Quantum impurity relaxometry of magnetization dynamics

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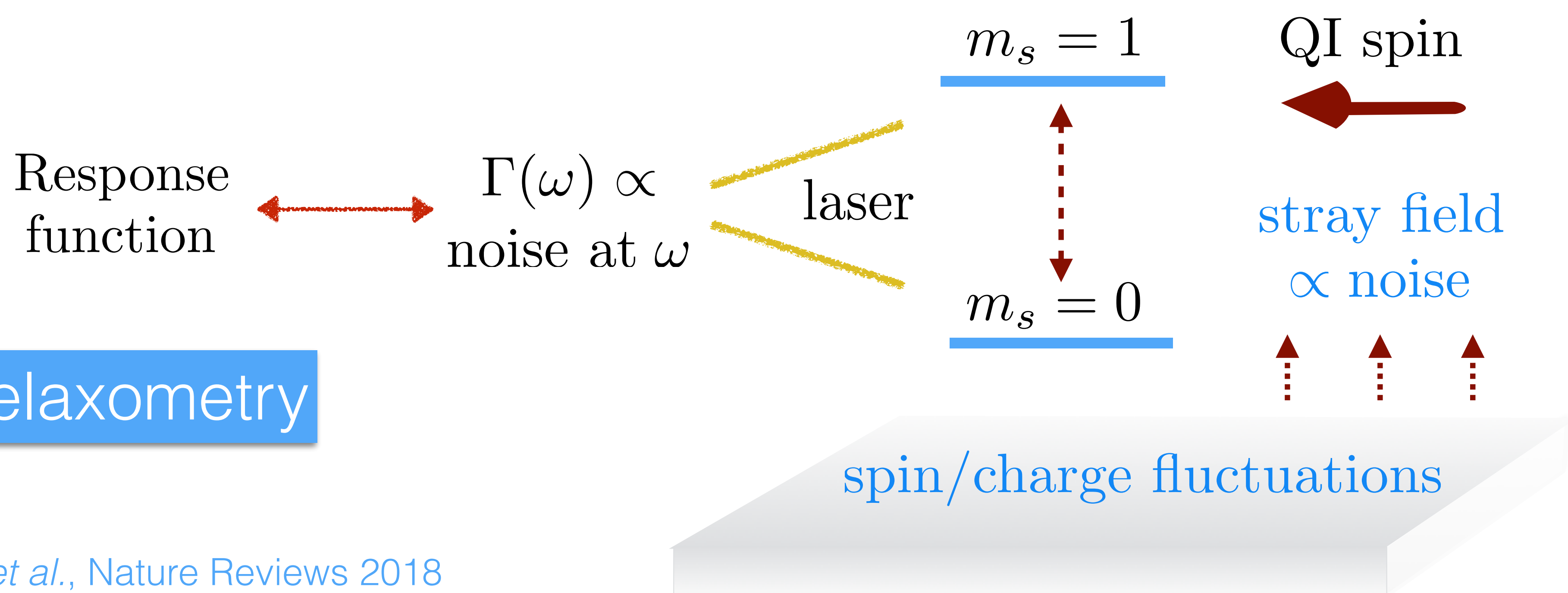
B. F. and Y. Tserkovnyak, arXiv:1804.02417

B. F., H. Ochoa, Y. Tserkovnyak and P. Upadhyaya, *in preparation*

Quantum impurity spins

Impurity spins (e.g., NV and SV centers in diamond)

- exceptional sensitivity to magnetic fields
- long relaxation and dephasing times
- spin state can be initialized and read out optically
- widely used to image static magnetic fields (magnetometry)



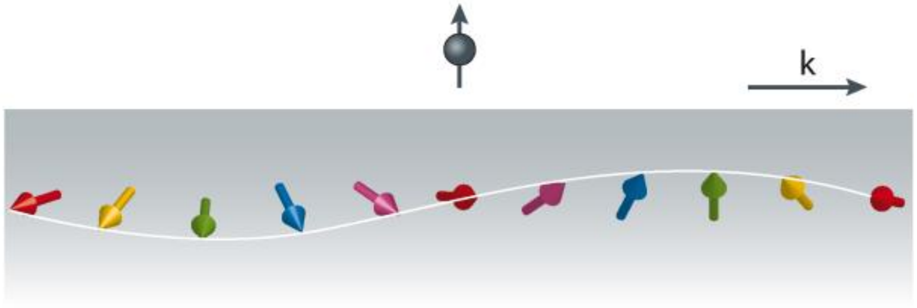
QI relaxometry

F. Casola *et al.*, Nature Reviews 2018

Relaxometry of insulating magnetic systems

- collective magnetic excitations
(spin-wave transport properties, dynamical phase transitions)

- spatial magnetic textures
(antiferromagnetic domain-walls)



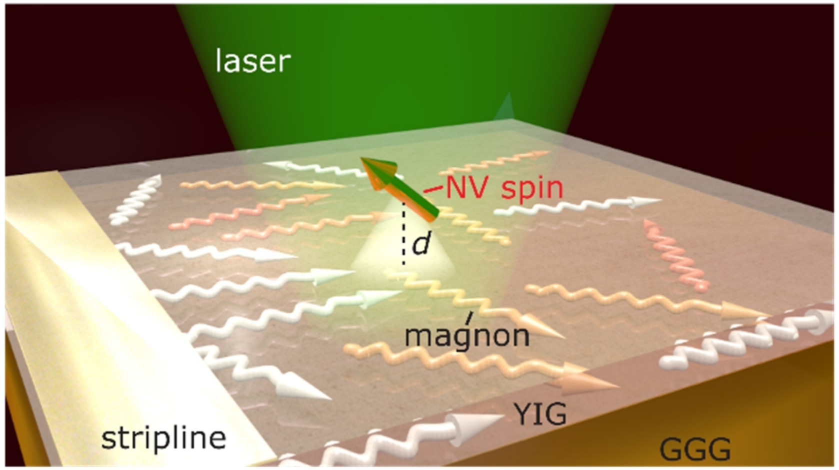
F. Casola *et al.*, Nature Reviews 2018

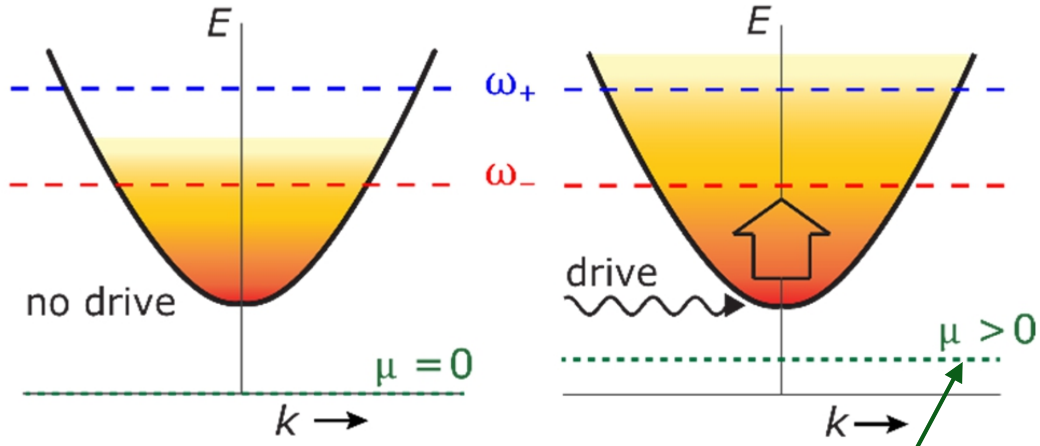
magnetometry?

→ static fields, not dynamic properties

Relaxometry → spectroscopic image of magnetic textures

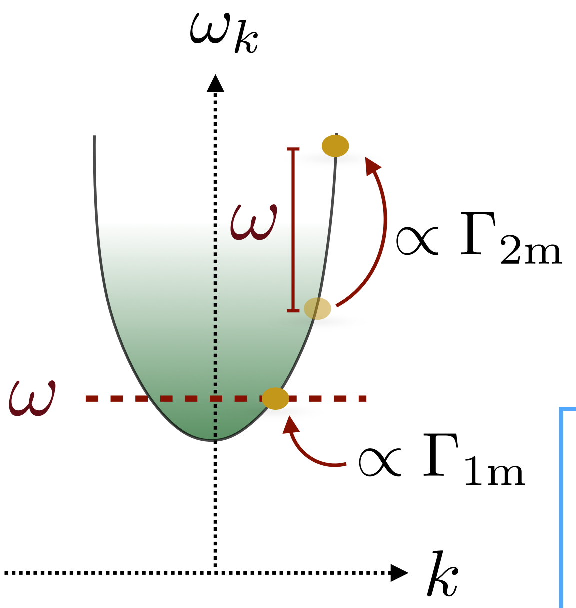
QI relaxometry of magnetic insulators



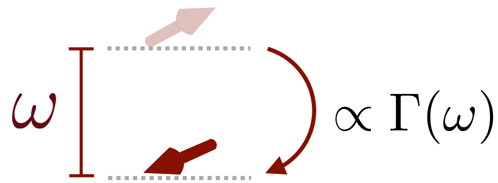


Excites FMR mode ⟶ interplay between coherent/incoherent spin dynamics ⟶ Increase of magnon chemical potential

B. Flebus *et al.*, PRB 2016



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



First direct measurement of magnon chemical potential

C. Du *et al.*, Science 2017

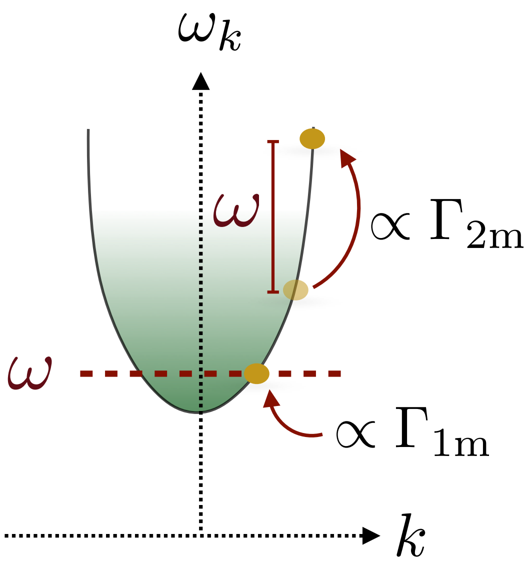
$$\boxed{\Gamma_{1m}(\omega) \propto n_{\mathrm{BE}}\left(\frac{\hbar\omega - \mu}{k_B T}\right)}$$

What about systems with large spin-wave gaps?

QI relaxometry of magnetic insulators

One-magnon relaxometry

Two-magnon relaxometry



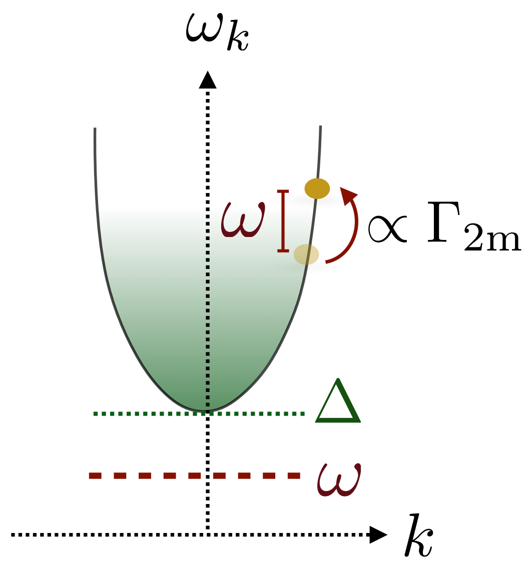
$\Gamma(\omega) \sim \Gamma_{1\mathrm{m}}(\omega)$

$$\Gamma_{2m} \propto \ldots ?$$

e.g., large spin-wave gap (AFs)

$$\omega \lesssim 100\ \mathrm{GHz}$$

F. Casola *et al.*, Nature Reviews 2018



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

We find that two magnon-noise can probe :

- dynamical phase transitions, such as magnon Bose-Einstein condensation
- diffusive spin-wave bulk transport properties directly

B.F. and Y. Tserkovnyak, arXiv:1804.02417

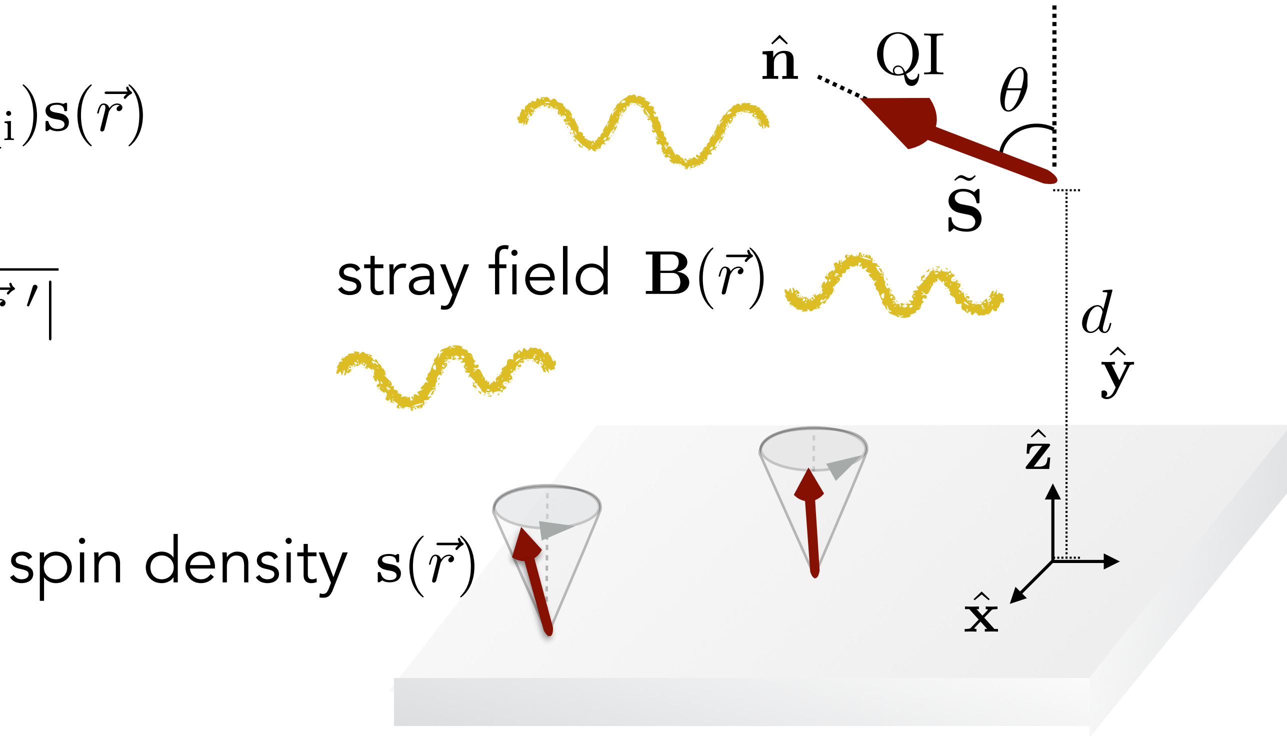
Model

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 : $\Gamma(\omega) = 2 \int dt\, e^{-i\omega t} \{ Y^\dagger(t), Y(0) \}$

Spin response

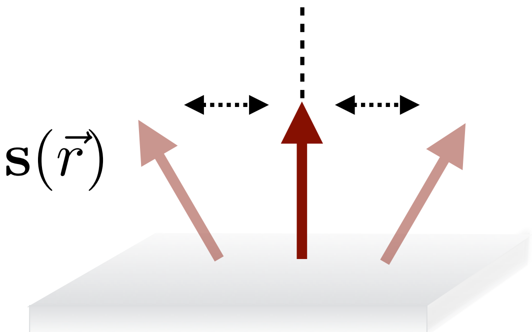
$$\boxed{\text{relaxation rate: } \Gamma(\omega) \propto C_{xx(zz)}(\vec{k}, \omega)}$$

transverse (longitudinal) noise: $C_{xx(zz)}(\vec{r}_i, \vec{r}_j; t) = \langle \{ s_{x(z)}(\vec{r}_i, t), s_{x(z)}(\vec{r}_j, 0) \} \rangle$

<u>fluctuation-dissipation theorem:</u> $C_{xx(zz)}(k, \omega) = \coth(\beta\hbar\omega/2)\boxed{\chi''_{xx(zz)}(k, \omega)}$

spin susceptibility

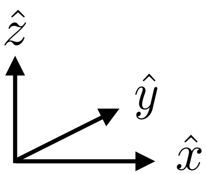
equilibrium $\parallel \hat{z}$



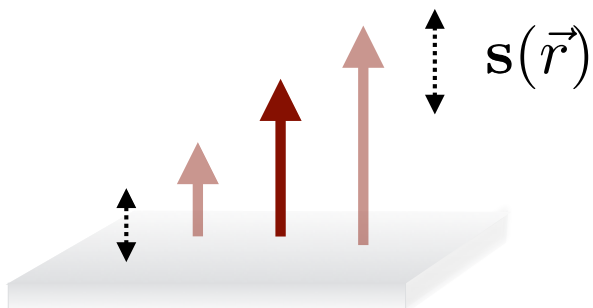
transverse fluctuations

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

one-magnon processes



equilibrium $\parallel \hat{z}$



longitudinal fluctuations

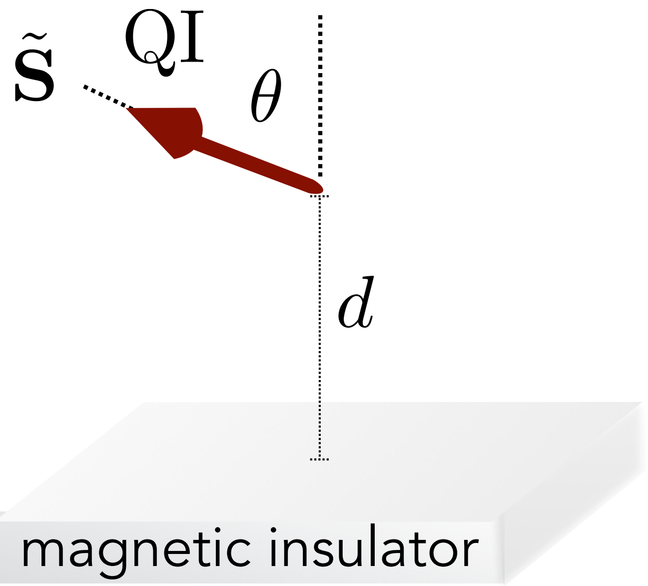
$$s^z(\vec{r}) \propto s - a^\dagger(\vec{r})a(\vec{r})$$

two-magnon processes

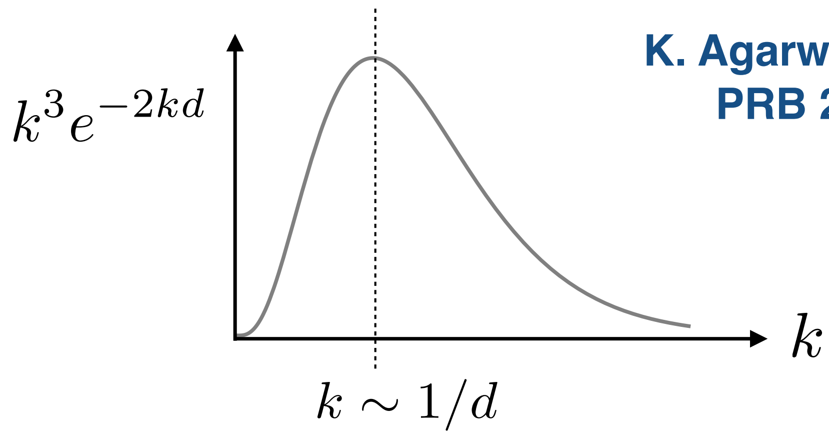
Relaxation rate

$$\Gamma(\omega) = f(\theta)\coth(\beta\hbar\omega/2)\int_0^{\infty} dk\, k^3 e^{-2kd}\left[\chi''_{xx}(k,\omega) + \chi''_{zz}(k,\omega)\right]$$

$$f(\theta) \propto 5 - \cos 2\theta$$



- dipolar filtering function:



K. Agarwal *et al.*, PRB 2017

- we focus on the regime in which two-magnon response dominates :

$$\chi''_{xx}(k,\omega) \ll \chi''_{zz}(k,\omega)$$

$$\longrightarrow \quad \omega \lesssim \Delta - 1/\tau_s$$

spin-wave gap Δ

spin relaxation time τ_s

Transport properties

$$\Gamma(\omega) \propto \int dk\ k^3 e^{-2kd} \chi''_{zz}(k,\omega) \sim \frac{\chi''_{zz}(1/d,\omega)}{d^4}$$

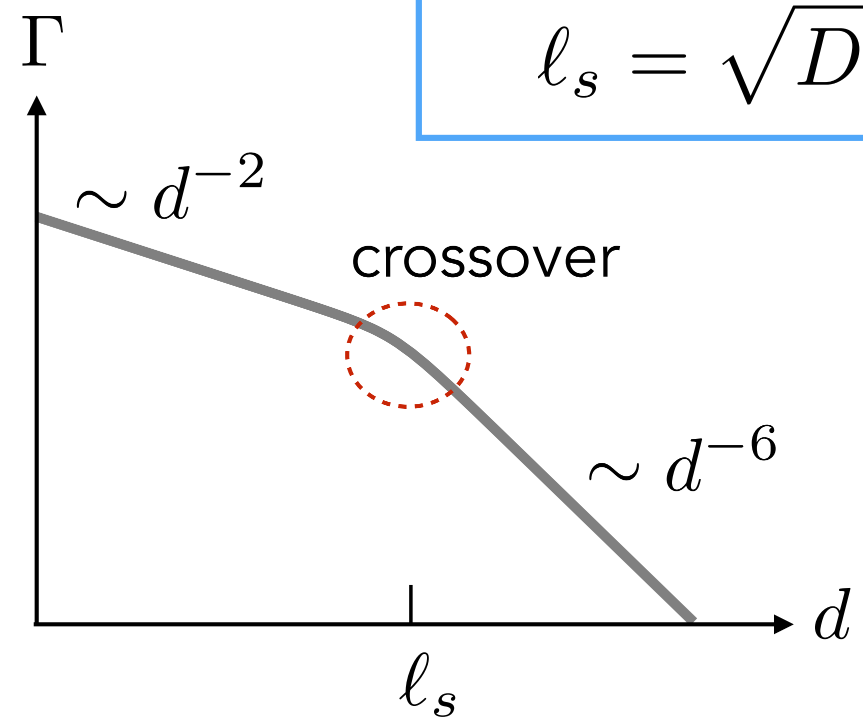
Spin diffusion equation $\longrightarrow$ $\chi''_{zz}(k,\omega) = \dfrac{\chi\omega D k^2}{(Dk^2 + 1/\tau_s)^2 + \omega^2}$

Spin diffusion length

$$\ell_s = \sqrt{D\tau_s}$$

$\sim d^{-2}$ long wavelengths

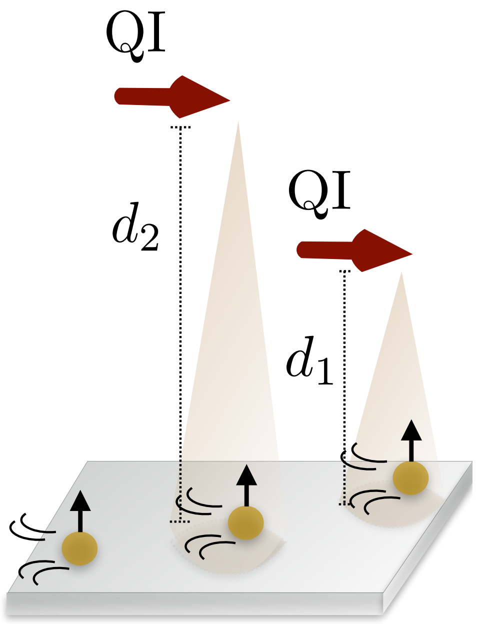
$\sim d^2$ short wavelength

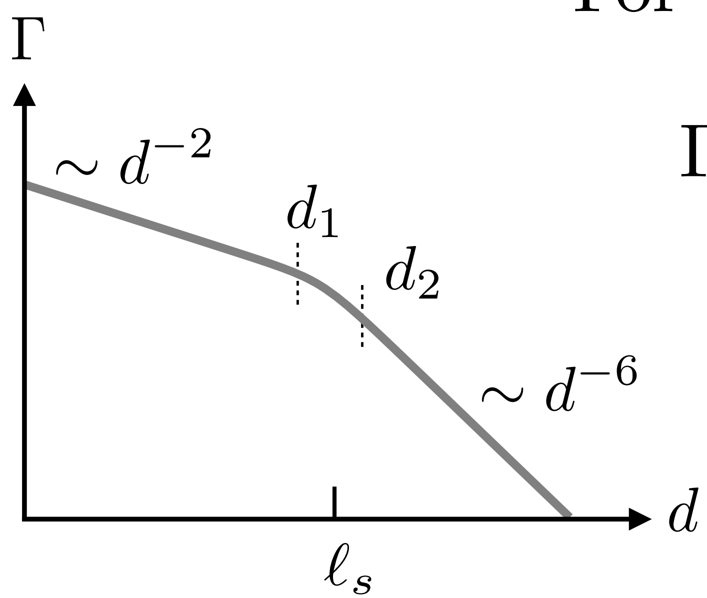


For $\omega \ll D/d^2$ $(\sim \mathrm{THz})$,

$$\Gamma \sim \left[d + d^3/\ell_s^2\right]^{-2}$$

Spin diffusion length

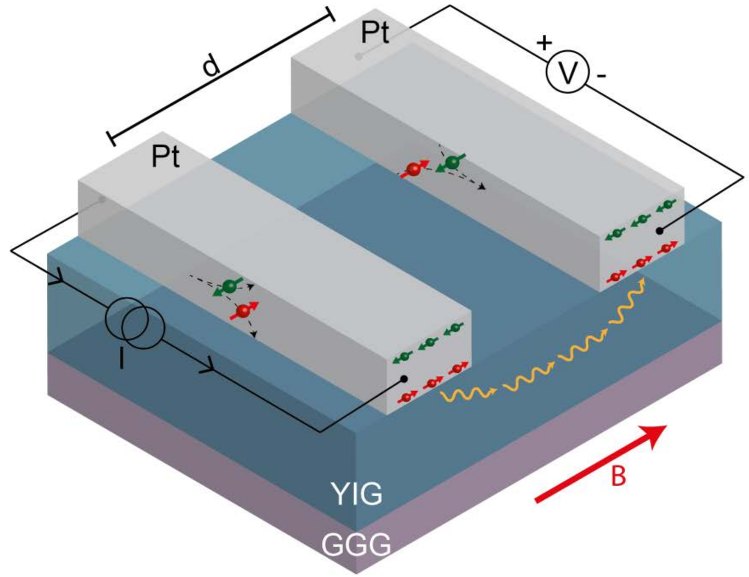




For $\omega \ll D/d^2$ ($\sim$ THz),

$$\Gamma \sim \left[d + d^3/\ell_s^2\right]^{-2}$$

non-local measurement



By measuring the relaxation rate while varying the QI height,

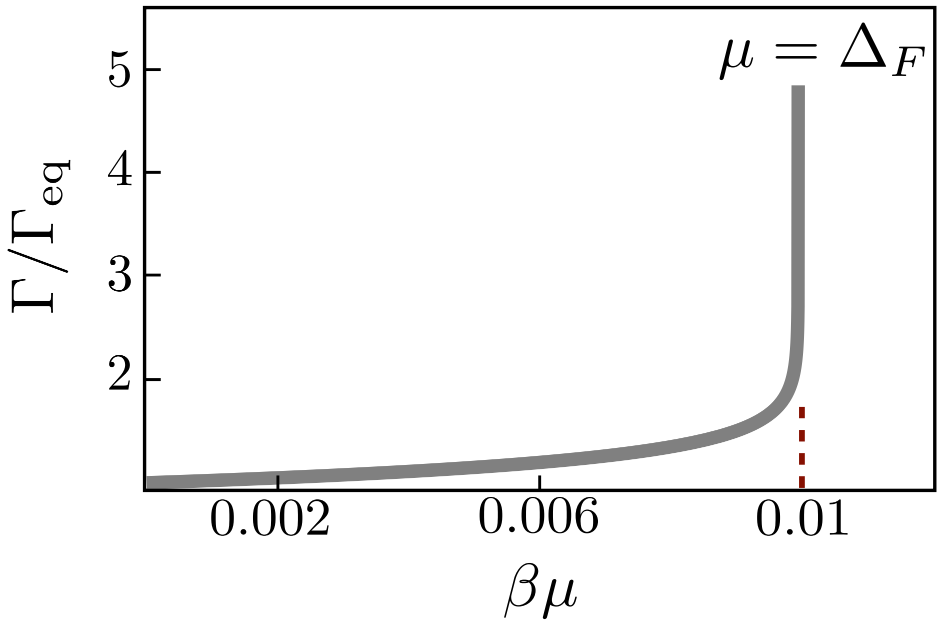
$$\ell_s^2 \sim \frac{d_1^3\sqrt{\Gamma(d_1)/\Gamma(d_2)} - d_2^3}{d_2 - d_1\sqrt{\Gamma(d_1)/\Gamma(d_2)}}$$

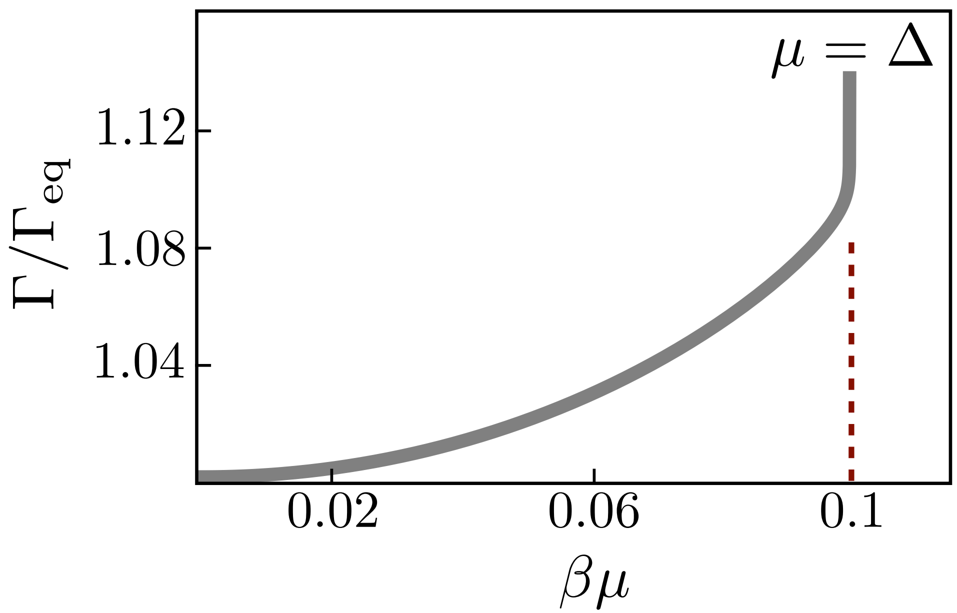
L. Cornelissen *et al.*, Nat. Phys. 2015

First direct measurement of the spin diffusion length

Magnon Bose-Einstein condensation

<u>Ideal magnon gas</u>





Y. Tserkovnyak, B.F. et al, PRB 2016

(RF field, thermal gradients)

Ferromagnet

$$\Gamma \propto \ln\left[\frac{A}{d^2(\Delta_F - \mu + \omega)}\right]$$

$$\text{YIG } (T \sim 100 \text{ K})$$

$$\Gamma^{-1} < \Gamma_{\rm NV}^{-1}$$

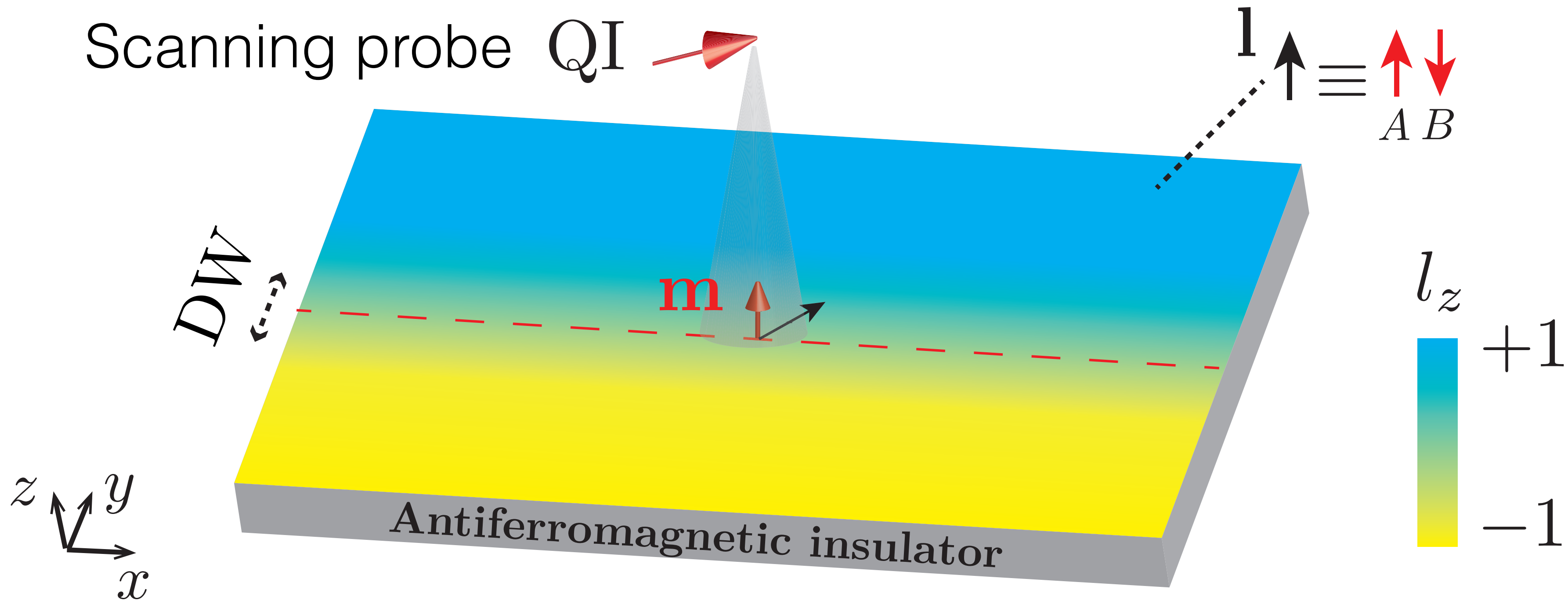
Antiferromagnet

$$\text{RbMnF}_3 \ (T \sim 10 \text{ K})$$

$$\Gamma^{-1} < \Gamma_{\rm NV}^{-1}$$

Antiferromagnetic domain-wall

Relaxometry → Spectroscopic imaging spin textures



Relaxation rate ↔ Spin susceptibility

→ Spin susceptibility of DW Goldstone modes

Antiferromagnetic domain-wall

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

<u>Collective DW modes</u>

- domain-wall position

$$Y \to Y(x,t)$$

string mode

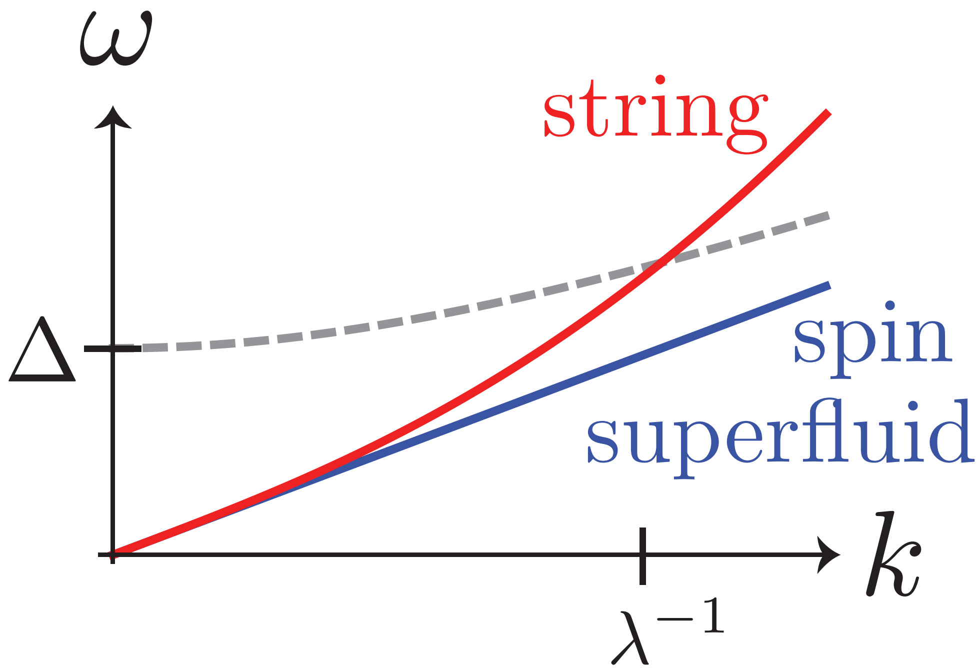
(translational symmetry)

- azimuthal angle

$$\Phi \to \Phi(x,t)$$

spin superfluid

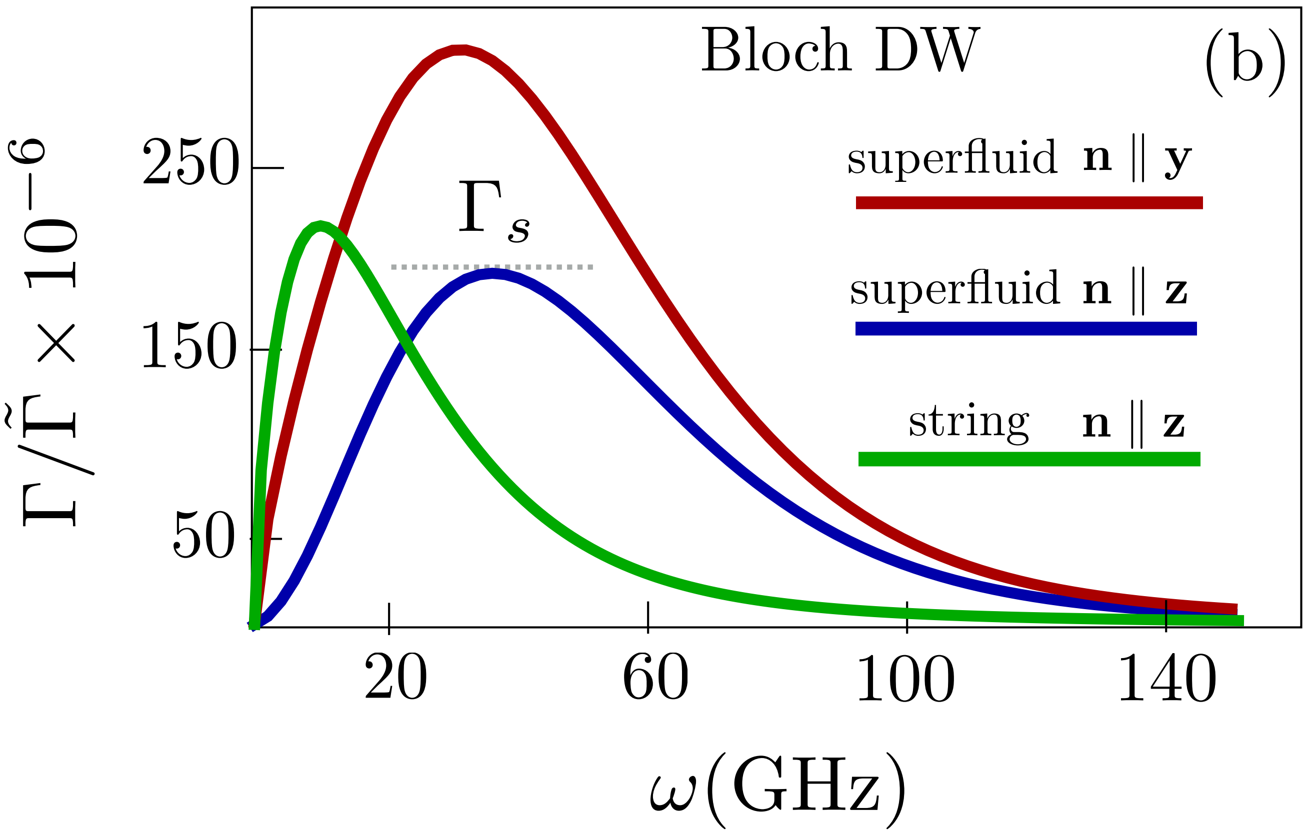
(U(1) symmetry)



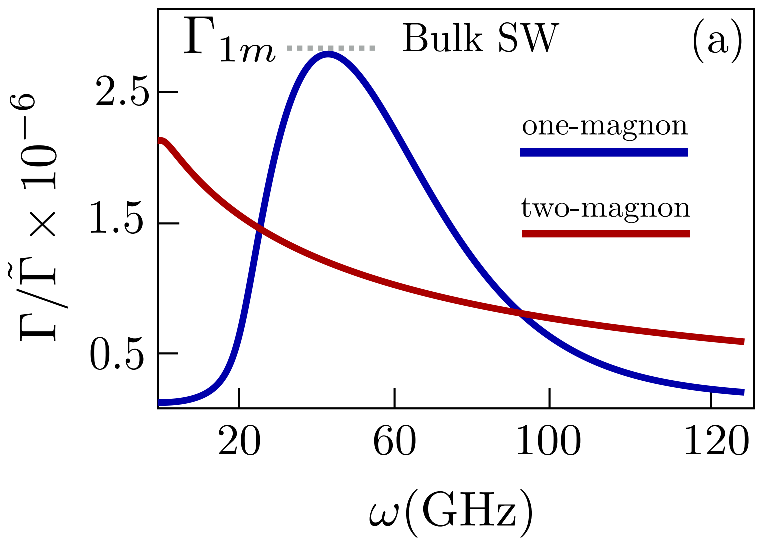
Hollander et al, arXiv:1806.02646
experimental evidence of low-lying energy modes hosted by DWs

Antiferromagnetic DW detection

<u>Domain-wall modes</u>



Homogeneous film



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

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

DW noise much larger than the bulk SW ones

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

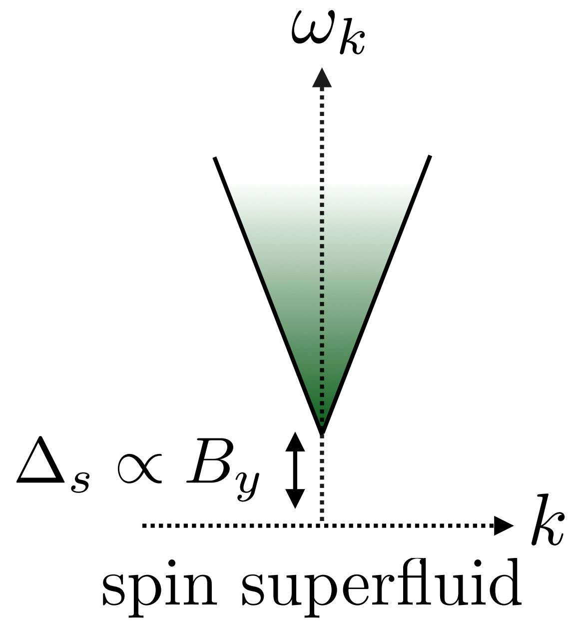
Check

How to rule out other contributions to the signal?

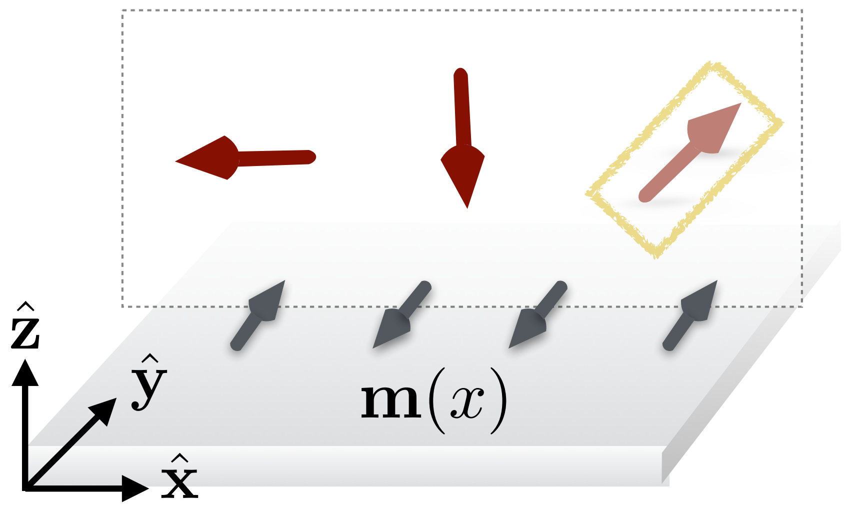
- $U(1)$ symmetry $\longrightarrow$ in-plane magnetic field B_y

$$\boxed{\omega \lesssim \Delta_s - 1/\tau_s}$$

spin superfluid noise vanishes



- in-plane magnetic field B_y



$\longrightarrow$ reorient QI spin along $\hat{\mathbf{y}}$

String mode noise vanishes

Conclusions

Quantum-impurity spin relaxometry

- in terms of one- and two-magnon processes
- as a non-intrusive probe of spin-wave transport properties
- detection of BEC at frequencies lower than the spin-wave gap
- dynamical detection of an antiferromagnetic domain-wall