# Nonlinear Chiral Magnonic Resonators: Towards Magnonic Neurons

K.G.Fripp, Y. Au, A. V. Shytov and V. V. Kruglyak
University of Exeter, United Kingdom

## Abstract

In this work, we explore chiral magnonic resonators as building blocks of artificial neural networks. Using micromagnetic simulations and analytical modelling, we demonstrate that the first anti-symmetric confined ('dark') mode of a stripe chiral magnonic resonator may exhibit a strongly nonlinear response when resonantly excited by incoming spin waves, owing to energy concentration. For modest excitation levels, the effect can be described in terms of a nonlinear shift of the resonant frequency ('detuning'), which results in amplitude-dependent transmission of monochromatic spin waves. This behaviour can be harnessed to realise a sigmoid-like activation, and thus implement artificial neurons in a network linked by spin waves propagating in a linear medium. The nonlinearity is manifested in bistability and hysteresis akin to those occurring in non-linear oscillators when the excitation strength exceeds a threshold set by the decay rate of the mode. In magnonic resonators, the latter includes both the Gilbert damping and the radiative decay due to the coupling with the medium. The results of our simulations are well described by a phenomenological model in which the nonlinear detuning of the confined mode is quadratic in its amplitude, while the propagation in the medium is linear.

## Magnonic Neural Networks

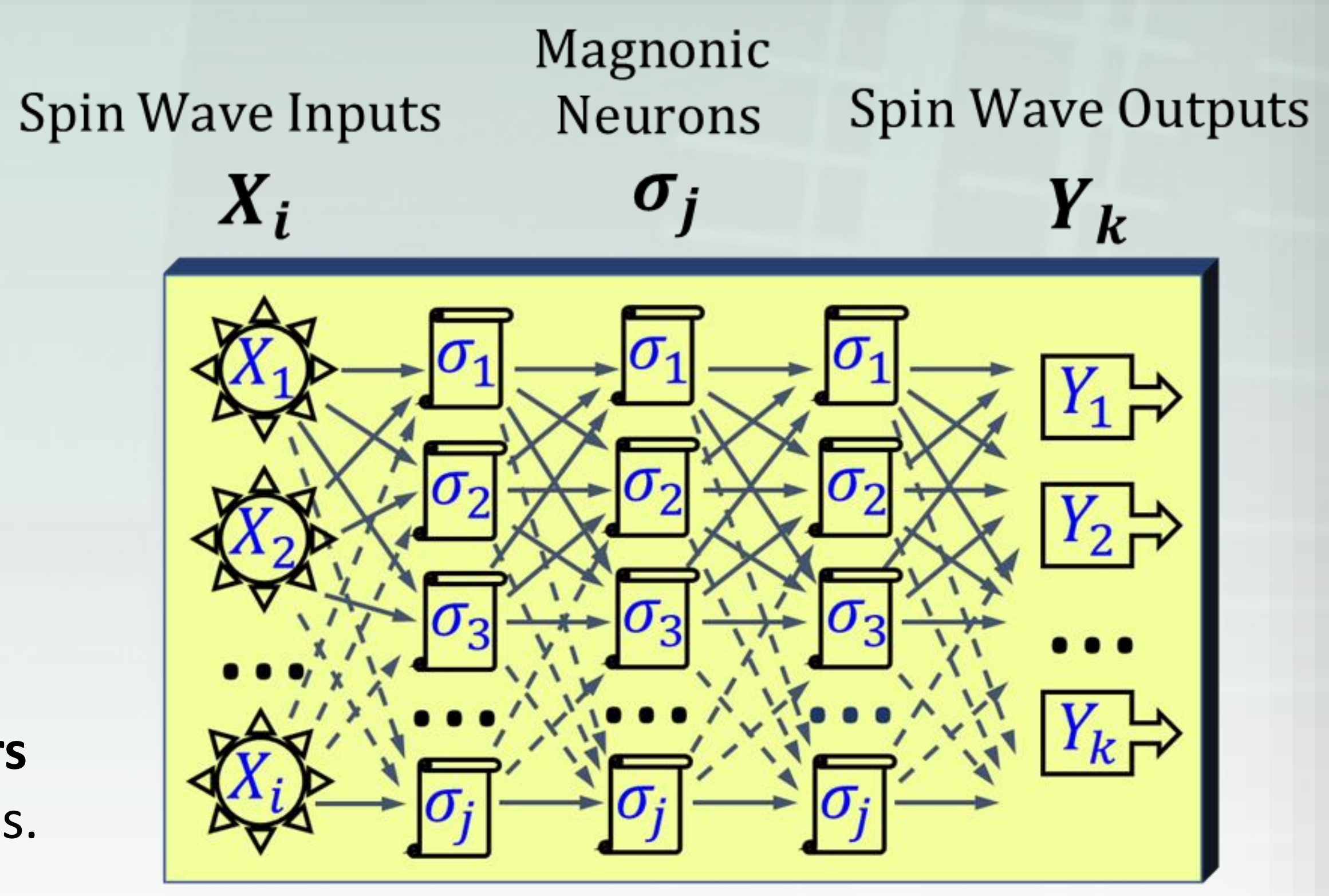
Can an all magnonic neural network be built?

What are the properties of a magnonic neuron?

### Magnonic Neurons:

- Feed-forward information propagation
  -> Non-reciprocal transmission
- Activation
  -> Non-linear transmission

We propose **chiral magnonic resonators** to act as the artificial magnonic neurons.

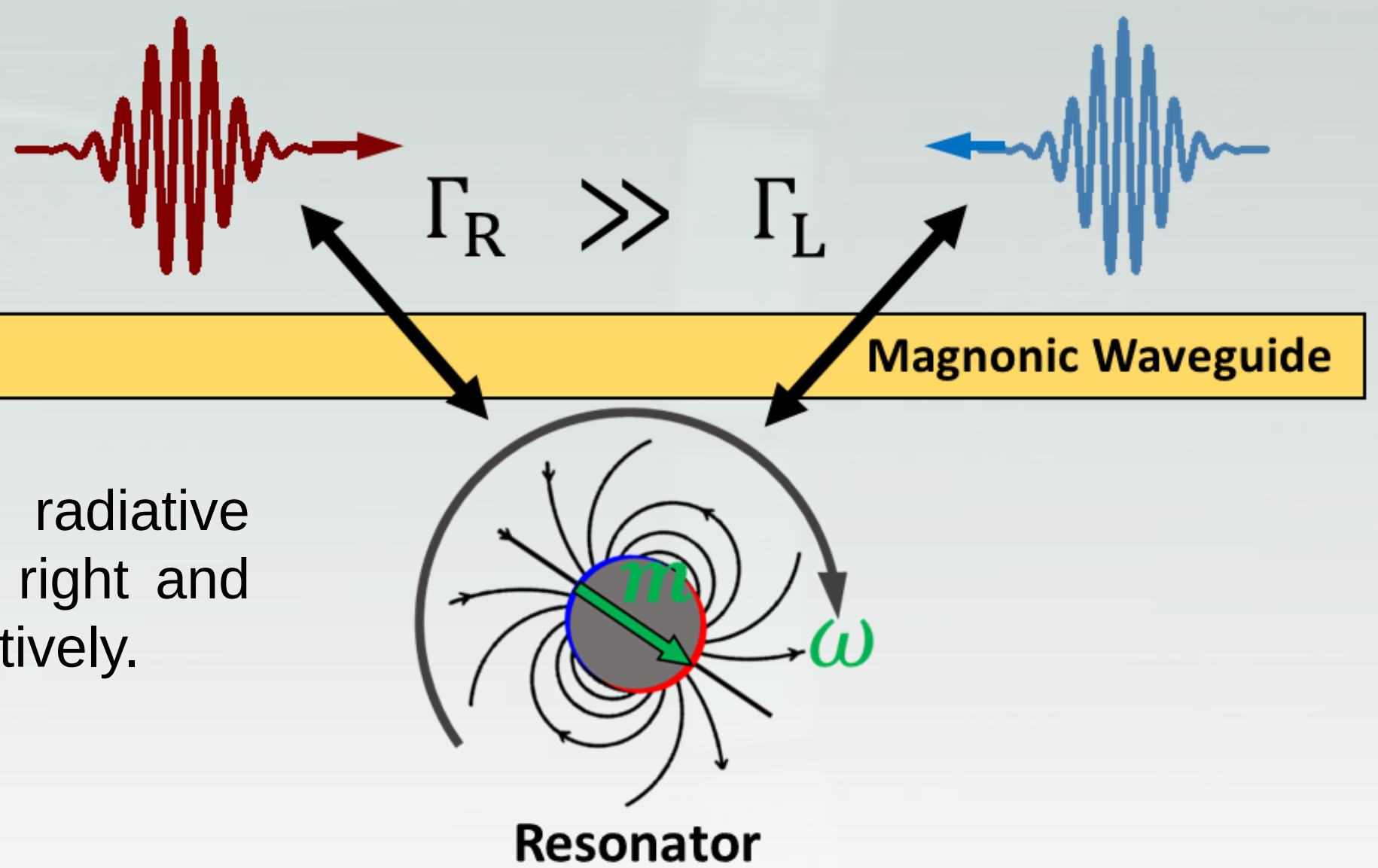


***What are chiral magnonic resonators?***

## Chiral Magnonic Resonators

Chiral coupling arises from the relative sense of rotation between a resonator's precession and a spin wave's dynamic stray field:

**Unidirectional spin wave transmission**

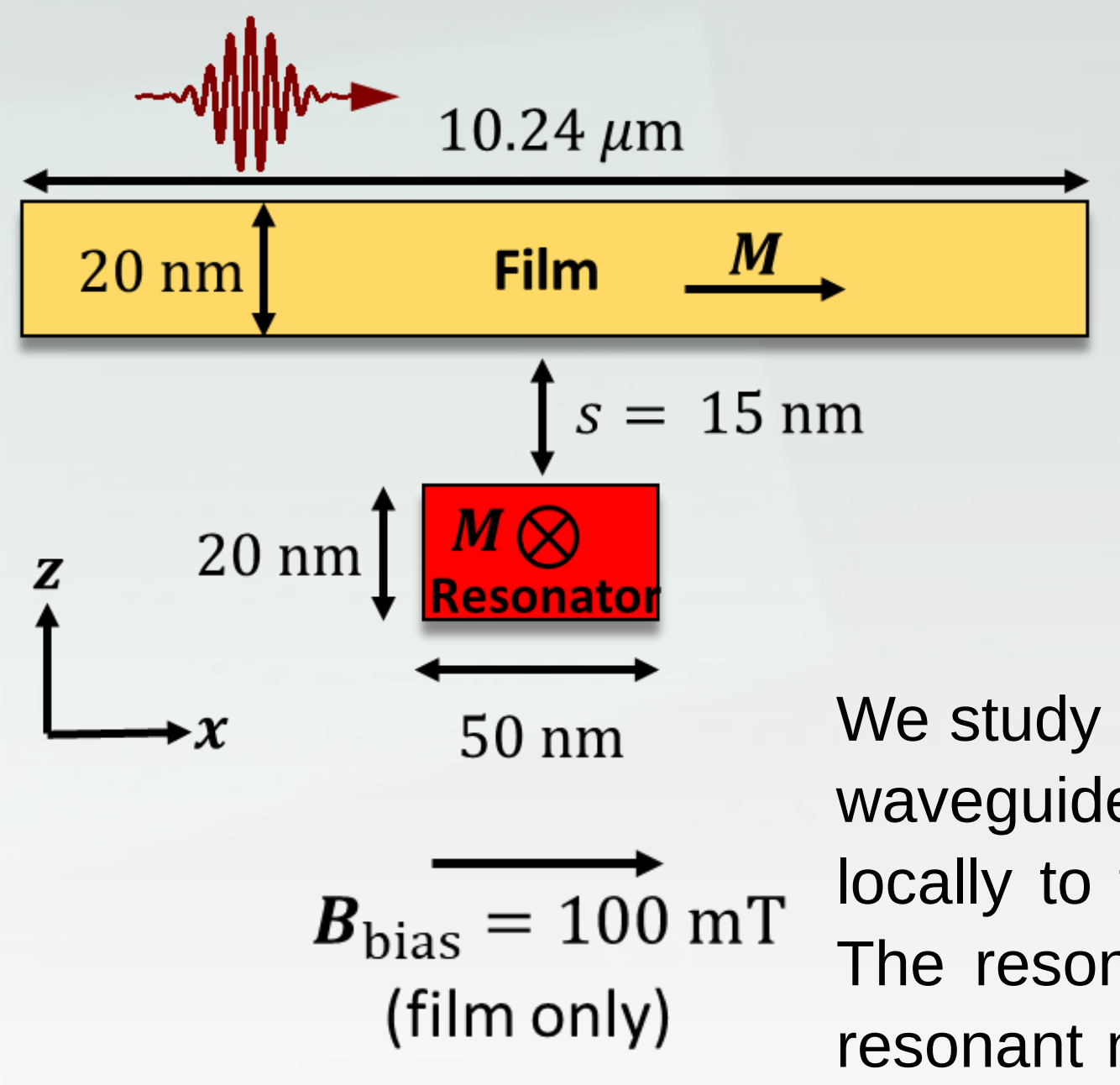


$\Gamma_R$ and $\Gamma_L$ are radiative linewidths to the right and to the left, respectively.

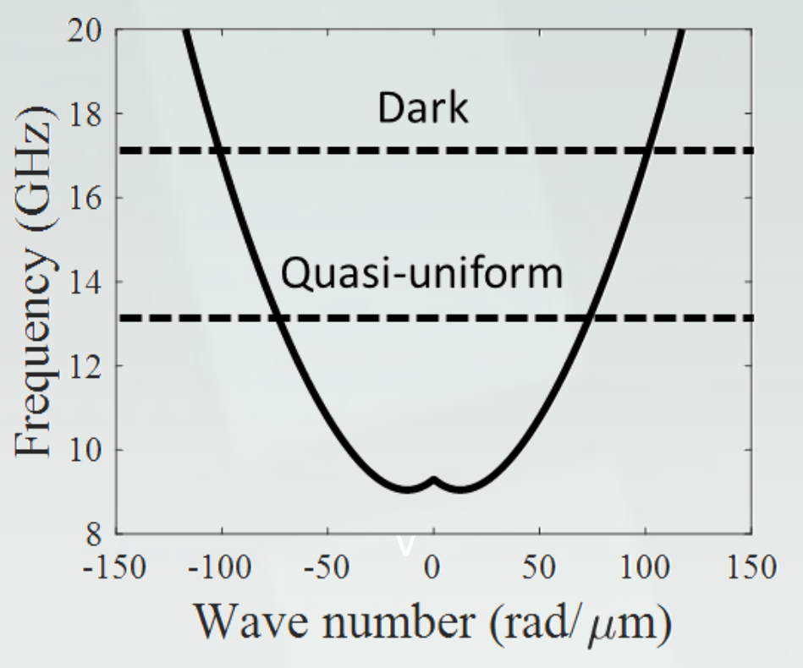
The transmission of spin waves by a magnonic neuron represents its activation. → We model the transmission of spin waves using micromagnetic simulations.

## A Stripe Resonator and Thin Film

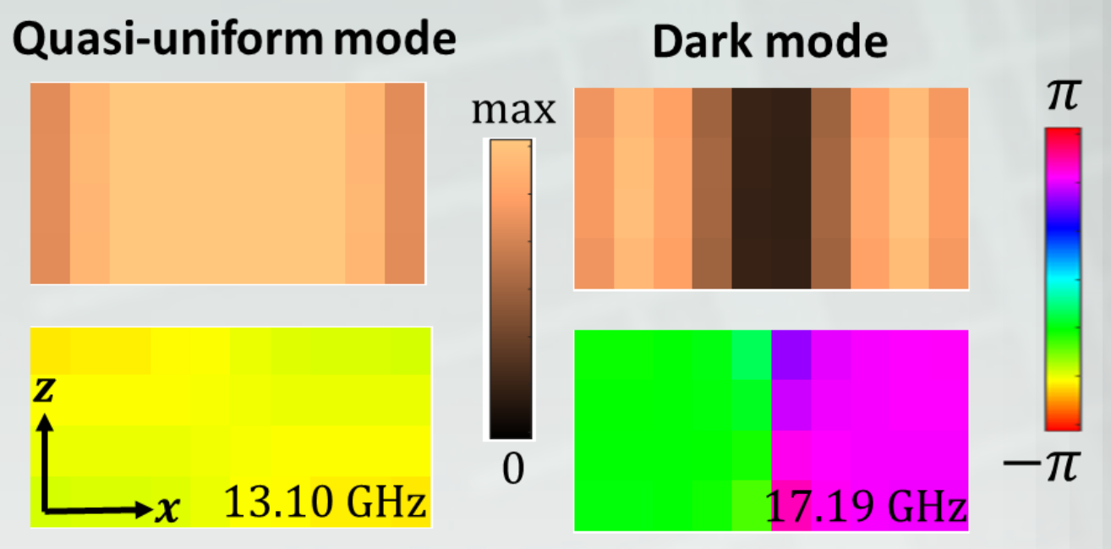
### Geometry



### Thin Film Dispersion



### Resonator Modes



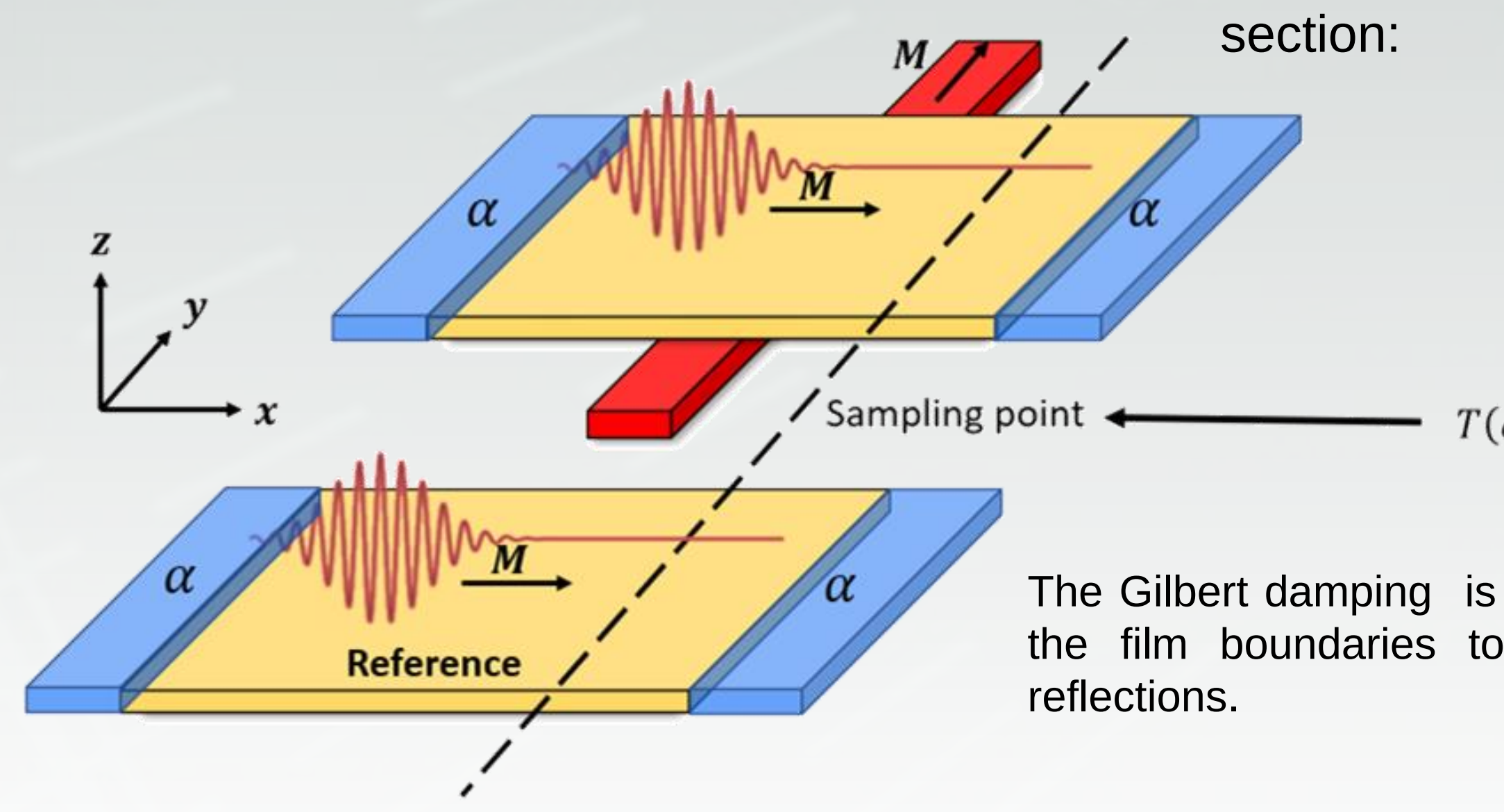
We study the transmission of a stripe chiral magnonic resonator spaced to a thin film waveguide. We assume permalloy parameters throughout and apply a bias field locally to the film to saturate the magnetisation in the backward volume geometry. The resonator is saturated by its shape anisotropy. The resonator possesses two resonant modes. A lower frequency quasi-uniform mode with approximately uniform amplitude and phase, and a higher frequency mode. This higher frequency mode is the first anti-symmetric or 'dark' mode of the resonator.

***How are spin waves transmitted across?***

## Methodology

We launch a broadband wave packet:

We compute the transmission coefficient as the ratio of the complex Fourier amplitudes, averaged in the $yz$ cross-section:



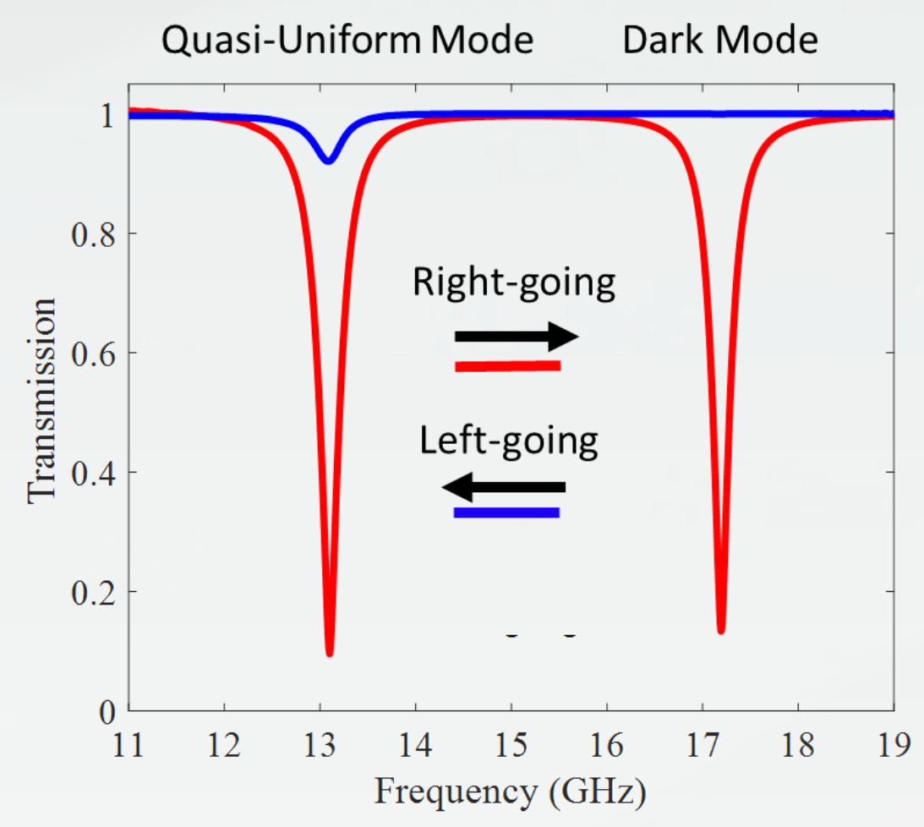
$$T(\omega) \approx \left\langle \frac{\mathcal{F}_\omega\{M_z\}}{\mathcal{F}_\omega\{M_z^{\text{ref}}\}} \right\rangle_{\text{cross-section}}$$

The Gilbert damping is ramped at the film boundaries to suppress reflections.

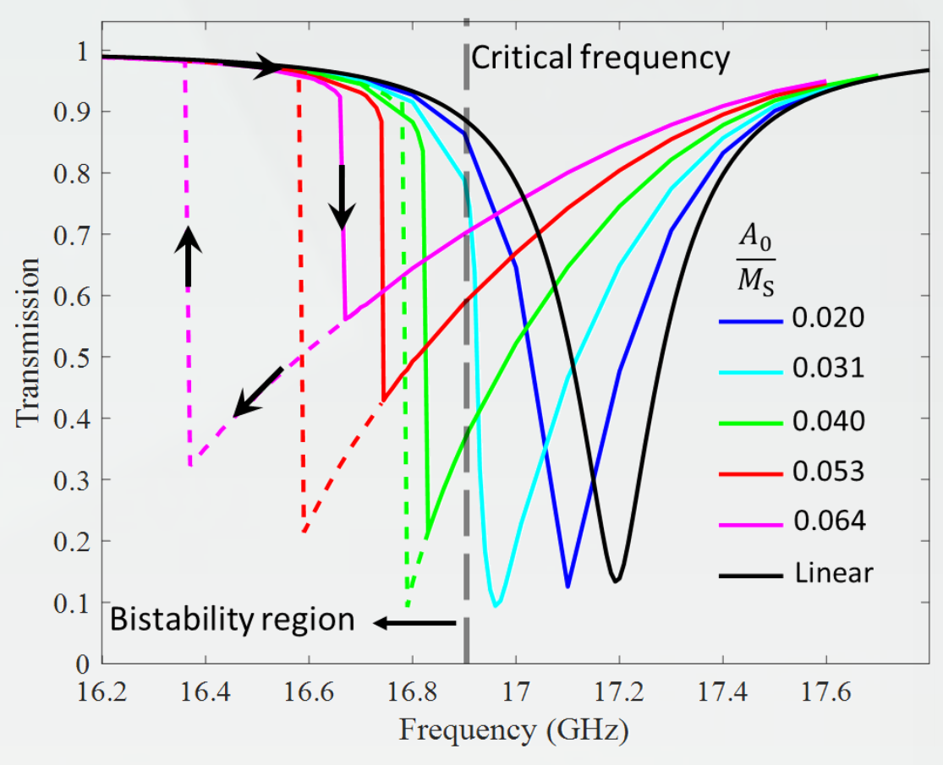
***What is the frequency dependence of $T(\omega)$?***

## Transmission

### Linear



### Nonlinear

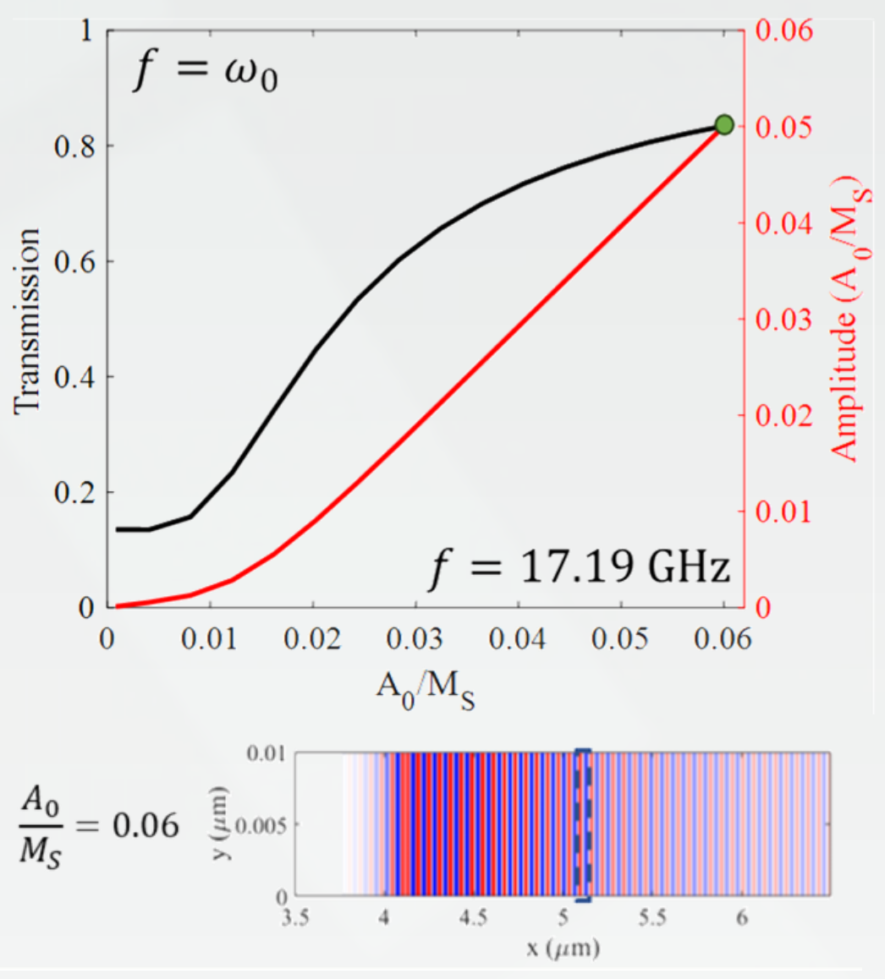


In the linear case we see the curves for the transmission for waves propagating towards the right and the left for the two resonant modes. In both cases nearly identical behaviour for right-propagating spin waves occurs. A sharp Lorentzian dip with maximum attenuation of about 10%. Ultimately, the character of the resonant modes differs but the transmission behaviour is very similar. We may probe the nonlinear behaviour by looking only at dark mode resonance.

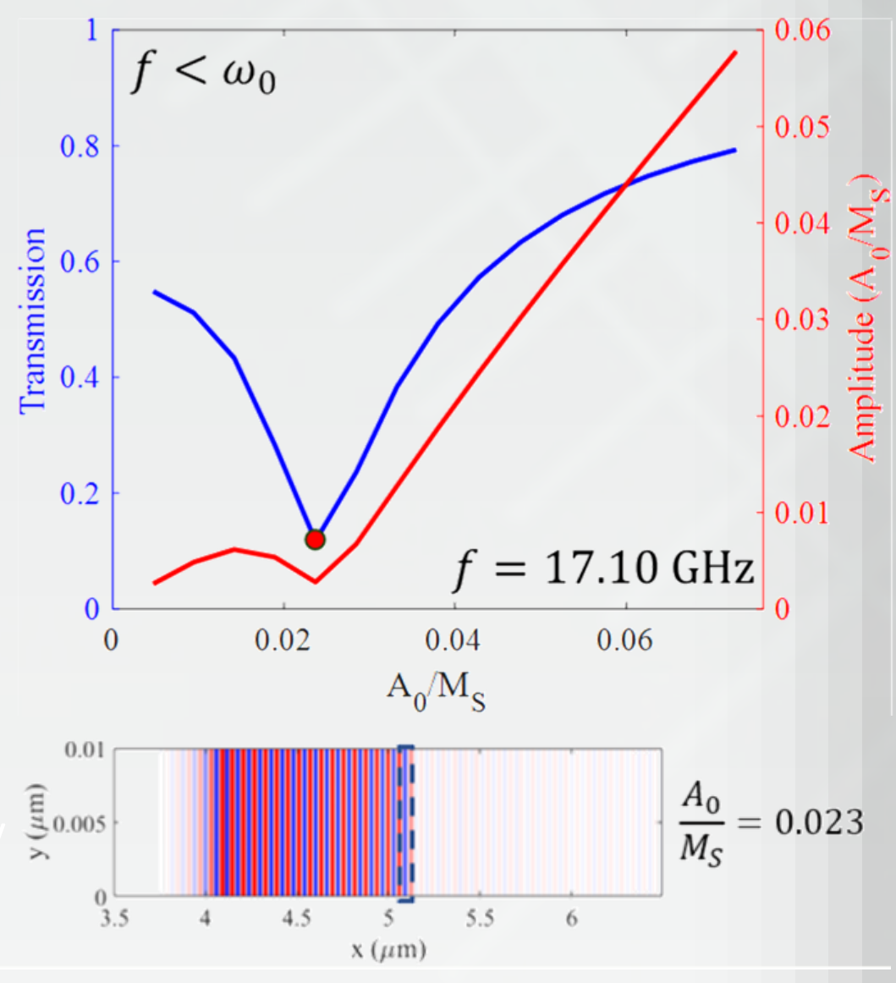
We now see the transmission curves for increasing amplitudes of incident spin waves. At low powers (blue and black), the transmission experiences minimal frequency shifting. At moderate powers (light blue) there is more detuning, and the curves are now asymmetric. At higher powers (green to pink), the left edge of the curves have become vertical, and the curves detuned further. Beyond the dashed line, the critical region of bistability is entered. Indicated by the dashed curves, the transmission has developed bistable behaviour.

## Activation

### Activation



### Power Limiting



By driving the resonator at the resonance frequency at higher spin wave powers, we observe a sigmoidal-like activation response (top left). The shifting of the transmission curve to lower frequencies has allowed spin waves at higher amplitudes to break through. The snapshot of the dynamic magnetisation shows this breakthrough of the spin waves.

Additionally, if we drive the resonator at a frequency below the resonance, we create a power limiter (top right). The shifting of the transmission curves has now aligned the minima of transmission at the lower frequency. The snapshot shows the reduction of spin wave amplitude in transmission.

***How may these results be modelled?***

## Modelling

We can model the local resonator mode $\phi$ as a driven, damped harmonic oscillator with cubic nonlinearity:

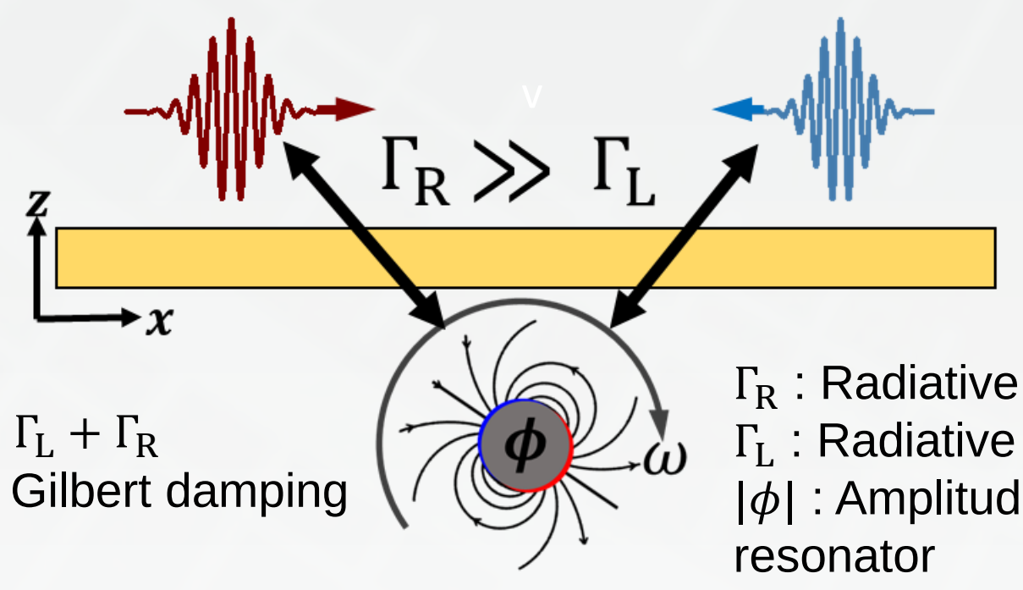
$$i\frac{\partial\phi(t)}{\partial t} = \underbrace{\omega_0\phi(t)}_{\text{Harmonic}} - \overset{\text{damping}}{i\Gamma_{\text{tot}}\phi(t)} - \underbrace{\lambda|\phi(t)|^2\phi(t)}_{\text{Nonlinearity}} + \overset{\text{Spin Wave}}{A(t)}$$

### Transmission

$$\tau_R(\omega, A) = 1 - i\frac{2\Gamma_R}{\omega - \omega_0 + \lambda|\phi|^2 + i\Gamma_{\text{tot}}}$$

$$[(\omega - \omega_0 + \lambda|\phi|^2)^2 + \Gamma_{\text{tot}}^2]|\phi|^2 = |A_0|^2$$

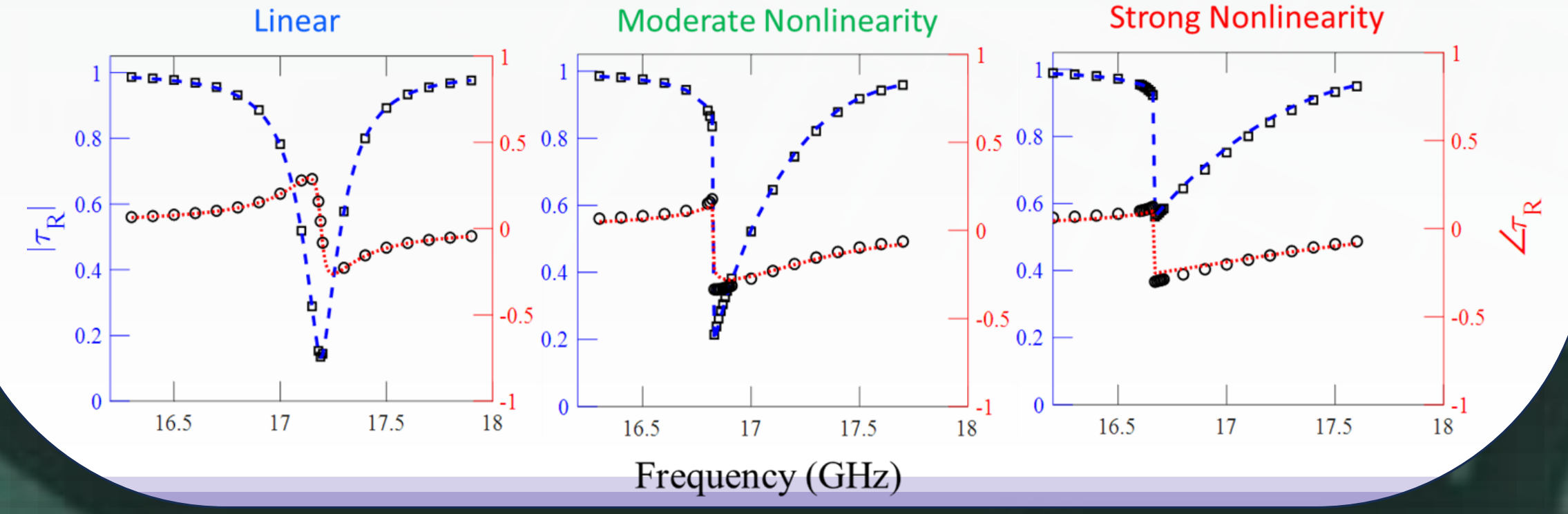
Detuning



$\Gamma_{\text{tot}} = \Gamma_0 + \Gamma_L + \Gamma_R$
$\Gamma_0$ : Linewidth due to Gilbert damping

$\Gamma_R$ : Radiative linewidth to the right
$\Gamma_L$ : Radiative linewidth to the left
$|\phi|$ : Amplitude of precession in the resonator

### Fitting to the Model



Co-funded by the European Union

Engineering and Physical Sciences Research Council

The research leading to these results has received funding from the UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding guarantee (grant number 10039217) as part of the Horizon Europe (HORIZON-CL4-2021-DIGITAL-EMERGING-01) under grant agreement number 101070347, and from EPSRC of the UK (projects EP/L019876/1 and EP/T016574/1).

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