\vec{r})a(\vec{r})\rangle \overset{?}{\rightarrow} = n_{BE}(\epsilon, T)$$

magnon number not conserved

$$\langle a^\dagger(\vec{r})a(\vec{r})\rangle \overset{?}{\rightarrow} = n_{BE}(\epsilon, T, \mu)$$

magnon number quasi-conserved

Transport and statistics in magnetic insulators

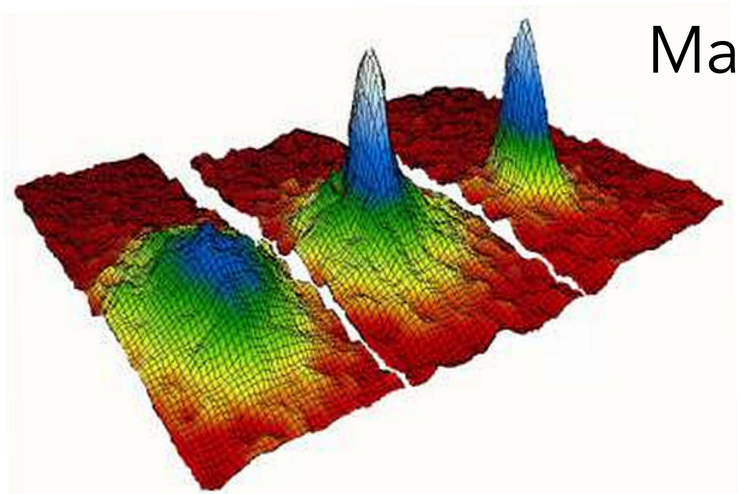
$$\langle a^\dagger(\vec{r})a(\vec{r})\rangle \to = n_{BE}(\epsilon, T)$$ magnon number not conserved

$$\langle a^\dagger(\vec{r})a(\vec{r})\rangle \to = n_{BE}(\epsilon, T, \mu)$$ magnon number ``approximately'' conserved

- Interpretation of non-local transport experiments suggests $n_{BE}(\epsilon, T, \mu)$

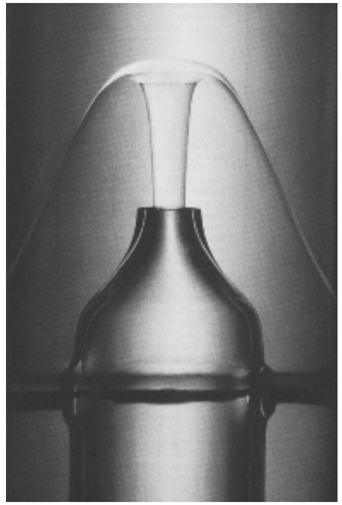
L. J. Cornelissen et al., PRB (2016)

Can we measure the magnon chemical potential directly?



Magnon Bose-Einstein condensation?

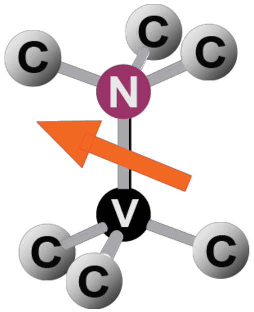
Spin superfluids?



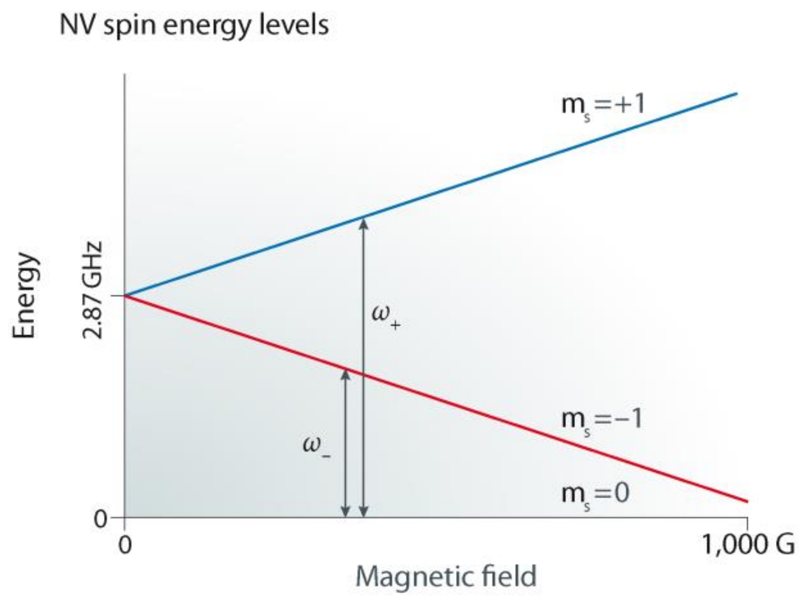
E. B. Sonin, Adv. Phys. (2010)

NV centers

Nitrogen vacancy (NV) center
in diamond



$$S = 1, \quad m_s = 0, \pm 1$$



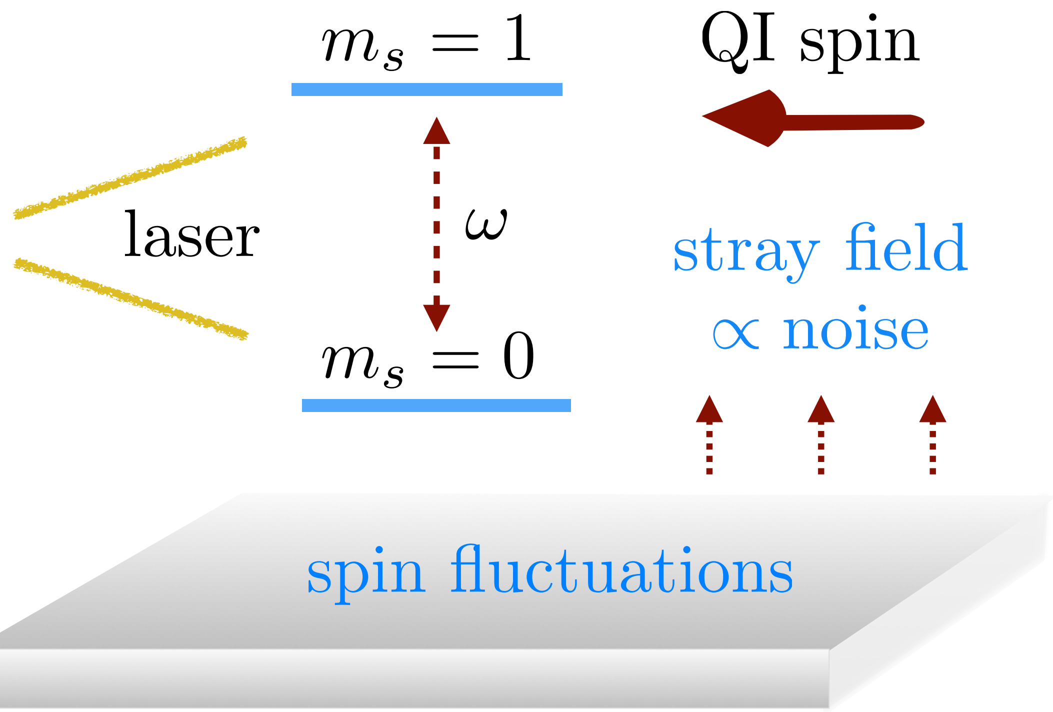
F. Casola *et al.*, Nature (2018)

- exceptional sensitivity to magnetic fields
- long relaxation and dephasing times
- spin state can be initialized and read out optically
- minimally-invasive magnetic field probe
- widely used to image static magnetic textures

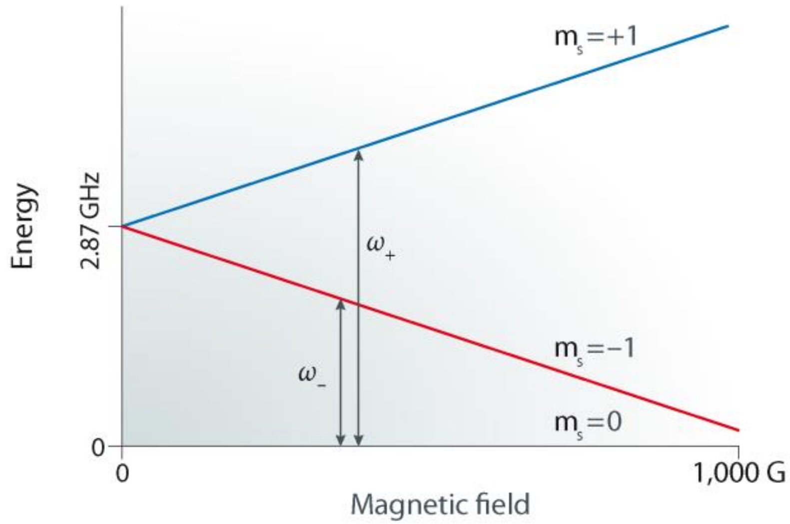
Relaxometry

Magnetic noise sensor probing **dynamical** magnetic phenomena

Response function ↔ $\Gamma(\omega) \propto$ noise at ω



Field-tunable spectrometer



T. van der Sar *et al.*, Nat. Comm. (2015)

C. Du *et al.*, Science (2017)

F. Casola *et al.*, Nature (2018)

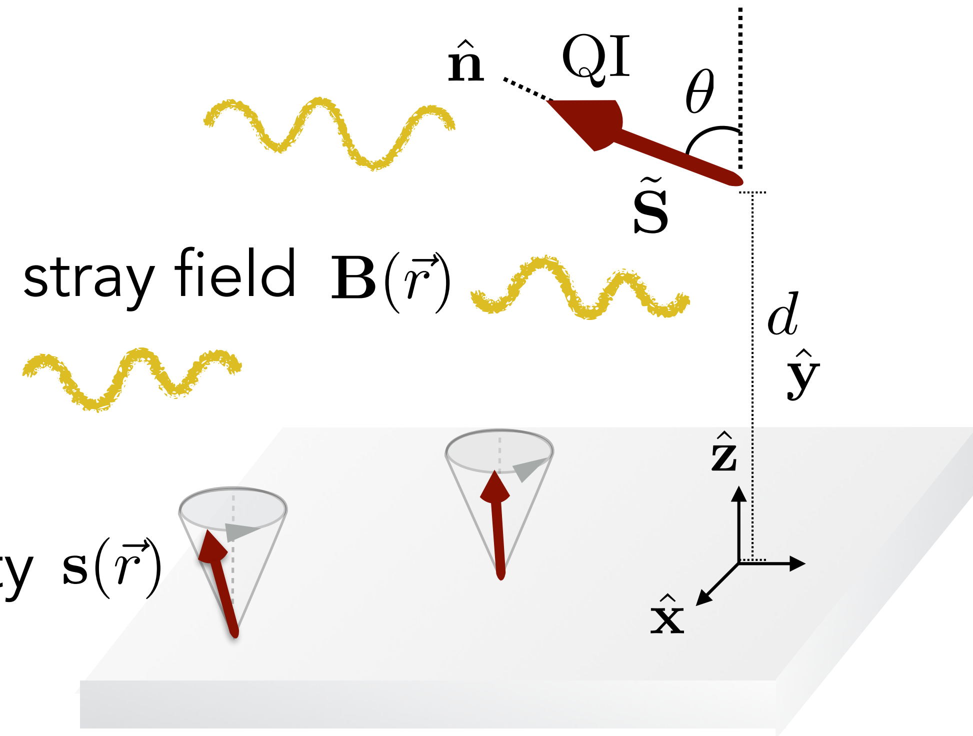
Model

U(1) symmetric magnetic insulating film

- Stray field at the QI position

$$\mathbf{B}(\vec{r}_{\rm qi}) = \gamma \mathcal{R}(\theta) \int d\vec{r}\, \mathcal{D}(\vec{r}, \vec{r}_{\rm qi}) \mathbf{s}(\vec{r})$$

$$\mathcal{D}_{\alpha\beta}(\vec{r}, \vec{r}\,') = -\frac{\partial^2}{\partial x_\alpha \partial x'_\beta} \frac{1}{|\vec{r} - \vec{r}\,'|}$$



- Zeeman coupling

$$\mathcal{H}_{\rm int} = \tilde{\gamma} \tilde{\mathbf{S}} \cdot \mathbf{B}(\vec{r}_{\rm qi})$$

$$\downarrow$$

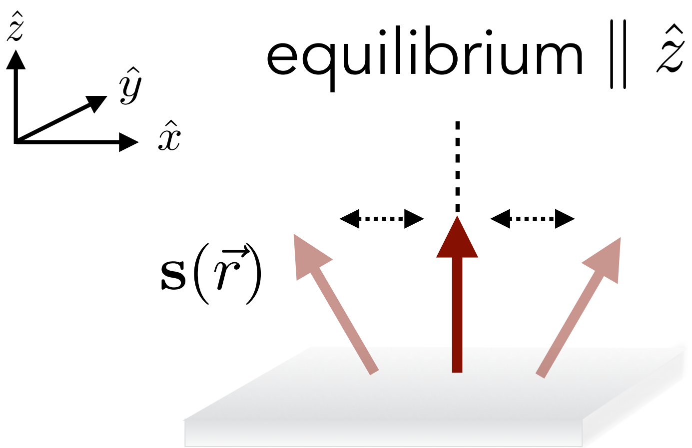
$$\mathcal{H}_{\rm int} = \boxed{\tilde{S}^+ \otimes Y} + \tilde{S}^z \otimes X$$

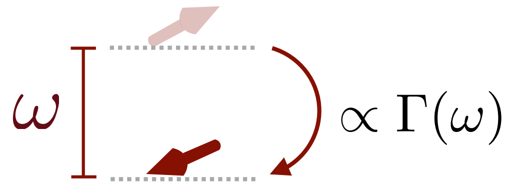
$$Y = \gamma\tilde{\gamma} \int d\vec{r} \left[a_{\vec{r}} s_x(\vec{r}) + b_{\vec{r}} s_y(\vec{r}) + c_{\vec{r}} s_z(\vec{r}) \right] , \quad a_{\vec{r}} = a_{\vec{r}}(\theta, d)$$

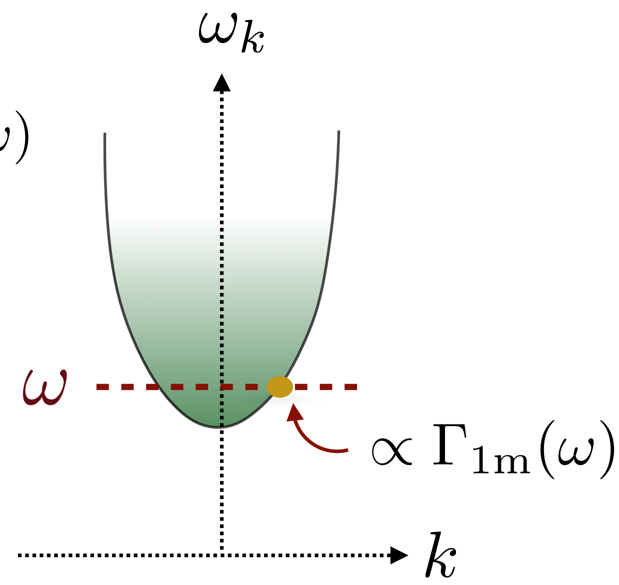
relaxation rate : $\Gamma(\omega) = \int dt\, e^{-i\omega t} \langle \{ Y^\dagger(t), Y(0) \} \rangle$

Quantum-impurity relaxometry as a single-quasiparticle probe

relaxation rate: $\Gamma(\omega) \propto \langle\{s_{x,z}(\vec{r}_i, t), s_{x,z}(\vec{r}_j, 0)\}\rangle$







transverse fluctuations

$$s_x(\vec{r}) \propto \sqrt{2s}a(\vec{r}), \sqrt{2s}a^\dagger(\vec{r})$$

one-magnon processes

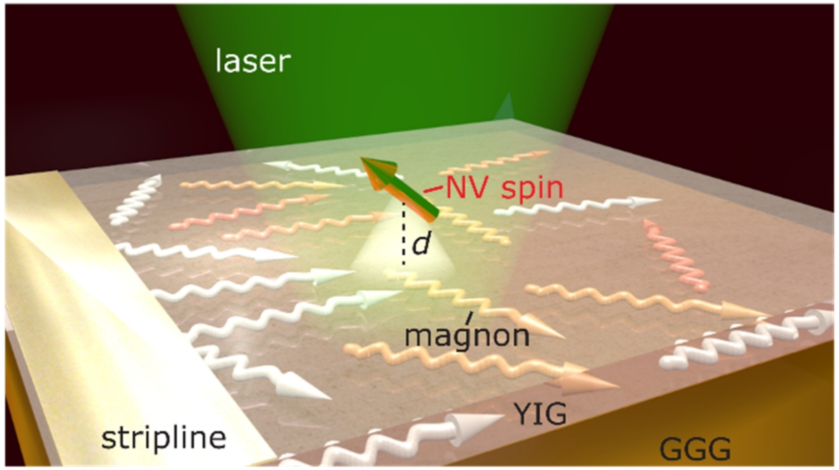
$$\Gamma(\omega) \sim \Gamma_{1\mathrm{m}}(\omega)$$

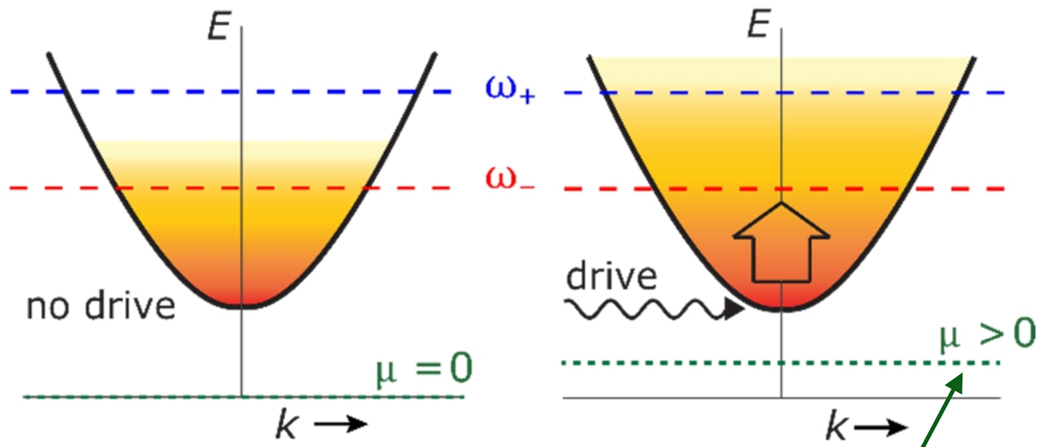
$$\Gamma_{1m}(\omega) \propto n_{\mathrm{BE}}\left(\frac{\hbar\omega - \mu}{k_B T}\right)$$

Direct measurement of the ferromagnetic chemical potential

C. Du *et al.*, Science (2017)

Measurement of the chemical potential





Excites FMR mode ⟶ interplay between coherent/incoherent spin dynamics ⟶ Increase of magnon chemical potential

B.F. *et al.*, PRB (2016)

C. Du *et al.*, Science (2017)

$$\Gamma_{1m}(\omega) \propto n_{\mathrm{BE}}\left(\frac{\hbar\omega - \mu}{k_B T}\right)$$

First direct measurement of magnon chemical potential

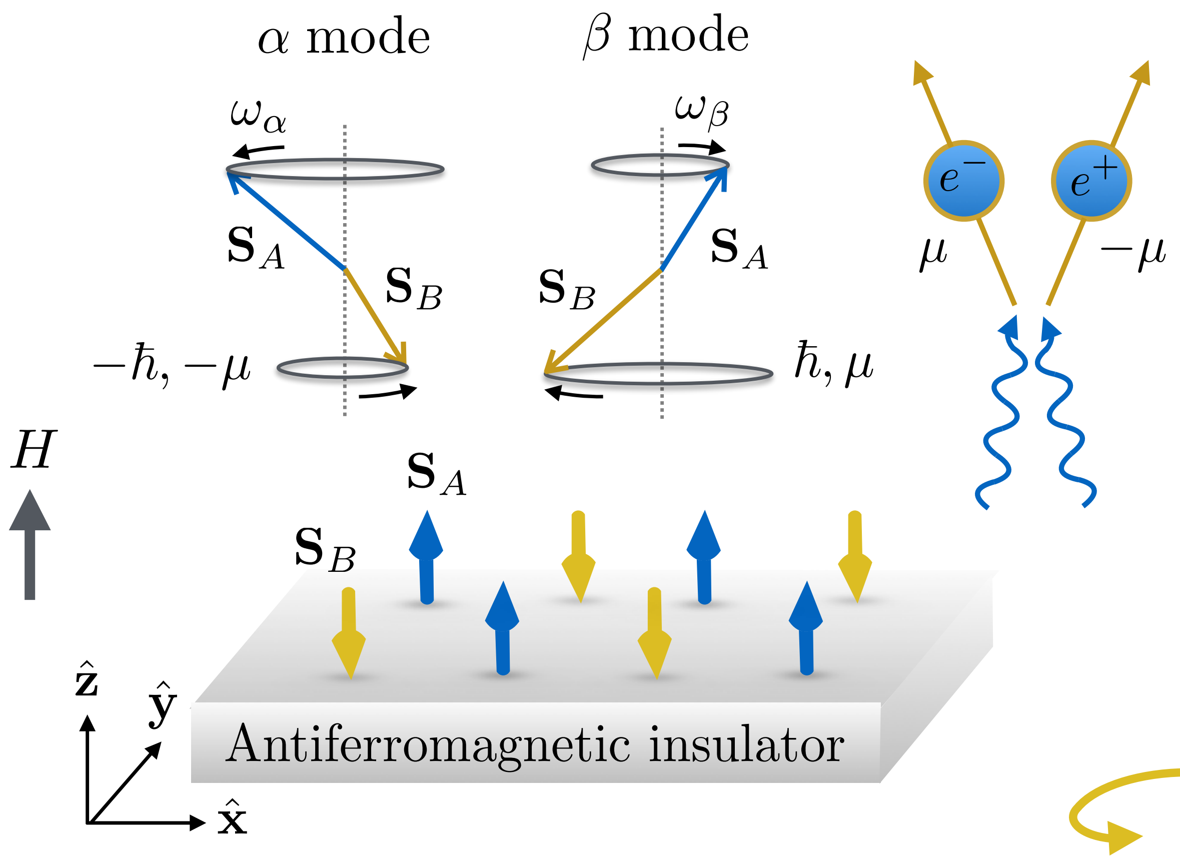
- Antiferromagnetic insulators much more abundant in nature

⟶ Can we measure their chemical potential?

- Antiferromagnetic chemical potential not rigorously defined !

Antiferromagnetic chemical potential

- $U(1)$-symmetric magnetic insulator



magnon-magnon scattering much faster than spin non-conserving processes

↓

<u>particle-antiparticle pair</u>

$$n_{\mathrm{BE},\beta(\alpha)}(\omega_{\beta(\alpha)}, T, \pm\mu)$$

with $\mu = \dfrac{\partial U}{\partial(N_\beta - N_\alpha)}$

$$\Gamma_{1m}(\omega) \propto n_{\mathrm{BE}}\left(\frac{\hbar\omega \pm \mu}{k_B T}\right)$$

B.F., PRB (2019)

⟶ excites α mode

$-\mu$ increase

circularly-polarized RF source

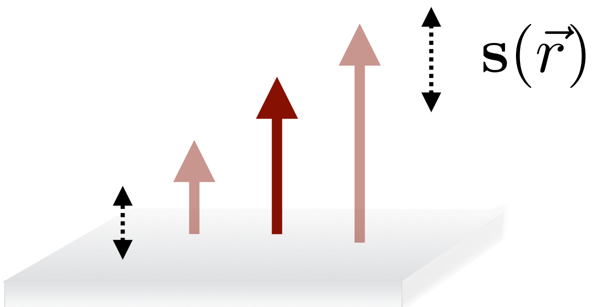
⟶ excites β mode

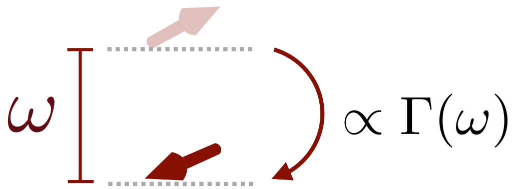
μ increase

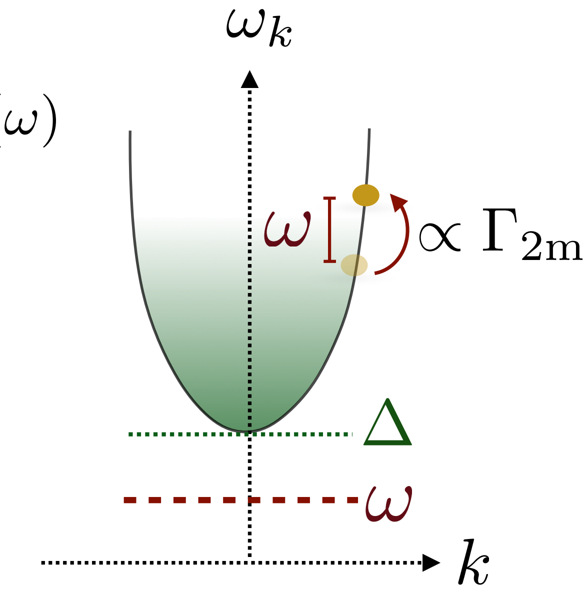
Quantum-impurity relaxometry as a transport probe

relaxation rate: $\Gamma(\omega) \propto \langle \{ s_{x,z}(\vec{r}_i, t), s_{x,z}(\vec{r}_j, 0) \} \rangle$

equilibrium $\parallel \hat{z}$







longitudinal fluctuations

$$s^z(\vec{r}) \propto s - a^\dagger(\vec{r}) a(\vec{r})$$

two-magnon processes

$$\Gamma(\omega) \sim \Gamma_{2\mathrm{m}}(\omega)$$

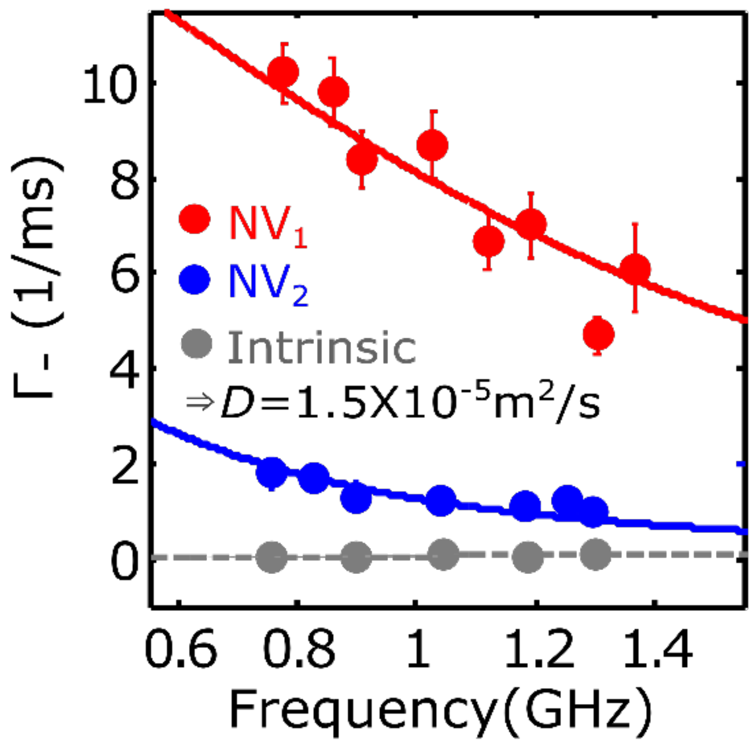
Two-magnon noise $\sim$ scattering processes

⟶ Two-magnon noise encodes magnon transport properties

Probing bulk transport properties

relaxation rate: $\Gamma(\omega) \propto \langle \{ s_z(\vec{r}_i, t), s_z(\vec{r}_j, 0) \} \rangle$

B.F., Y. Tserkovnyak, PRL (2018)



X. Wang, B.F. *et al., under PRL review*

- Spin diffusion equation

$$\partial_t s_z - D\nabla^2 s_z = -\frac{s_z}{\tau_s}$$

YIG spin diffusion coefficient D
from two-magnon noise
$D \sim 10^{-5}\ \mathrm{m}^2 \cdot \mathrm{s}^{-1}$

in very good agreement with
the nonlocal transport results
of Cornelissen et al., PRB (2016)

Purely bulk measurement (no need for external spin excitations)

Up to now ...

Quantum-impurity spin relaxometry

- in terms of one- and two-magnon processes
- as probe of magnon statistics (e.g., AF chemical potential)
- as probe of bulk spin-wave diffusive transport properties

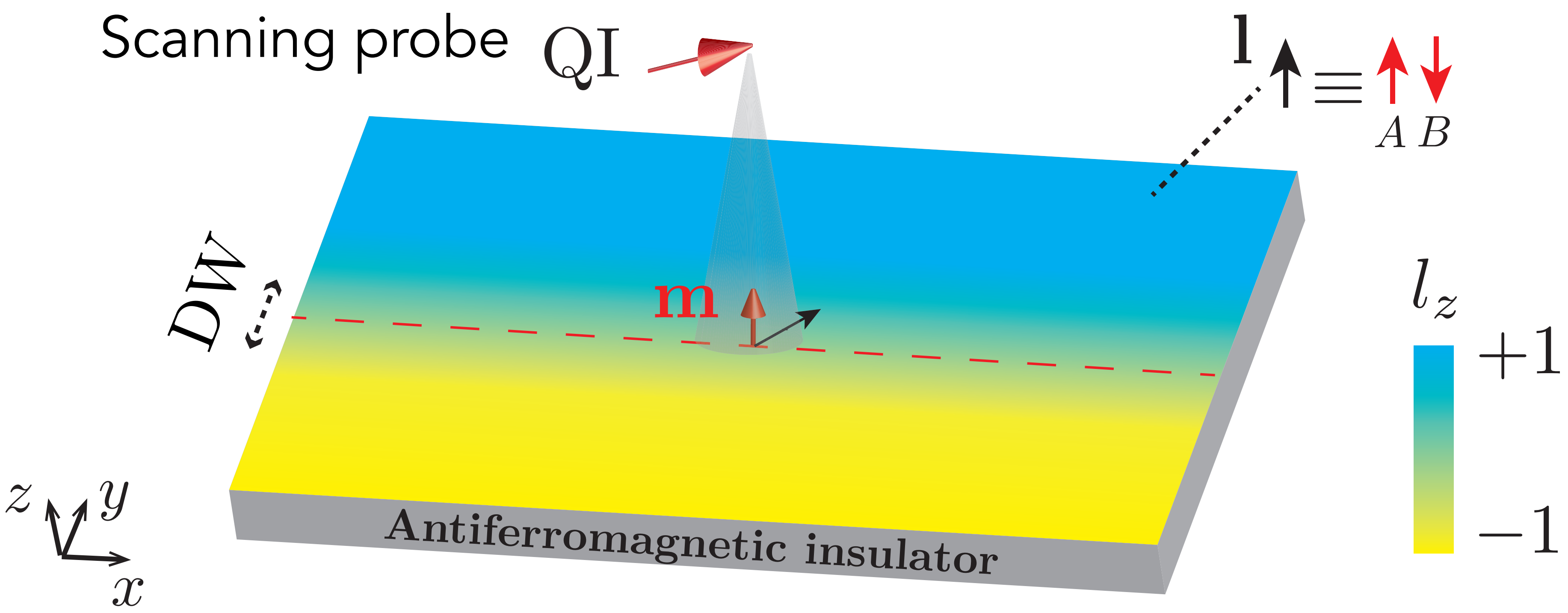
→ applicable to any spin transport regime

Questions?

... Coming next : NV centers and spin textures

Spectroscopic imaging spin textures

Example: domain wall in a $U(1)$-symmetric antiferromagnet



- Collective spin modes of the DW and of the bulk
- Appropriate regime for DW modes detection
- Symmetry-based checks

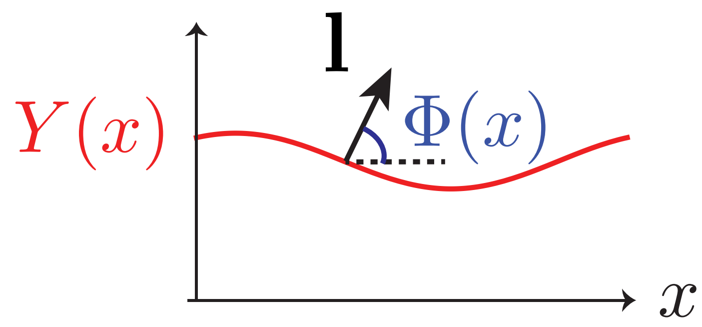
Antiferromagnetic domain-wall

$$\mathcal{L} = \int d\vec{r} \left[\frac{\chi}{2} (\partial_t \mathbf{l})^2 - \frac{A}{2} (\partial_i \mathbf{l})^2 - \frac{K}{2} |\mathbf{l} \times \hat{\mathbf{z}}|^2 \right]$$

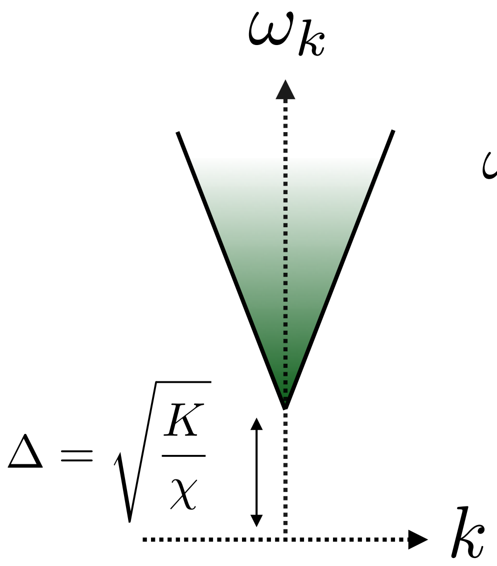
Nonlinear sigma model

spin density : $\mathbf{m} = \chi \mathbf{l} \times \partial_t \mathbf{l}$

A.F. Andreev *et al.*, Sov. Phys. Uspekhi (1980)



<u>spin-wave solution</u>



$$\omega_k = \sqrt{c^2 k^2 + \Delta^2}$$

$$c = \sqrt{A/\chi}$$

<u>domain-wall solution</u>

$$l_z(y \to \pm\infty) = \pm 1$$

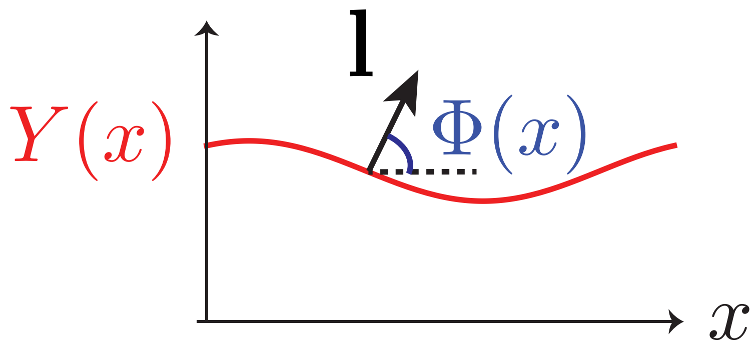
$$\cos\theta\,(\vec{r}) = \tanh[(y - Y)/\lambda]$$

$$\phi\,(\vec{r}) = \Phi, \quad \lambda = \sqrt{A/K}$$

Domain-wall modes

$Y \to Y(x,t)$: translational symmetry-restoring Goldstone mode

$$\mathcal{L}_{\text{string}} = \frac{1}{2}\int dx \left[\varrho(\dot{Y})^2 - \sigma(\partial_x Y)^2 \right]$$



string mode $\quad \varrho = 2\chi/\lambda\,,\ \sigma = 2\sqrt{AK}$

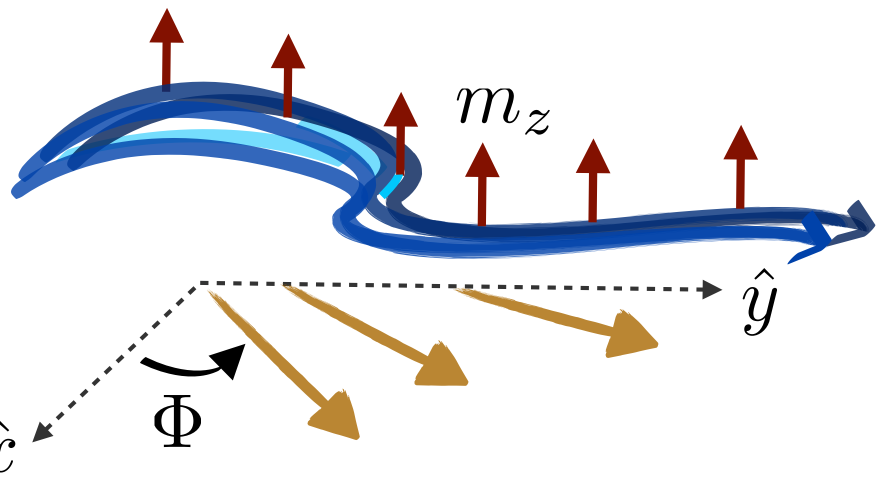
$\Phi \to \Phi(x,t)$: $U(1)$ symmetry-restoring Goldstone mode

$$\mathcal{L}_{\text{ss}} = \frac{1}{2}\int dx \left[I\left(\dot{\Phi}\right)^2 - \mathcal{A}(\partial_x \Phi)^2 \right]$$

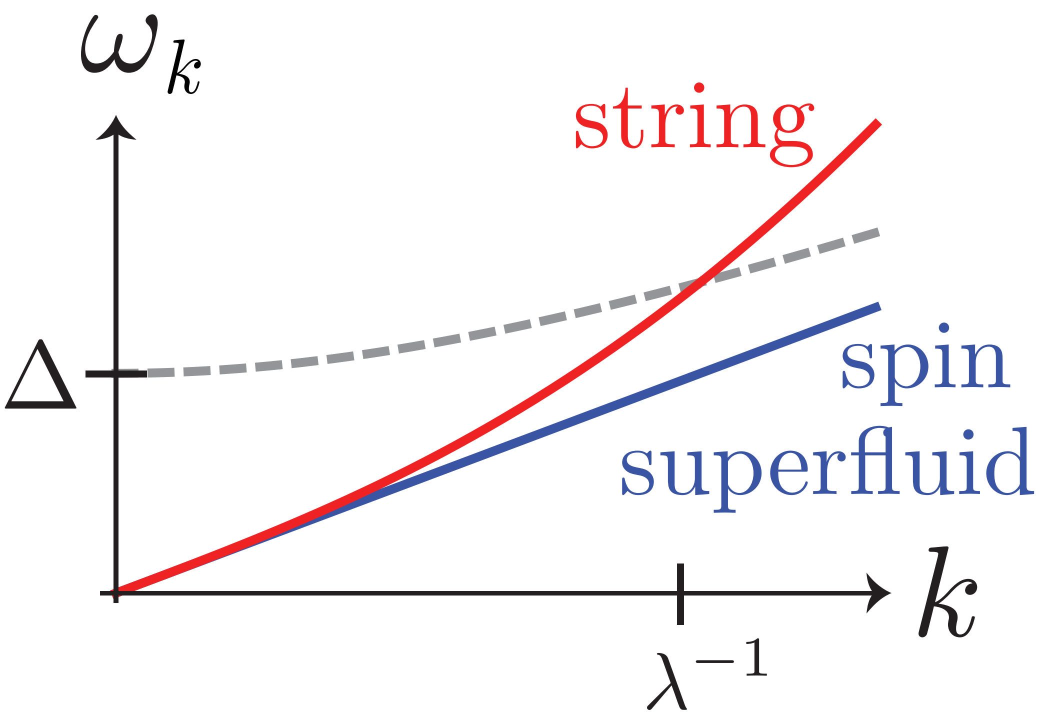
$\mathcal{A} = 2\lambda A \qquad \sim$ spin superfluid mode

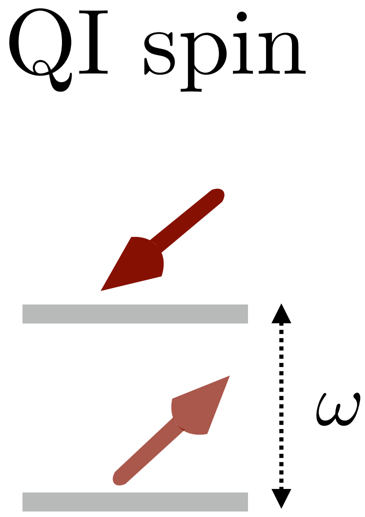
$I = 2\lambda\chi$

E. B. Sonin, Adv. Phys. (2010)



Domain-wall detection





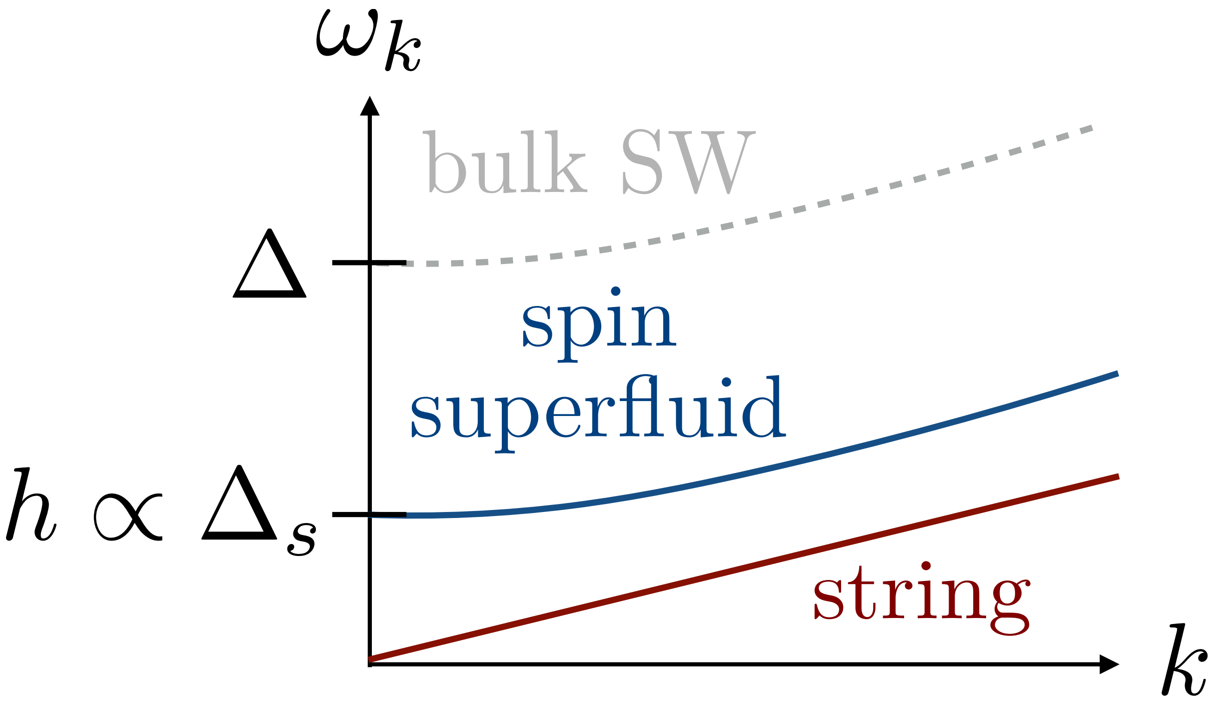
- $\omega \ll \Delta$: negligible one-magnon noise from bulk SW
- $T \ll \Delta$: negligible two-magnon noise from bulk SW

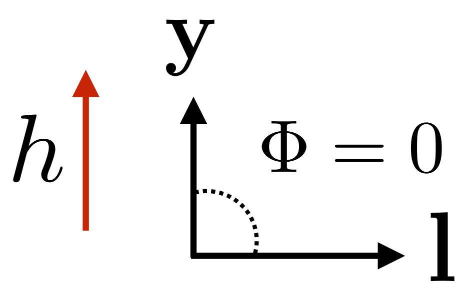
Spin-superfluid mode detection

Spin superfluid → $U(1)$ symmetry-restoring Goldstone mode

- Planar magnetic field h breaks $U(1)$-symmetry

  $\sim$ it pins the azimuthal angle Φ



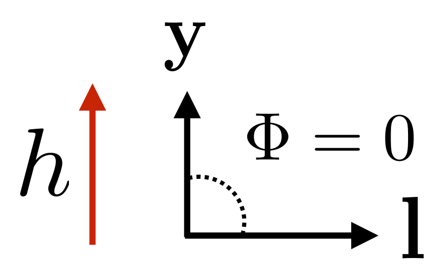


- $\omega \ll \Delta_s$: negligible one-magnon noise from spin superfluid

String mode detection

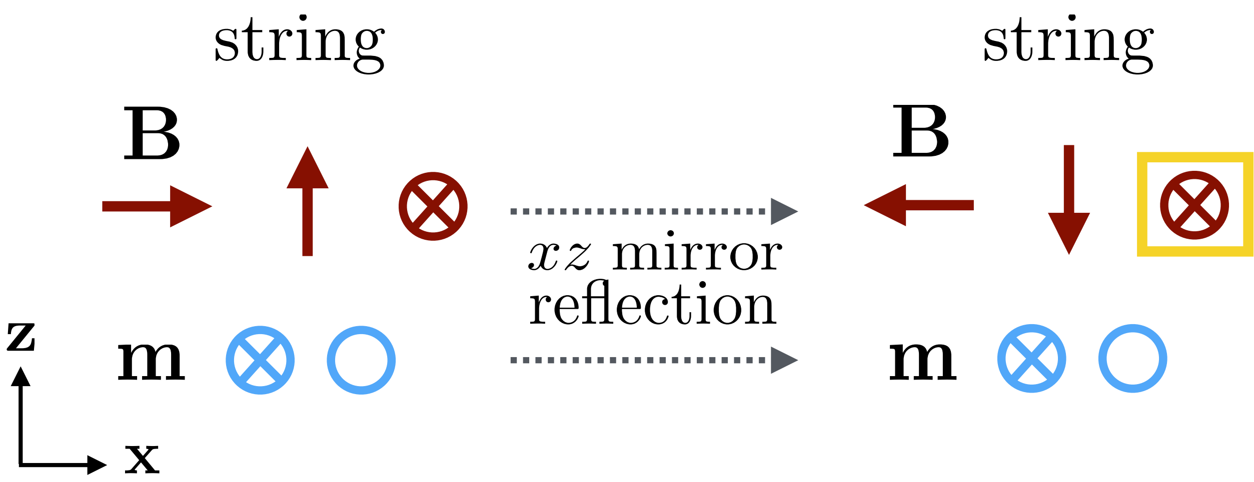
geometry in which string mode does not produce a stray field transverse to the QI anisotropy axis?

- $\mathbf{h} = h\mathbf{y}$ enforces a Bloch DW configuration



- stray field allowed only along **y**

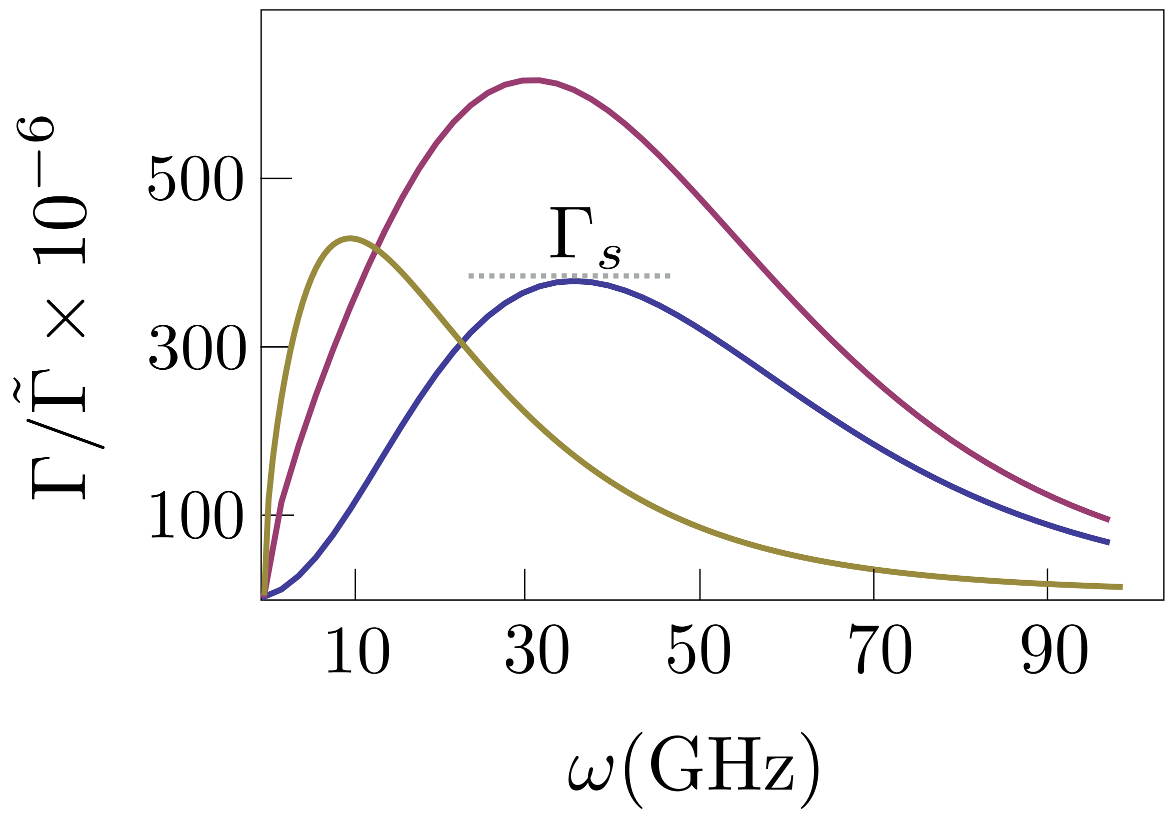
$\mathbf{m} \cdot \mathbf{l} = 0$



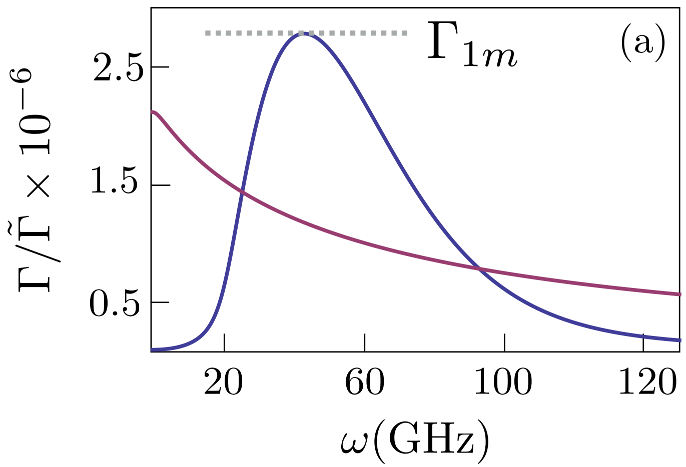
- Orienting QI spin along **y**: no relaxation due to the string mode

Is the noise strong enough?

Domain-wall modes



Homogeneous film



$$\tilde{\Gamma} = (\gamma\tilde{\gamma})^2\chi/8\pi a_0^4$$

$$\Gamma_s/\Gamma_{1m} \sim 2^9\lambda/d$$

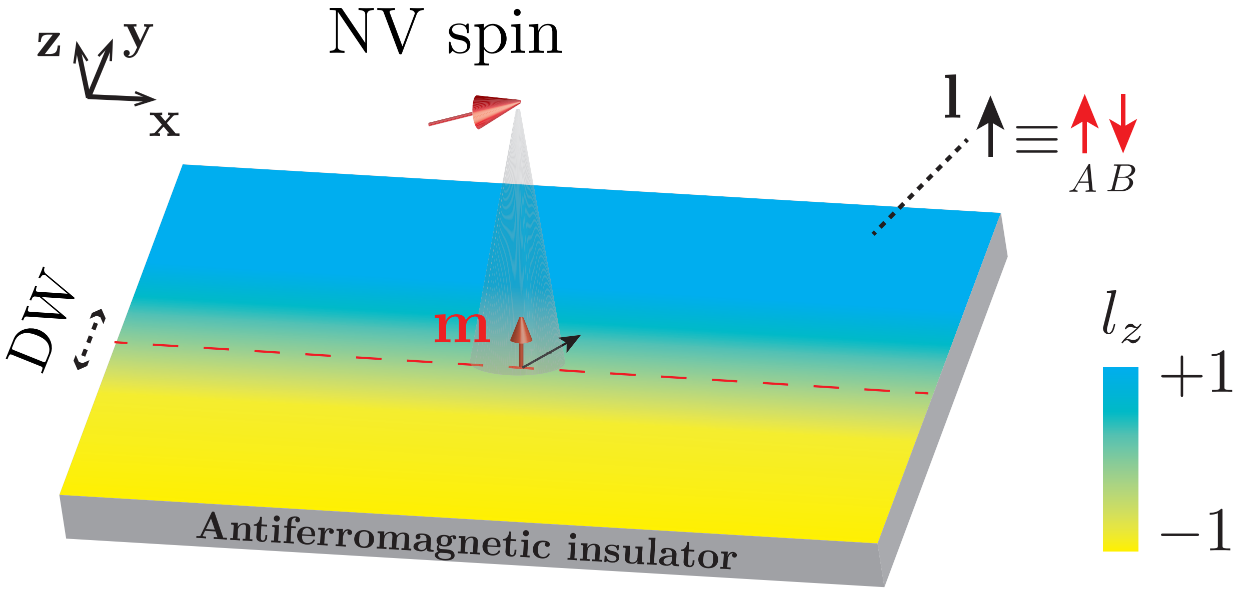
- $\Phi = 0,\ \hat{\mathbf{n}} \parallel \hat{\mathbf{z}}$ spin superfluid (blue) and string (yellow)
- $\Phi = 0,\ \hat{\mathbf{n}} \parallel \hat{\mathbf{y}}$ spin superfluid (purple)

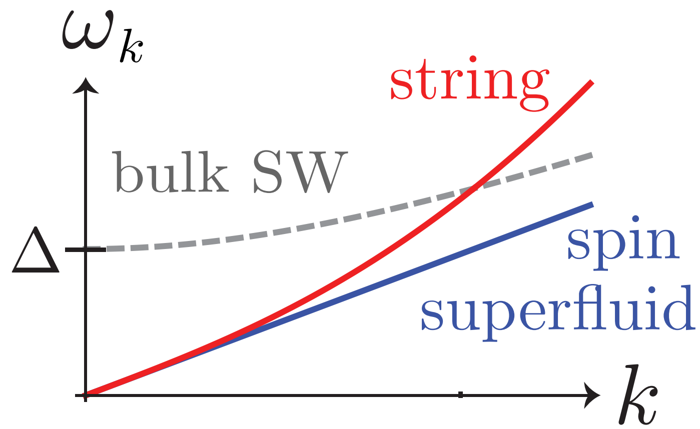
Yes!

$\mathrm{RbMnF_3}$ $\hat{\mathbf{n}} \parallel \hat{\mathbf{z}}\,,\ \ \omega = 10$ GHz → $\Gamma^{-1} \sim \mathrm{ms}\ (T \sim T_N/2)$

Up to now: Imaging spin textures spectroscopically

Example: domain wall in a $U(1)$-symmetric antiferromagnet





B.F. *et al.*, PRB Rapids (2018)

One can probe each mode (couple separately to it) via NV relaxometry by controlling the external magnetic field and the frequency, orientation and position of the NV center

→ selective coupling NV center - spin mode (strong spin-spin coupling)

Coupling distant quantum impurities

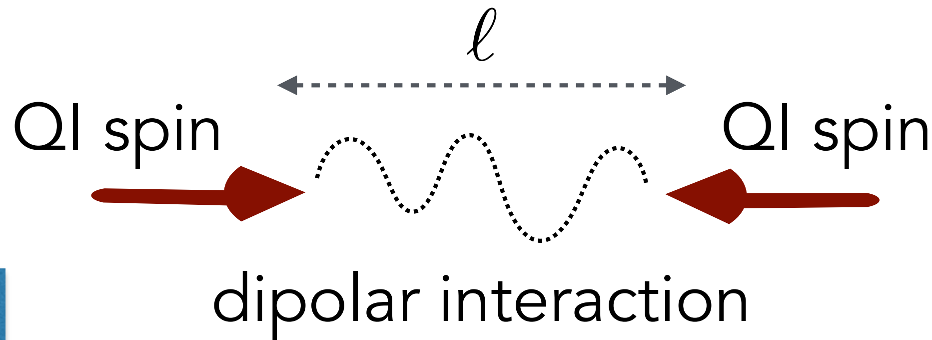
- coherent coupling between impurity spins

limit for large-scale entanglement schemes:

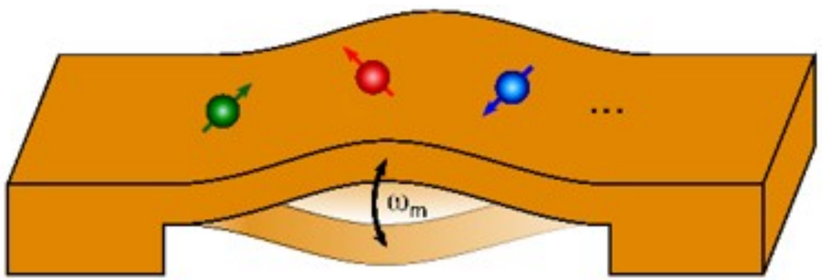
$$\ell \lesssim 20 \text{ nm}$$

solution? ↓

hybrid quantum architectures

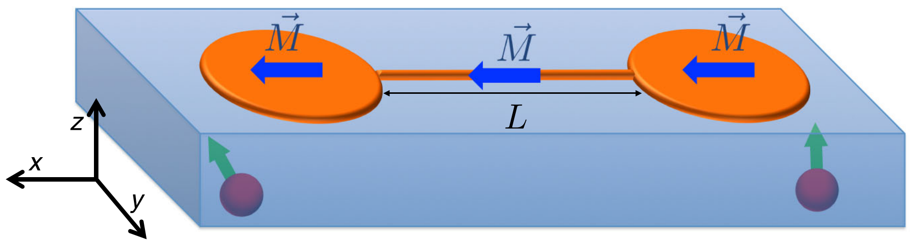


Diamond mechanical resonator



S. B. Bennett *et al.*, PRL 2013

Dogbone-shaped FM

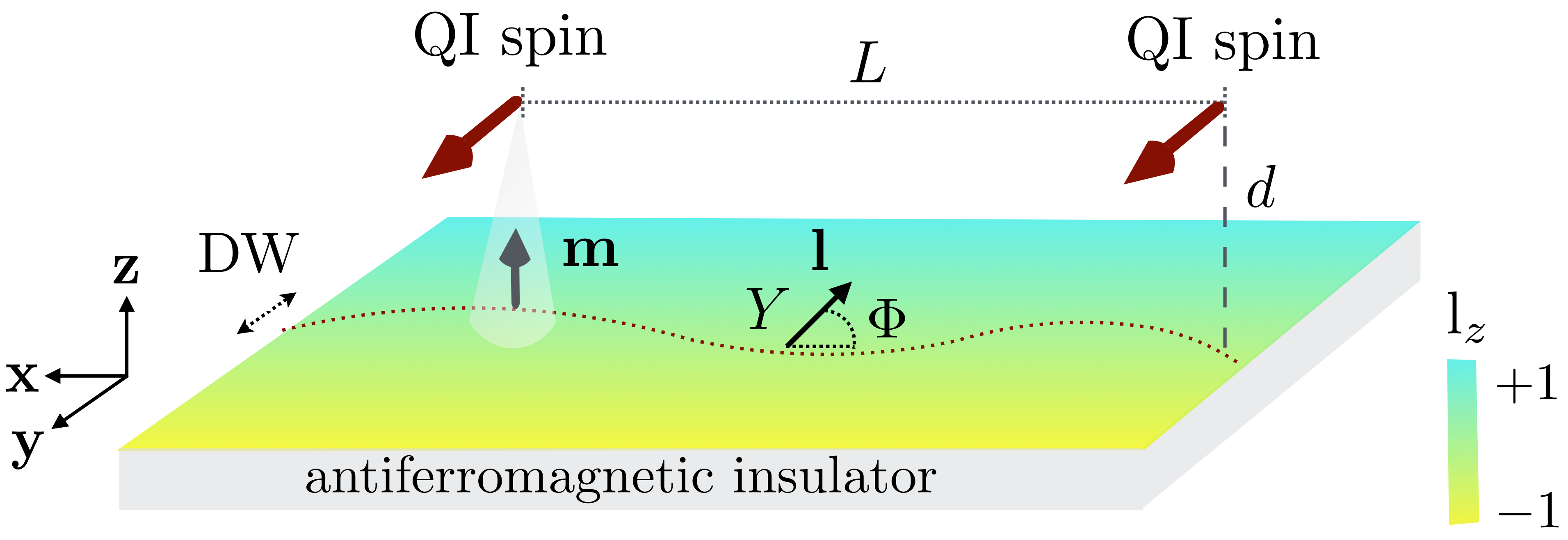


F. Trifunovic *et al.*, PRX 2013

... via antiferromagnetic domain-walls?

Coupling QIs via an AF domain wall

B.F. *et al.*, PRB Rapids (2019)

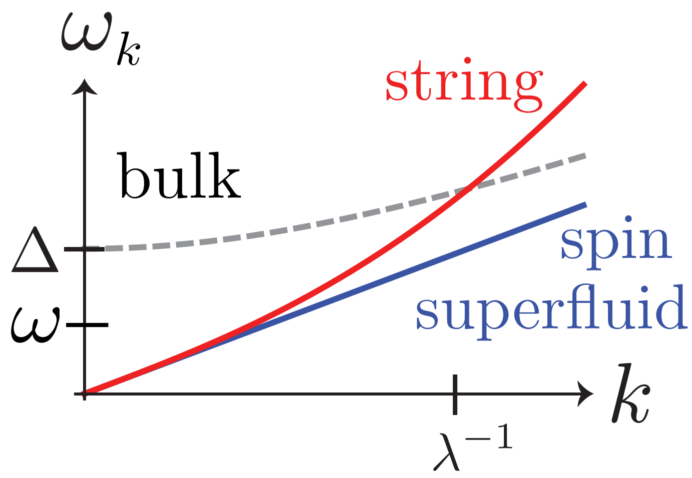


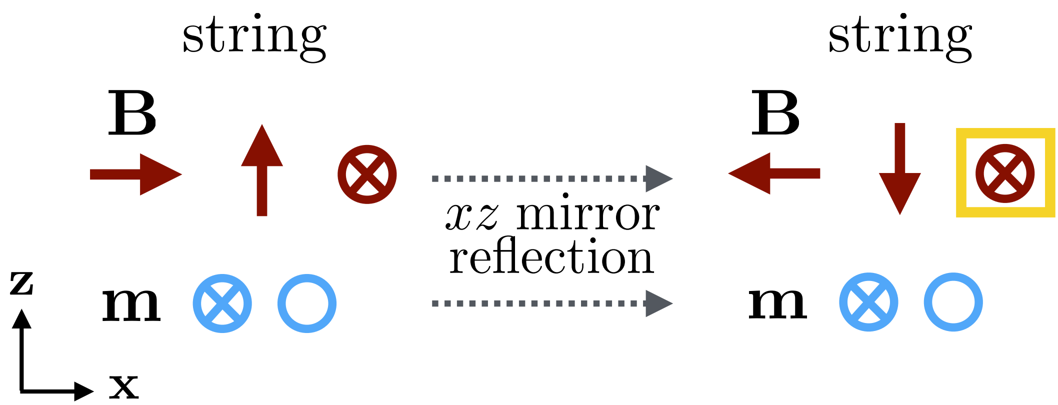
- string mode → gap not easily tunable
  → noise can be completely gapped out
- <u>spin superfluid mode</u>
  → gap easily tunable via external field

Noise

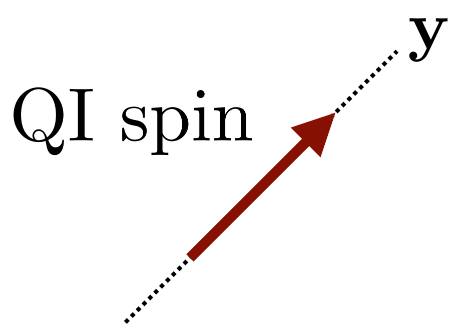
- Gap noise from magnetic bulk

→ $\omega, T \ll \Delta$





- Gap noise from string mode via a magnetic field

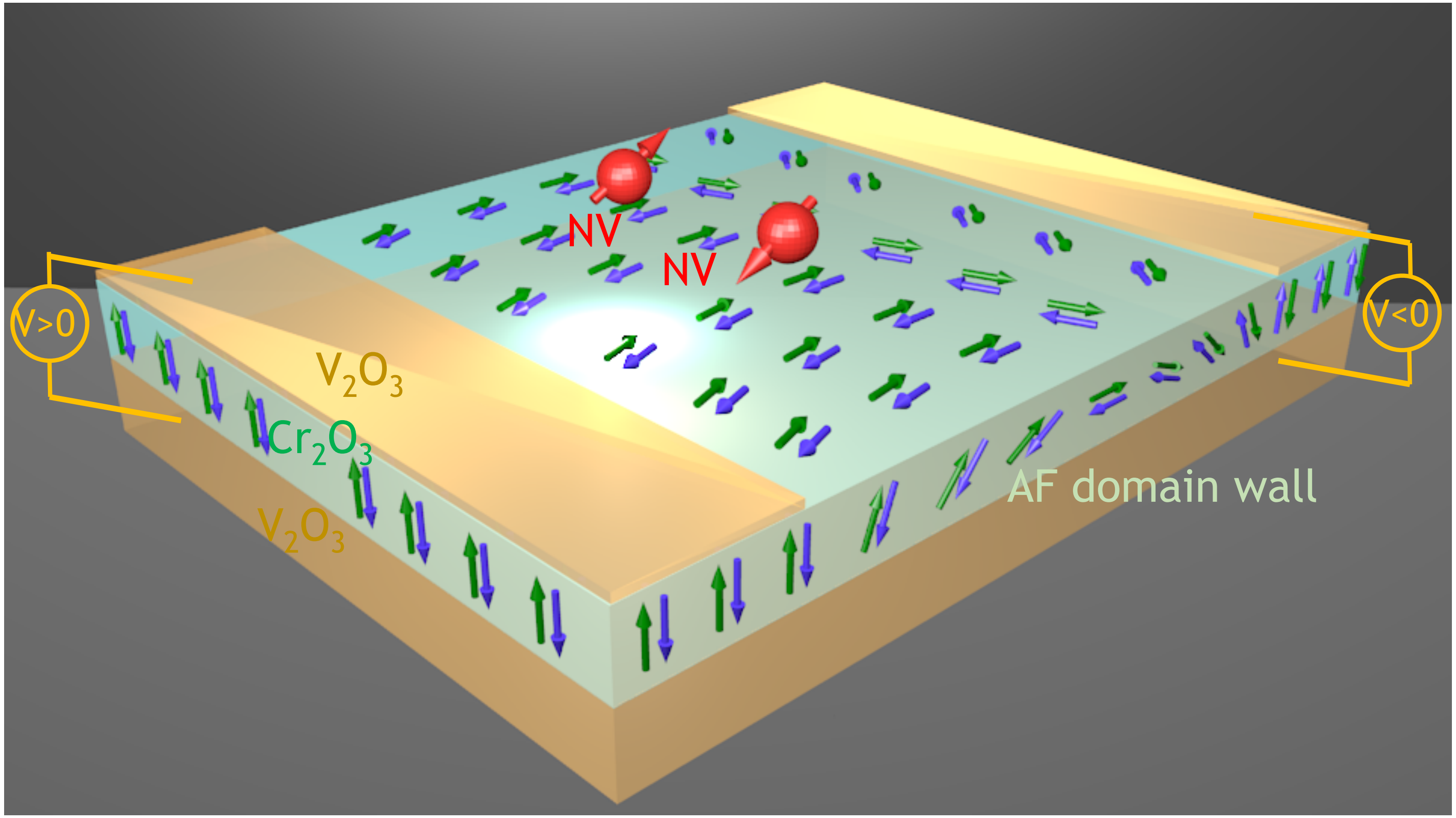


Under these conditions, both coupling and noise are due to the spin superfluid mode

Entanglement via spin modes

A spin superfluid mode hosted by an antiferromagnetic domain wall can mediate coherent coupling between QI spins at distances $\sim 1\ \mu\text{m}$

B.F. *et al.*, PRB Rapids (2019)



courtesy of C. Du and I. Krivotorov

Thanks to …

Y. Tserkovnyak
(UCLA)

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(Purdue)

C. Du
(UCSD)

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And thank you
for the attention!

… Questions ?