Spin-wave-mediated Skyrmionics for Spiking Neurons

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CA4 Presentation

Executive Summary

Considerations

Current artificial synaptic devices that use displacement **are limited by device size**

Current artificial synaptic devices that store weights are **limited by the number of the skyrmions**

The resolution of firing is often not analogue, but **dependent on the number of skyrmions**

Objective

How can spin-wave mediated skyrmionics overcome the limitations faced by current skyrmionics synaptic devices?

Proposal

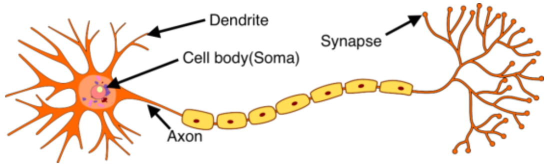
Introducing Spin-wave mediated Skyrmionics for Spiking Neurons

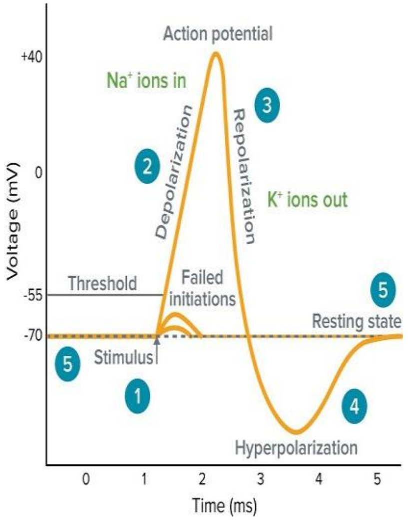
Using the arrangement of skyrmions to mediate the interfering waves offers promise in developing a spin-wave mediated spiking neuron which can overcome limitations of size and dependencies on the number of skyrmions

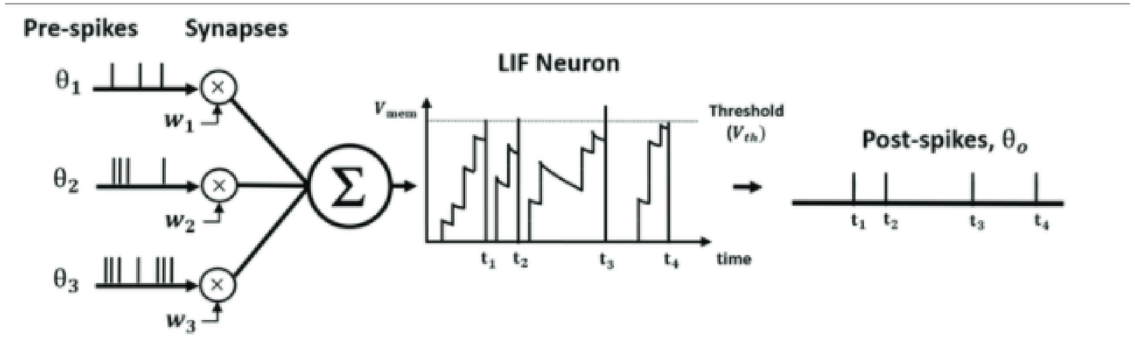
Results

Investigating skyrmion arrangement and spin-wave phenomenon → Develop spin-wave mediated spiking neuron using ring configuration → Develop spin-wave mediated spiking neural network using individual spiking neurons

Biological Neurons are being modelled mathematically







- **Energy efficient**
- Better at processing spatio-temporal data[1]

- **LIF Model**

1) Leaky – constant leakiness if no input
2) Integrate – integration of inputs
3) Firing Threshold – At the action potential neuron fires and resets

[1] M. Pfeiffer, T. Pfeil , *Deep Learning With Spiking Neurons: Opportunities and Challenges*., Frontiers in Neuroscience, 2018

J. Stone, Principles of neural information theory: Computational neuroscience, Sebtel Press, 2018.

C. Lee, S.S. Sarwar, P. Panda, G. Srinivasan, K. Roy. *Enabling Spike-Based Backpropagation for Training Deep Neural Network Architectures*. Frontiers in Neuroscience, 2020

Spintronic hardware are strong candidates for modelling neuron behaviour

Current Devices

- Traditional hardware suffers from **high energy consumption and area requirements**

More devices are required to store weights and the connections between weights

Spintronic Hardware

- Allows for **non-linear magnetisation dynamics and stochastic processes** that can be manipulated to emulate neuron behaviour
- Skyrmions (magnetic solitons) can be used to as vectors of information with **better compactness and energy efficiency** than current electronic devices
- Skyrmion hardware gradually **becoming more realisable** – Room Temperature Stable Skyrmions

Comparison of Skyrmion Implementations

Author/Date	Integrate	Fire	Reset	Leaky	Learning	Improvements
Liang et al., 2020	Yes, distance d to detector from centre	Yes, when skyrmion reaches detector	(?) Can do both annihilation and moving skyrmion back to origin	Yes, boundary induced force sends skyrmion back	No	Hasn't been demonstrated in network
He et al., 2017	Yes, accumulation of skyrmions	Yes, when enough skyrmions are in the output region (number of skyrmions needed to depin domain wall)	Nucleate new domain wall pair by spin polariser and fire new input skyrmion (fan – out)	No	Yes, uses weight domain wall pair Network from excitatory, inhibitory neurons Offline learning Binary synapse	Offline learning Weight dependent on number of skyrmions
Chen et al., 2018	Yes, distance d to the detector and mapping motion of skyrmion	Yes, once skyrmion reaches the end of the 'free layer'	Reverse current and move skyrmion back to origin	No	Validated on MNIST Offline Learning Different conductance branches Weight – device conductance (read current)	Offline Learning Weight dependent on number of 'setups'
Huang et al., 2018	Yes, number of skyrmions at detector	Yes, when enough skyrmions reach detector	Reverse current and move skyrmion back to origin	No	Skyrmions left in the post-synaptic area (detector) affect the weight as a matter of driving force	Weight dependent on number of skyrmions

Adaptive weight but size and resolution limited: Huang et al. (2017)

Y. Huang, W. Kang, X. Zhang, Y. Zhou and W. Zhao, "Magnetic skyrmion-based synaptic devices," *Nanotechnology*, vol. 28, 2017.

Nanotechnology **28** (2017) 08LT02

Replace with

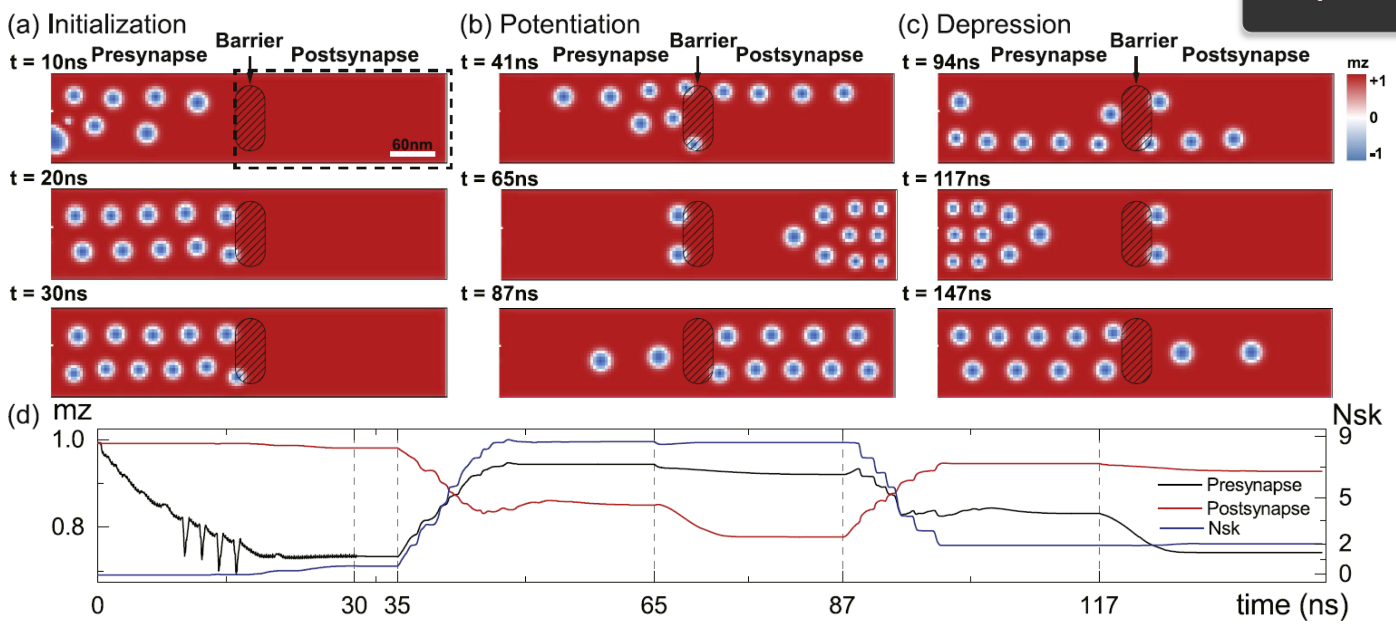


Figure 2. Micromagnetic simulations of the operation modes of our proposed skyrmionic synaptic device. (a) Initialization (from 0 to 35 ns): skyrmions are generated in the presynapse region; (b) potentiation mode (from 35 to 87 ns): a positive stimulus (from 35 to 65 ns) drives skyrmions from the presynapse region to the postsynapse region, increasing the synaptic weight of the device; and (c) depression mode (from 87 to 147 ns): a negative stimulus (from 87 to 117 ns) drives skyrmions from the postsynapse region into the presynapse region, decreasing the synaptic weight of the device. In each operation mode, the device is relaxed to the equilibrium state. (a)–(c) Show snapshots of the magnetization of the nanotrack, and (d) shows the time-resolved normalized mz (the average magnetization component in the *z* direction) of the presynapse and postsynapse regions. The skyrmion number Nsk of the postsynapse is also shown in (d).

Example

- Integrate: Displacement
- Fire: Number of Skyrmions
- Weight: Number of Skyrmions

Weight resolution based on number of skyrmions

- Potentiation easier than Depression
- Skyrmions remaining in post synapse region

Evaluation of Spiking Neuron Devices

1) Displacement based devices are limited by size

Current artificial synaptic devices that use displacement **are limited by device size** during integration, and storage of weights as displacement

2) Dependency on the number of skyrmions for weight

Current artificial synaptic devices that store weights are **limited by the number of the skyrmions**

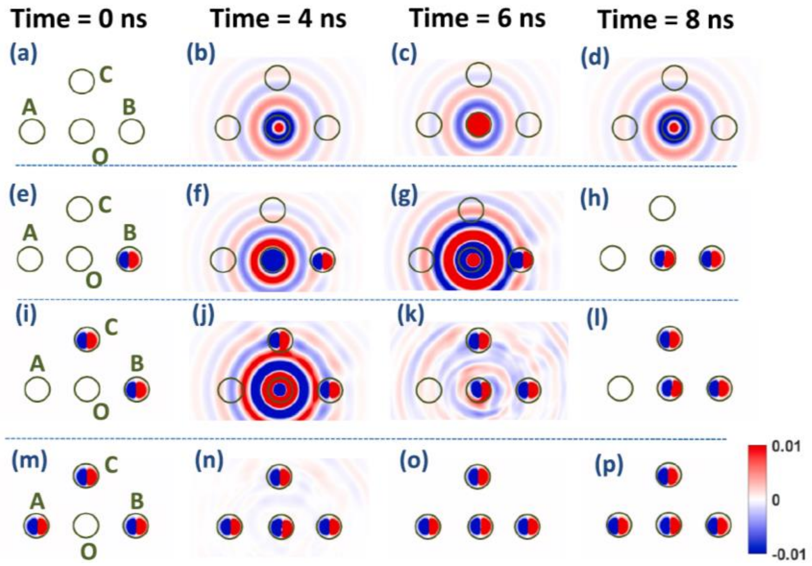
3) Dependent on the number of skyrmions to determine the firing threshold

The resolution of firing is often not analogue, but **dependent on the number of skyrmions because** more fidelity requires more skyrmion.

An alternative approach to displacement and number of skyrmion dependent devices could be spin waves!

Features of Skyrmions and Spin Waves (SWs) using Skyrmion Arrangement

- Skyrmions at certain distances can **amplify or attenuate the SWs from STNO**
- Skyrmions can be created by **SWs**
- Skyrmions are treated as **rigid particles**
- Skyrmions are measured by **measuring magnetoresistance**



V. P. K. Miriyala, Z. Zhu, G. Liang and X. Fong, "Spin-wave mediated interactions for majority computation using Skyrmions," Journal of Magnetism and Magnetic Materials, vol. 486, 2019.

Possible Approaches using Skyrmion and SWs

Advantages of SW approach

Not 'displacement' dependent

a. **Reduces limitation on size constraints**

Higher Resolution Weights

a. **Wave interference is the medium for integration** rather than displacement or number of skyrmions
b. **Dependent on skyrmion arrangements** rather than completely dependent on the number of skyrmions

Mapping to IF Model to Skyrmion Arrangement

1. Integration: Interference between spin-waves at the STNO region
2. Thresholding for Firing: Does a skyrmion nucleate or not in the STNO region after 7ns
3. **Synaptic Weights**:
    1) What are the different forms of skyrmion arrangement?
    2) How can one develop a spin wave-mediated spiking neuron?
    3) How can one develop a spin-wave mediated spiking neural network?

Motivation for Experiments

What are the different forms of skyrmion arrangement?

How can one develop a spin wave-mediated spiking neuron?

How can one develop a spin-wave mediated spiking neural network?

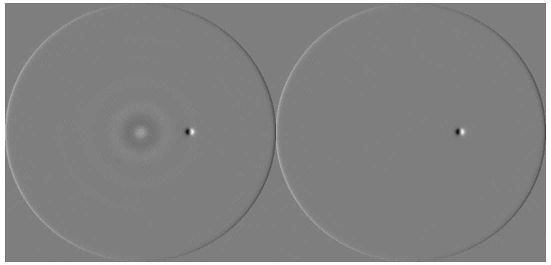
Experiments

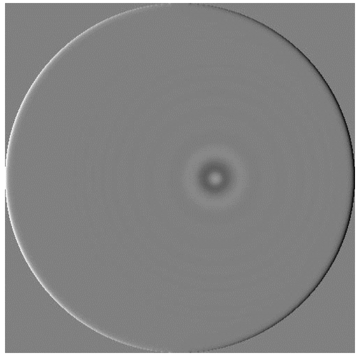
Investigating skyrmion arrangement and spin-wave phenomenon

Develop spin-wave mediated spiking neuron using ring configuration

Develop spin-wave mediated spiking neural network using individual spiking neurons

Results





Objective

How can spin-wave mediated skyrmionics overcome the limitations faced by current skyrmionics synaptic devices?

CA2 Proposed Experiments (Old)

a) **Skyrmion arrangement requirements**

i) Create amplification and attenuation SWs using skyrmions

ii) Can the interfering SWs be controlled? If so to what degree and how can it be done?

b) Multiple Skyrmion in STNO Region

i) Creates skyrmions in the STNO region via SW, and after firing annihilate a % of skyrmions

ii) Is this a viable alternative for adaptive learning?

c) Temporal based using STDP

Use skyrmion arrangement/current pulse width to change/store weight based on timing of input spikes

i) Could be used as an a proof of concept to integrate multiple inputs?

Develop spin-wave mediated spiking neuron using ring configuration

Develop spin-wave mediated spiking neural network using individual spiking neurons

Methodology

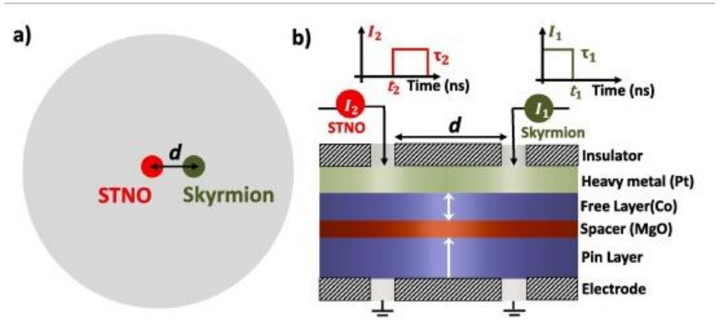
Tools

- Mumax3 – Lack in documentation
- OOMMF – More documentation
- Ubermag – Python based
- Mumax3 – Return since can run on cluster and more adept
- MATLAB (Analysis)
- Brian 2 – neural simulator (Analysis)

Steps

1. Developed testbed device in Mumax3
2. Currently conducted experiments in Mumax3

Testbed Device Setup



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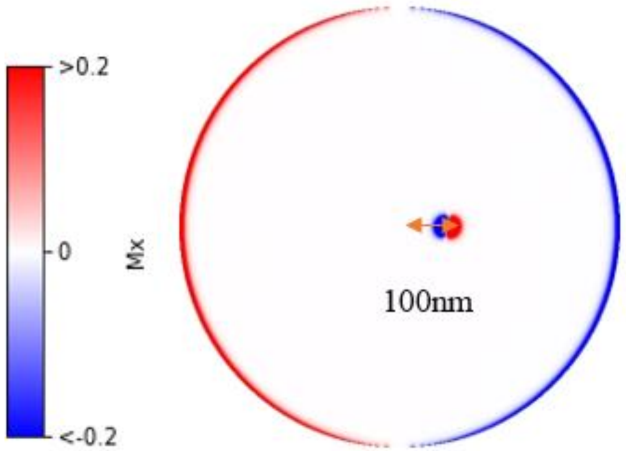
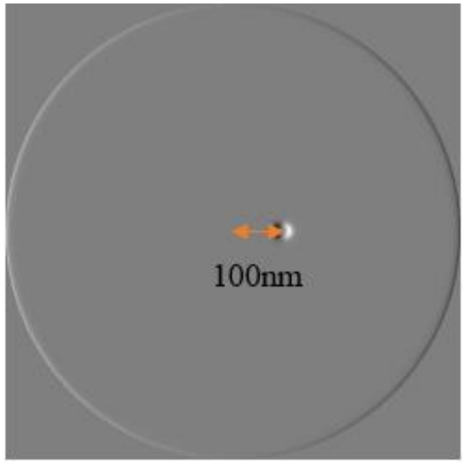
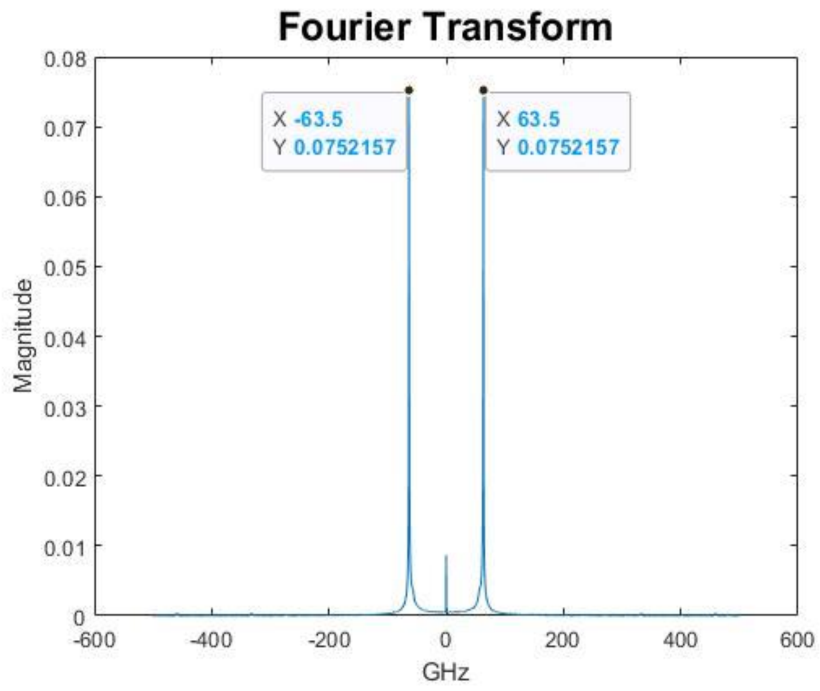
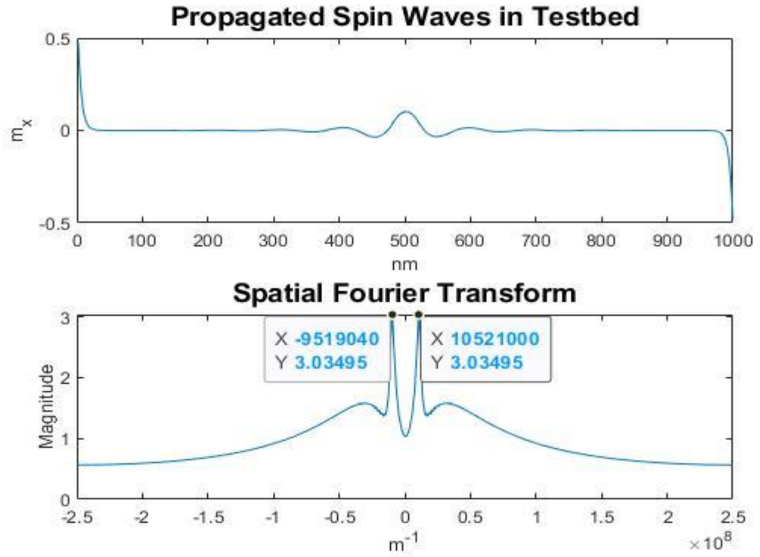




- 1um diameter disk
- 40nm diameter STNO region
- Skyrmions nucleated at different distances from STNO region

Testbed Verification: FFT and Spatial FFT





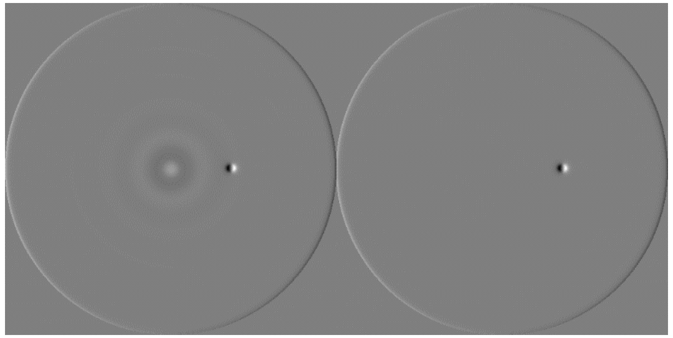
- **63.5 GHz spin wave, and 100.5nm spin wave wavelength which is approximate to the 63GHz and 100nm results recorded in previous experiments.**
- Therefore my experimental **testbed should replicate the same spin-wave interference phenomenon** according to previous experiments

Experiments Overview

Experiment #1

What are the different forms of skyrmion arrangement?

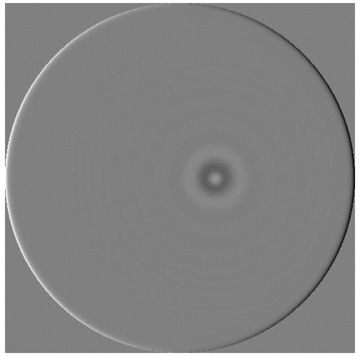
Investigating skyrmion arrangement and spin-wave phenomenon



Experiment #2

How can one develop a spin wave-mediated spiking neuron?

Develop spin-wave mediated spiking neuron using ring configuration



Experiment #3

How can one develop a spin-wave mediated spiking neural network?

Develop spin-wave mediated spiking neural network using individual spiking neurons

Objective

How can spin-wave mediated skyrmionics overcome the limitations faced by current skyrmionics synaptic devices?

Experiment 1: Skyrmion arrangement requirements

Investigate **how skyrmion arrangements affect reflected spin waves**

How to create amplification and attenuation skyrmions using spin waves?

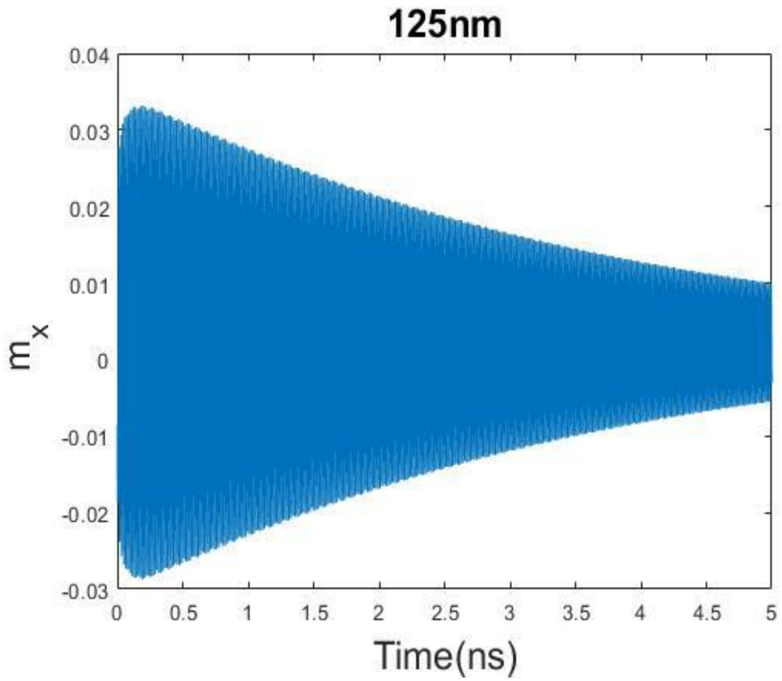
- ✓ Single Skyrmion
- ✓ Rectified Single Skyrmion for 175nm

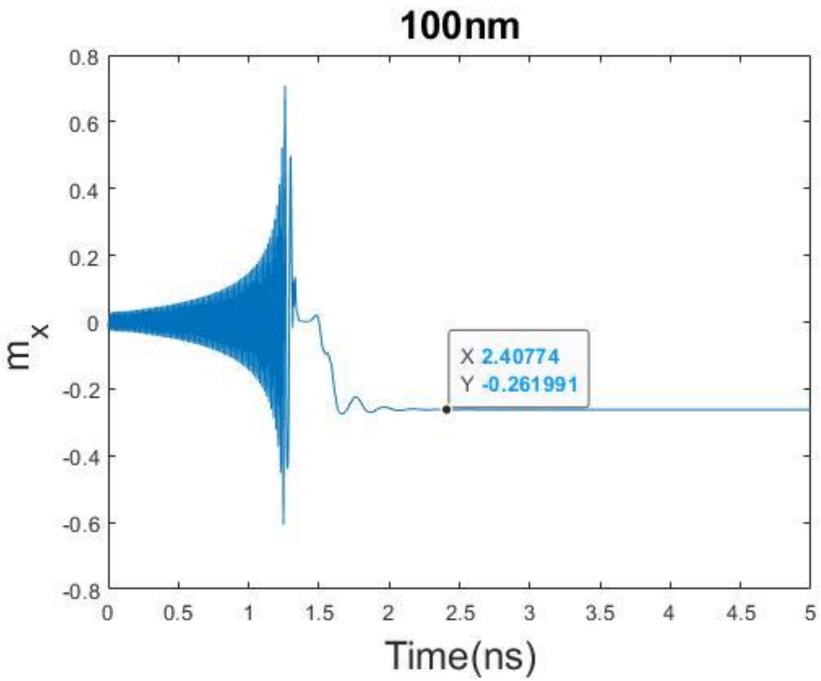
How can spin waves be controlled? And to what degree it can be done so?

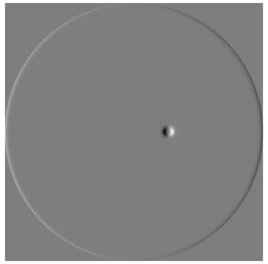
- ✓ Double Skyrmion
- ✓ Ring Configuration
- ✓ Current Density

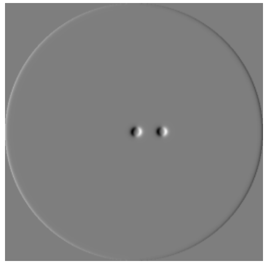
Experiment 1: Single Skyrmion Results Attenuation and Amplification

How to create amplification and attenuation skyrmions using spin waves?









Background Methodology Results Conclusion

Experiment 1: Single Skyrmion Analysis

How to create amplification and attenuation skyrmions using spin waves?

Single skyrmion (nm)	Wave	Skyrmion Creation	Localised Reduced Magnetisation (unit length)	Time (s)
No Skyrmion	*Control*	*Yes*	*-0.262*	*4.8e-08*
100	Amplification	Yes	-0.262	2.4E-09
125	Attenuation	No	N/A	N/A
150	Amplification	Yes	-0.262	3.6E-08
175	Attenuation	Yes	-0.262	4.9E-08
200	Amplification	Yes	-0.262	4.0E-08

Distance (nm)	Time(s)
100	2.4E-09
150	3.6E-08
200	4.0E-08

Distance (nm)	Time(s)
Control	4.8E-08
125	N/A
175	4.9E-08

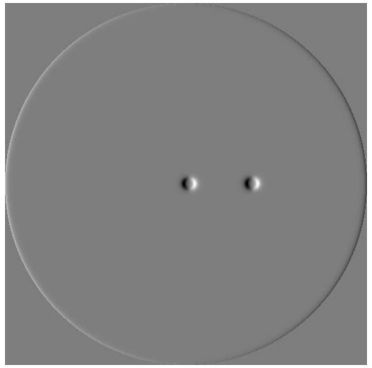
- **Amplification and attenuation** occur at standing wave **intervals of 50nm**
- **Further away** single skyrmions are, the **more reduced** their effect
- 175nm created a skyrmion in the STNO region despite being attenuation?

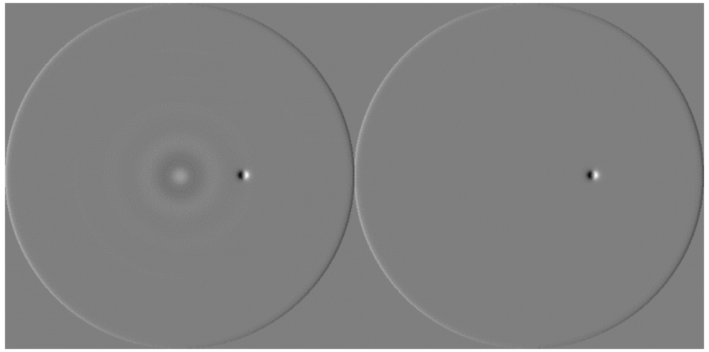
Experiment 1: Rectifying 175nm Results

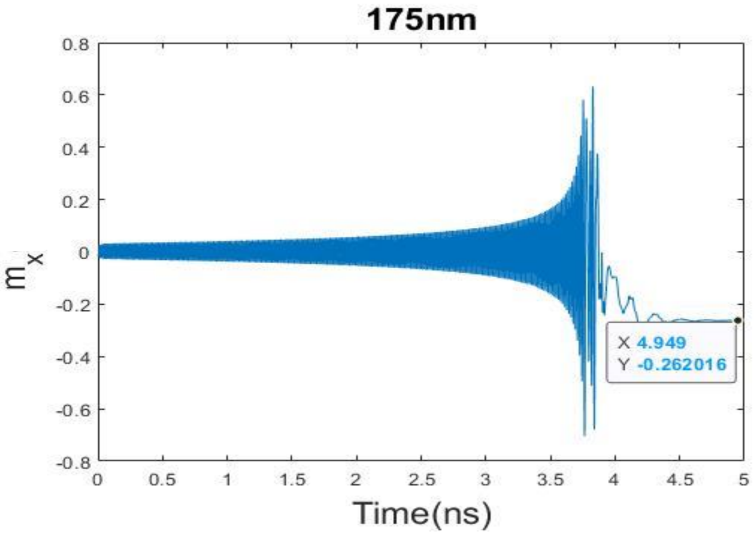
The spin waves in the STNO region with no skyrmion are biased to forming a skyrmion.

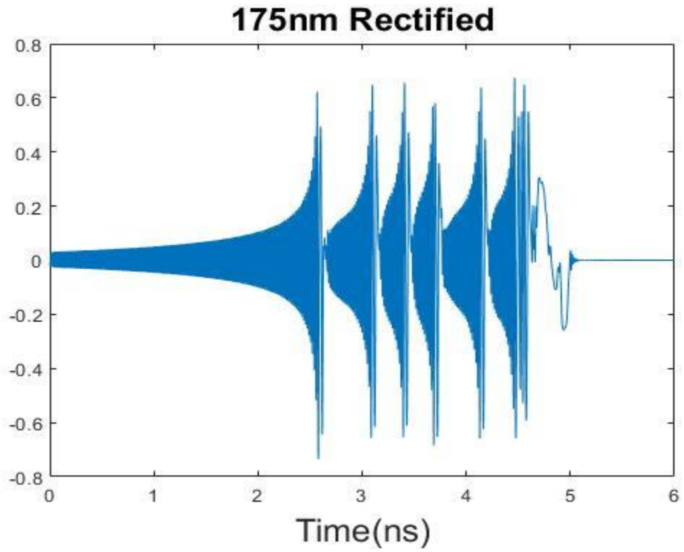
175nm is attenuating the spin waves since time taken to form the skyrmion in the SNTO region is delayed.

To avoid skyrmion nucleation in the STNO region, we can decrease interfacial DMI from $3.5 \times 10^{-3}\ J/m^2$ to $3.0 \times 10^{-3}\ J/m^2$







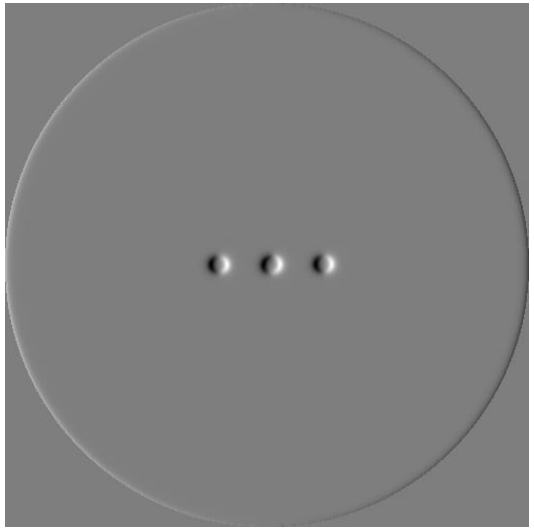


Experiment 1: Double Skyrmion Results

How can spin waves be controlled? And to what degree it can be done so?

When two *directly opposing* skyrmions are placed along the same plane (x-axis) at different distances to the STNO region

How do *Double Skyrmions* **affect spin waves?**



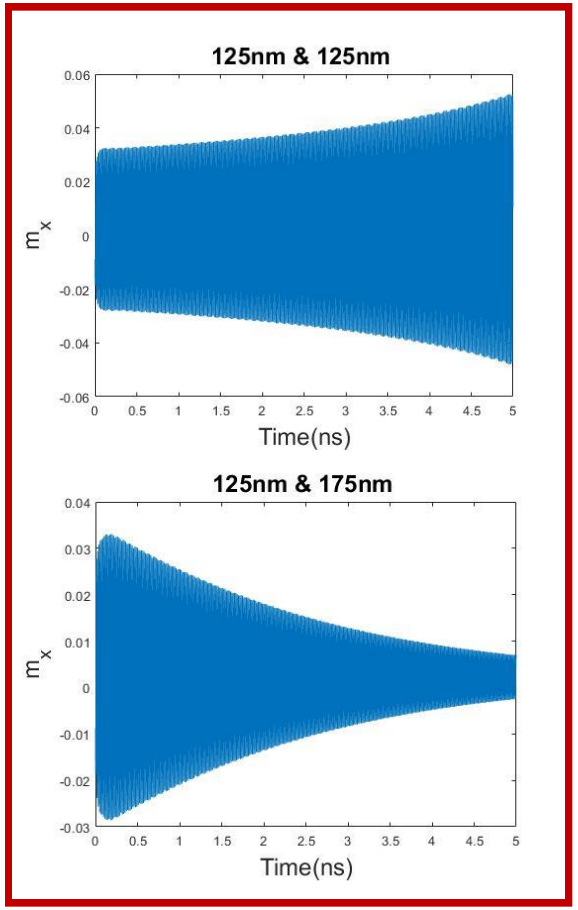
[100nm 100nm] Double Skyrmion Configuration

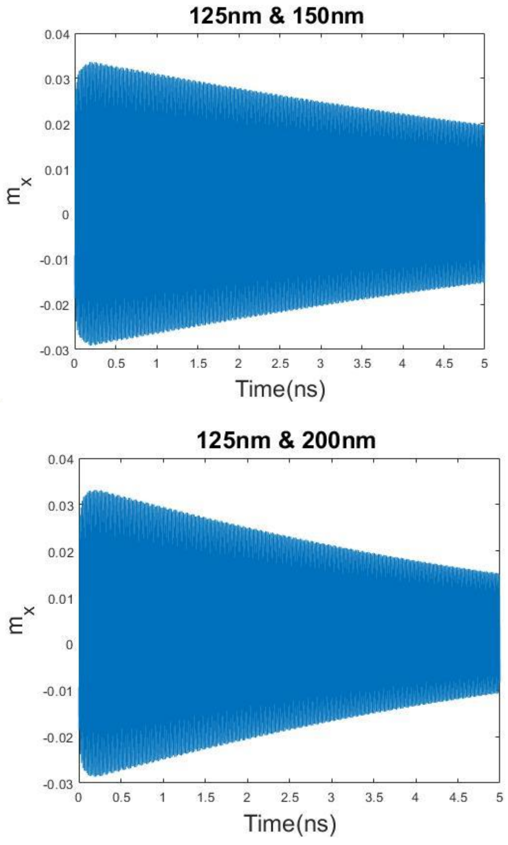
Experiment 1: Double Skyrmion Results

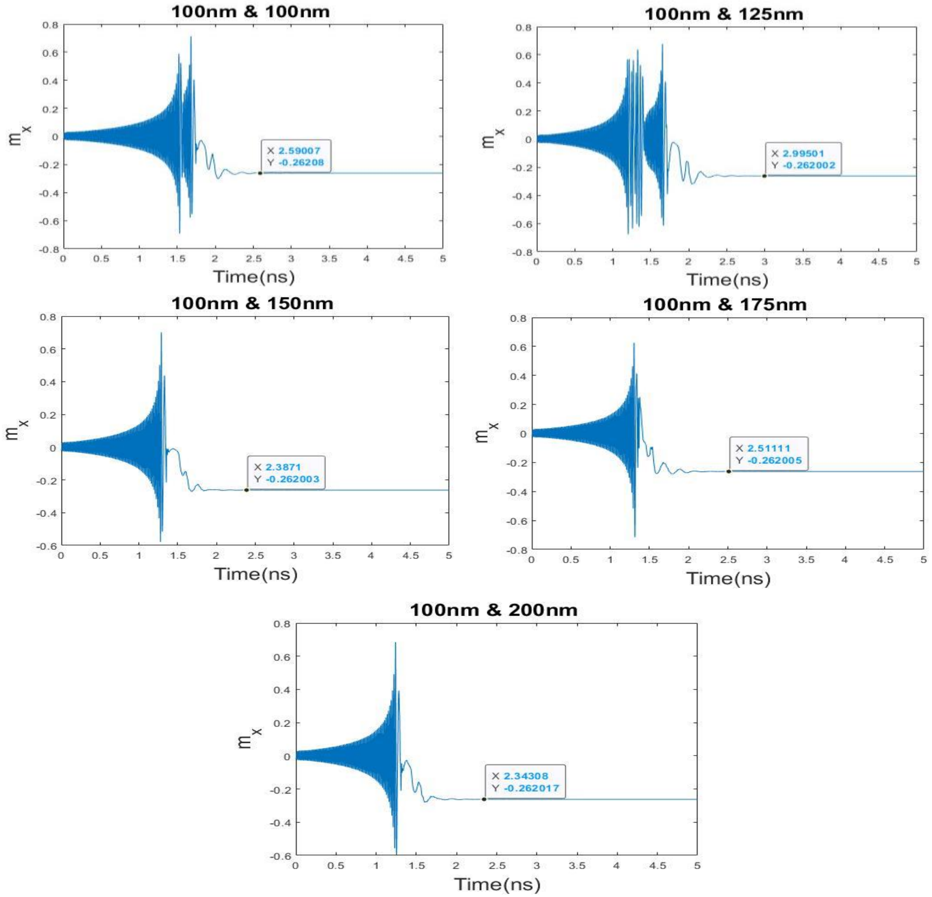
Skyrmion #1 (nm)	**Skyrmion #2 (nm)**	**Wave**	**Skyrmion Creation**	**Localized Reduced Magnetization (unit length)**	**Time (s)**
No Skyrmion	*No Skyrmion*	*Control*	*Yes*	*-0.262*	*4.8e-08*
100	-100	Amplification	Yes	-0.262	2.59E-9
100	-125	Amplification	Yes	-0.262	2.99E-9
100	-150	Amplification	Yes	-0.262	2.38E-9
100	-175	Amplification	Yes	-0.262	2.51E-9
100	-200	Amplification	Yes	-0.262	2.34E-9
125	-125	Attenuation	No	N/A	N/A
125	-150	Attenuation	No	N/A	N/A
125	-175	Attenuation	No	N/A	N/A
125	-200	Attenuation	No	N/A	N/A

When two *directly opposing* skyrmions are close in proximity, their overall amplification or attenuation effect is reduced.

Experiment 1: Double Skyrmion Graphical Results







1. Closest skyrmion determines the general interference pattern.
2. When two directly opposing skyrmions are close in proximity, their overall amplification or attenuation effect is reduced

Experiment 1: Double Skyrmion Analysis

When two directly opposing skyrmions are close in proximity, their overall amplification or attenuation effect is reduced

One possible reason could be that it takes longer for the STNO region to stabilize because of more complex spin-wave interference patterns occurring in the STNO region. For example, distortions to the standing wave are likely to magnified such as phase difference when the skyrmions are close in proximity. However, these perturbations do not change the overall amplification or attenuation pattern.

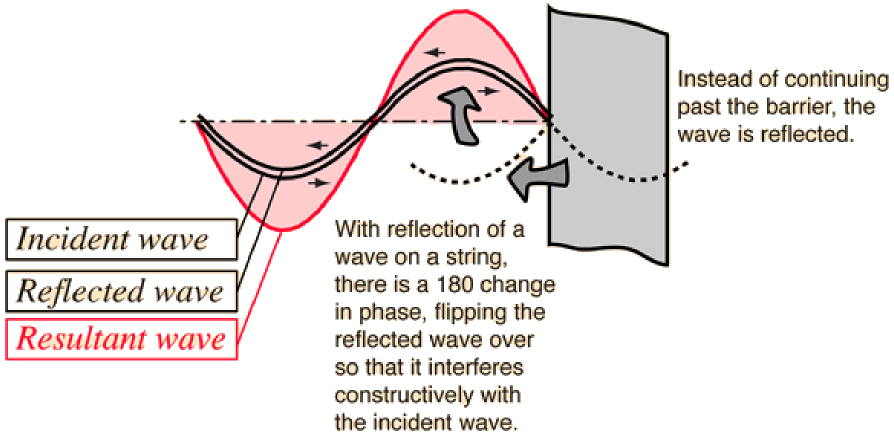


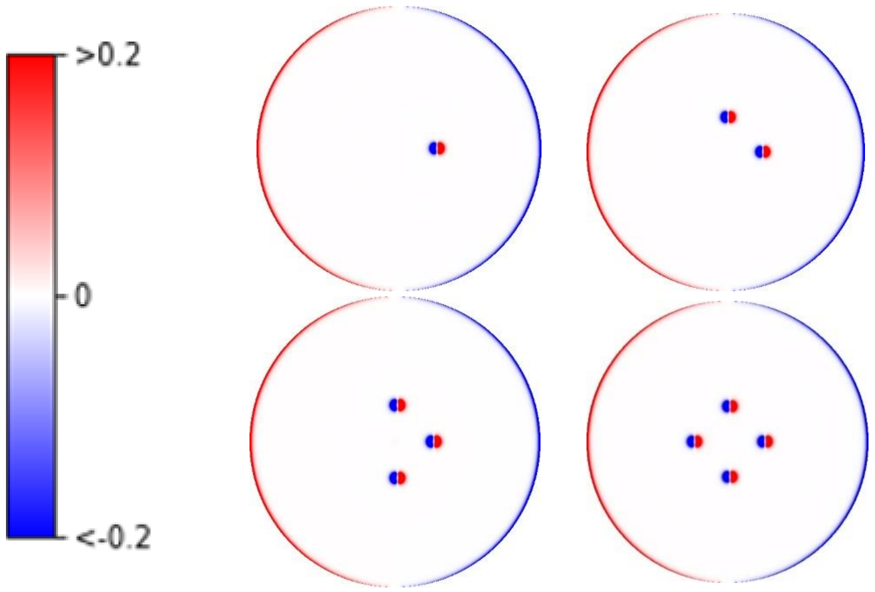
Image Source: R,Nave. Hyperphysics

Experiment 1: Ring Configuration

How can spin waves be controlled? And to what degree it can be done so?

Placing multiple skyrmions orthogonally in a ring around the STNO region.

How does *Ring Configuration* affect spin waves?



Experiment 2: Ring Configuration Results

Configuration (nm)	Skyrmion Formation	Reduced magnetisation (unit length)	Time (s)
125	No	-	-
125-125	No	-	-
125-125-125	No	-	-
125-125-125-125	No	-	-
100	Yes	-0.261991	2.40E-9
100-100	Yes	-0.261995	2.02E-9
100-100-100	Yes	-0.262263	1.99E-9
100-100-100-100	Yes	-0.261847	2.28E-9

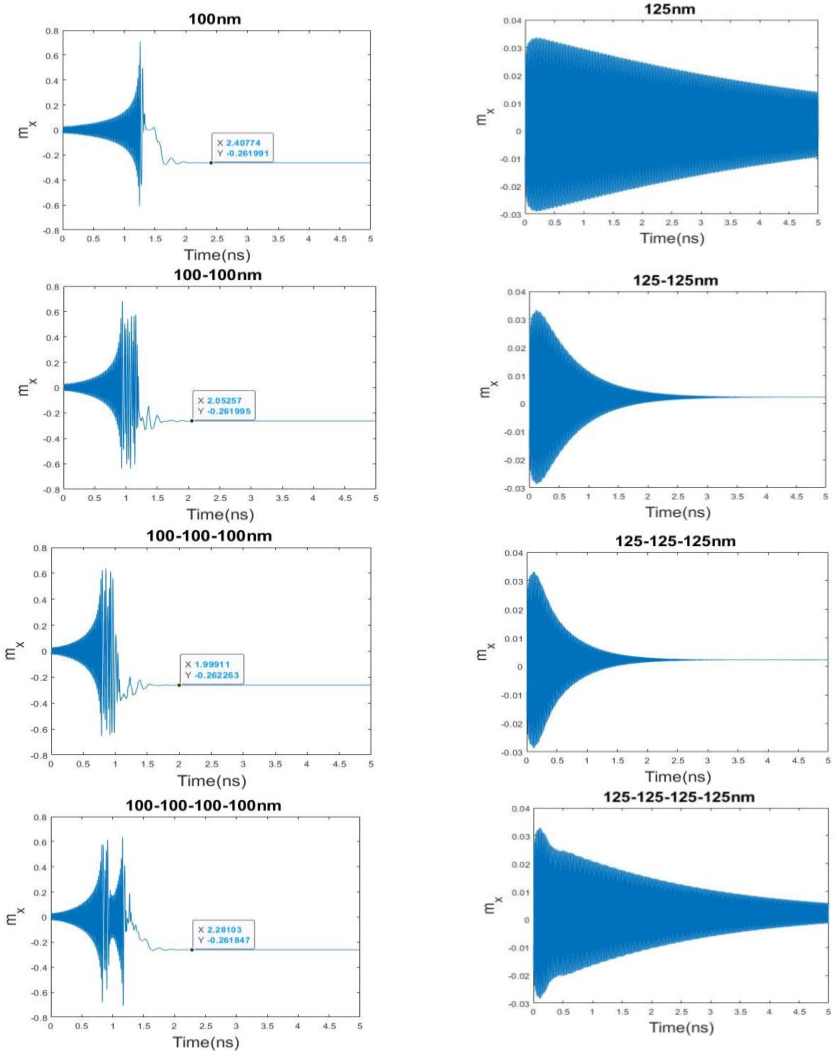
Up until three skyrmions, the time taken to nucleate skyrmion decreases.

Experiment 2: Ring Configuration Graphical Results

- Visually in the attenuation graphs the decreased attenuation effect of the four skyrmion ring configuration can be observed through the steepness of attenuation

- The attenuation effect, just like the amplification effect, is magnified until the presence of three skyrmions

- Possible reason why the four skyrmion ring has decreased effect could be addition of the *directly opposing skyrmion* which reduces the effectiveness of attenuation and amplification



Experiment 1: Current Density

How can spin waves be controlled? And to what degree it can be done so?

STNO Region Current Density (Am^{-2})	Skyrmion Nucleation in the STNO region
-5.4985e10	No
-5.4985e11 (Original)	Yes
-5.4985e12	Yes

- The injected spin current density must be above a certain threshold for skyrmions to form

Experiment 1: Summary

Investigate **how skyrmion arrangements affect reflected spin waves**

How to create amplification and attenuation skyrmions using spin waves?

- ✓ Single Skyrmion
- ✓ Rectified Single Skyrmion for 175nm

- **Amplification and attenuation occur at standing wave intervals of 50nm**
- **Further away single skyrmions are, the more reduced their effect**

How can spin waves be controlled? And to what degree it can be done so?

- ✓ Double Skyrmion
- ✓ Ring Configuration
- ✓ Current Density

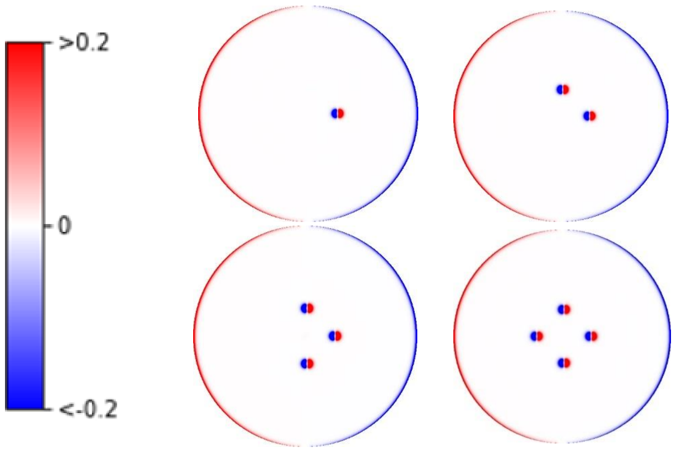
1. Closest skyrmion determines the general interference pattern.
2. When *two directly opposing* skyrmions are close in proximity, their overall amplification or attenuation effect is reduced

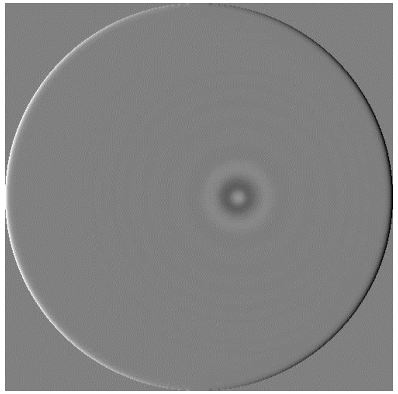
3. The attenuation effect and amplification effect, is magnified until the presence of three skyrmions
4. Decreased effect when skyrmions are *directly opposed*

5. The injected spin current density must be above a certain threshold for skyrmions to form

Experiment 2: Temporal based Spin Mediated Neuron Device

Choosing the **ring configuration** because of it not relying on **displacement and movement** of skyrmions as a method of skyrmion arrangement, we generate can generate a spiking neuron



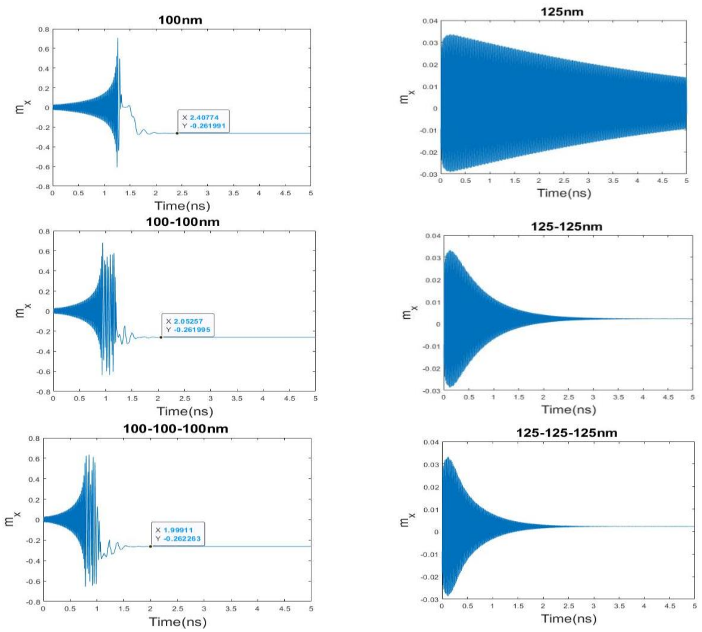


Experiment 2: Motivation for **Spike-timing-dependent plasticity self-learning model (STDP)**

From experiment #1 Ring Configuration :

3. The **attenuation effect and amplification effect, is magnified** until the presence of three skyrmions

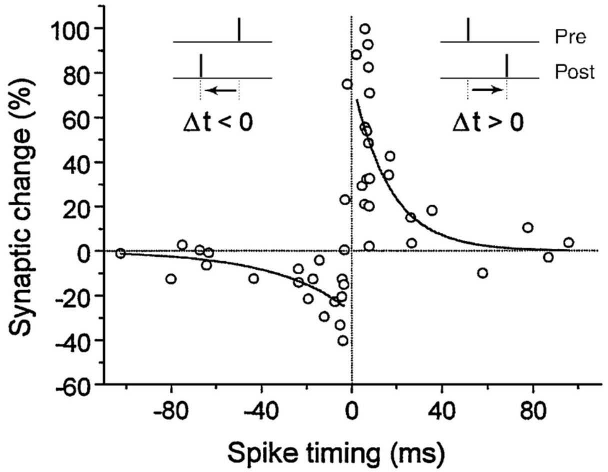
- Magnified effect is evidenced by **faster timings**



Spike-timing-dependent plasticity self-learning model (STDP)

- Biological process that **adjusts synaptic strength between neurons in the brain relative to the timing of spikes**

- Spike timings can be **mapped to synaptic weights, as well as discrete synaptic weights**



M.M. Asl, A. Valizadeh, P.A. Tass. *Propagation Delays Determine the Effects of Synaptic Plasticity on the Structure and Dynamics of Neuronal Networks. 2018*

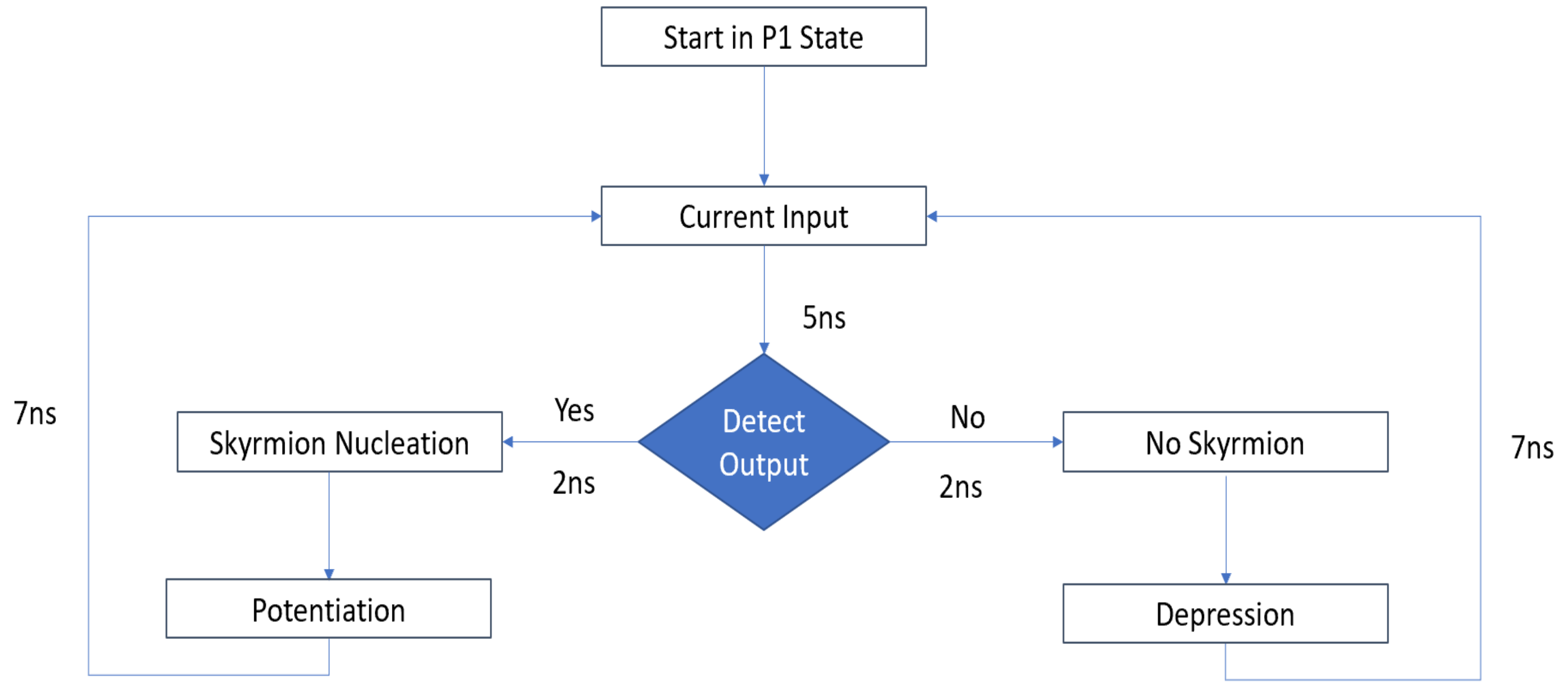
Experiment 2: STDP State Allocation

Discretized Weight	Configuration (nm)	Time (s)	Reduced magnetisation (unit length)
A1	125	-	-
A2	125-125	-	-
A3	125-125-125	-	-
P1	100	2.40E-9	-0.261991
P2	100-100	2.02E-9	-0.261995
P3	100-100-100	1.99E-9	-0.262263

Assign discretized weight states to each of the ring configurations since each ring timing has a different amplification and attenuation effect on the timing of skyrmion nucleation

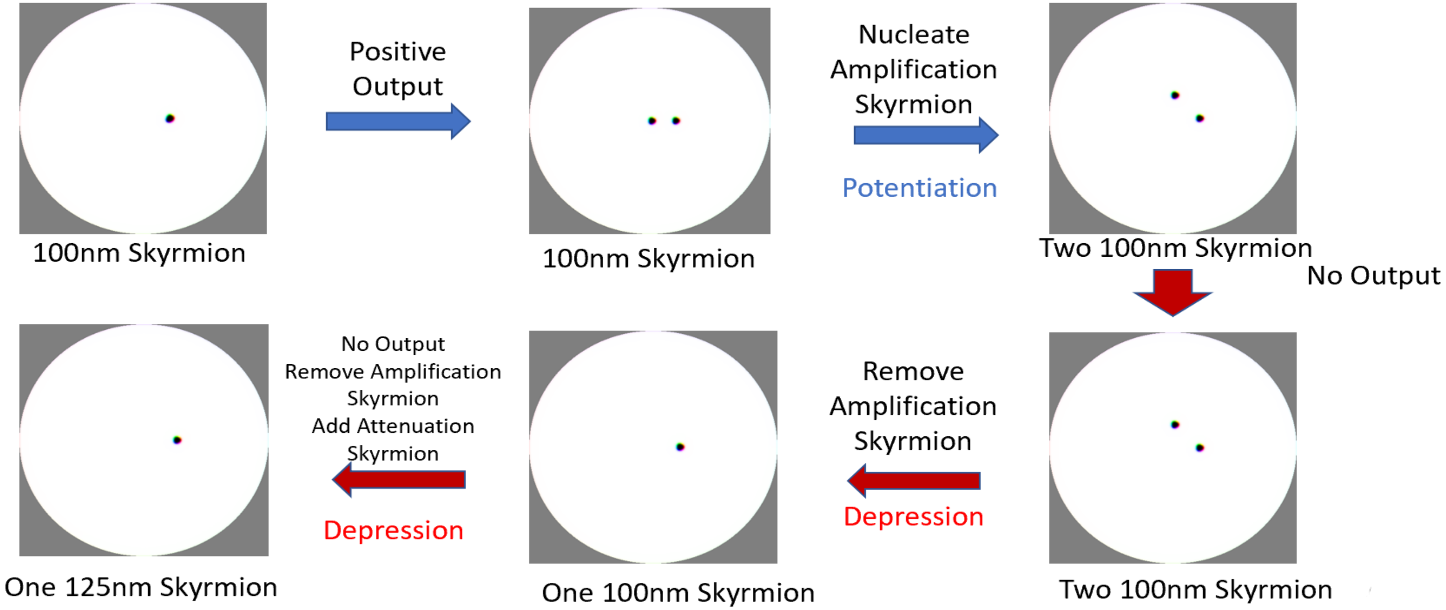
Mealy State machine : A3 ↔ A2 ↔ A1 ↔ P1 ↔ P2 ↔ P3

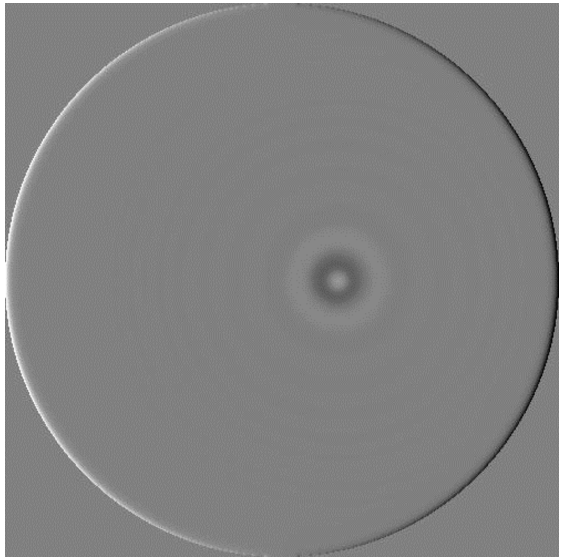
Experiment 2: Parameters for STDP Spiking Neuron



- Total 14ns = Input (5ns)+ Detection (2ns) + Adjustment (7ns)
- Refractory period (9ns) = Detection(2ns) + Adjustment (7ns)

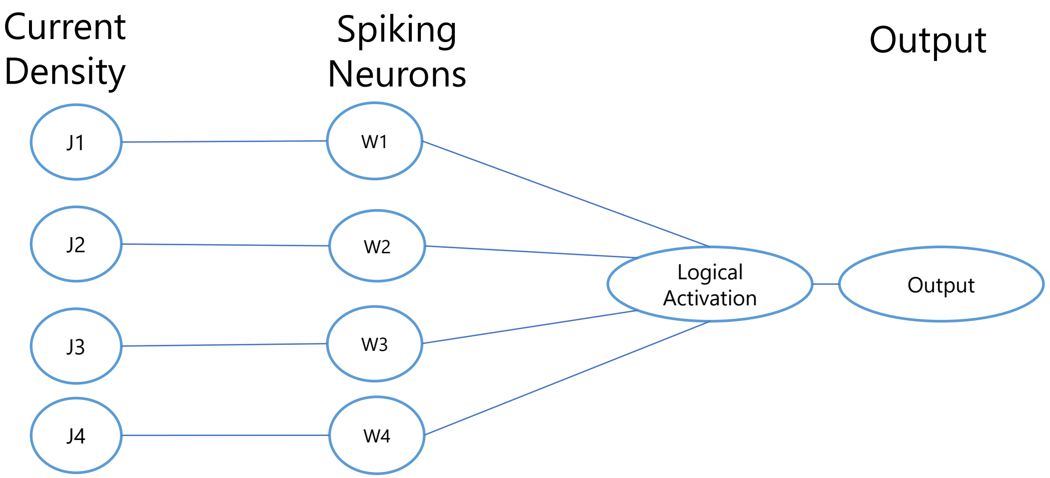
Experiment 2: Simulation

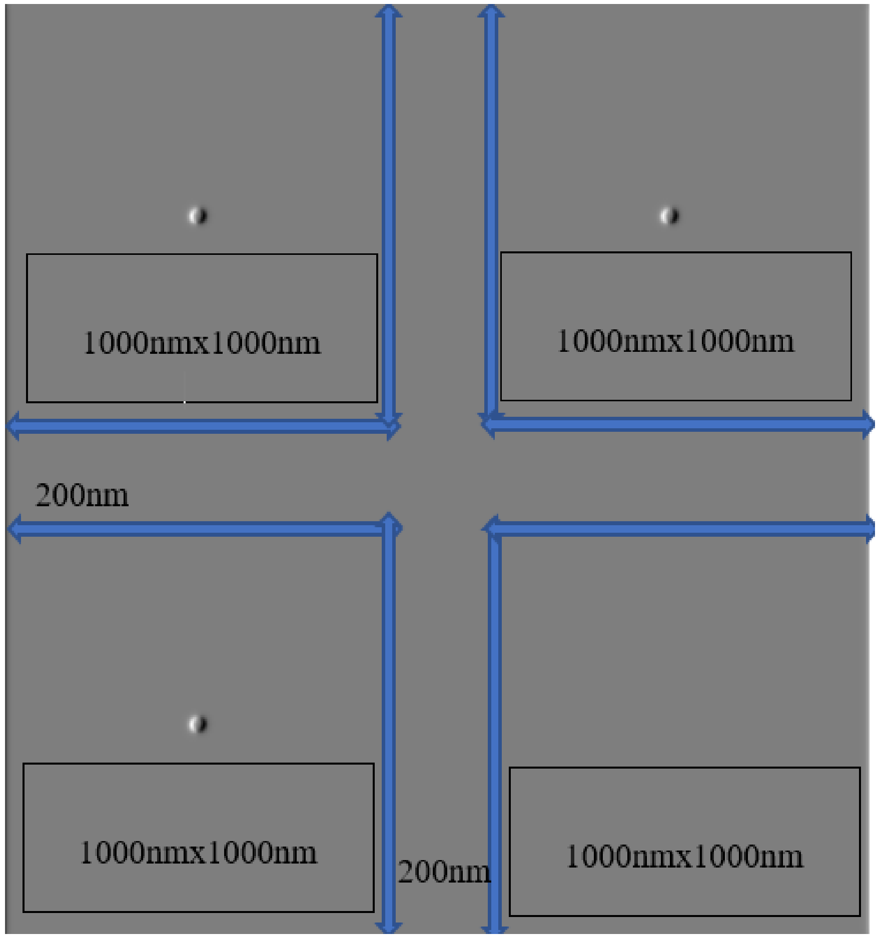




Experiment 3: SNN

- Combining multiple spiking skyrmion neuron devices together into an array, we can obtain the following network device
- Each single neuron device corresponds to one node in a spiking neural network. In this example, we represent at 4-4-1 network
- Output calculated as sum of outputs (skyrmions in STNO region) after the 7ns detection cycle





Device dimensions

Experiment 3: Simulation

Excitatory

Region 1: Start Zero State ⟶ Potentiation P1 ⟶ Potentiation P2

Region 2: Start Zero State ⟶ Potentiation P1 ⟶ Potentiation P2

Excitatory/Inhibitory

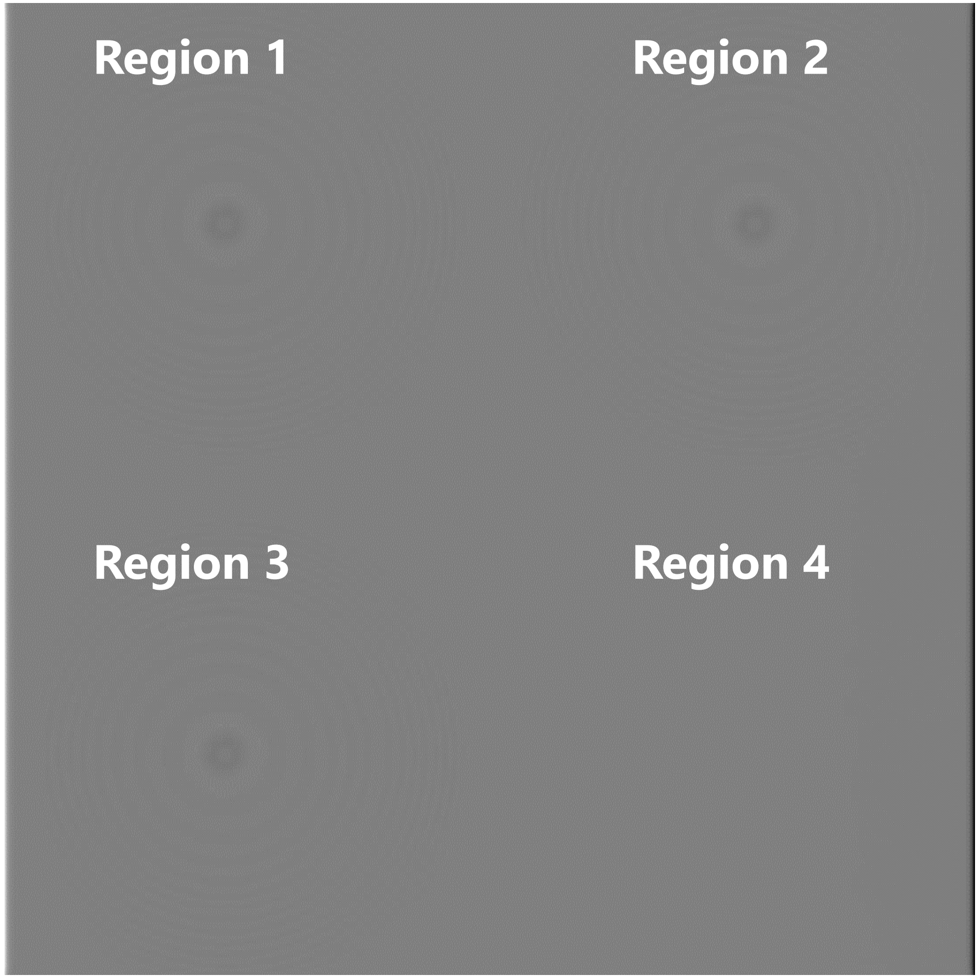
Region 3: Start Zero State ⟶ Potentiation P1 ⟶ Depression A1

Inhibitory

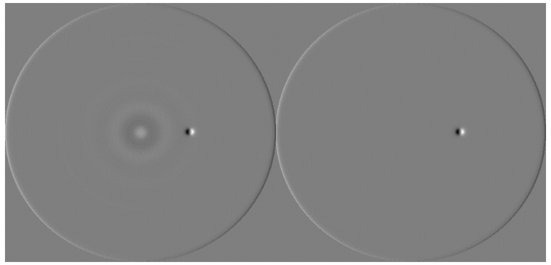
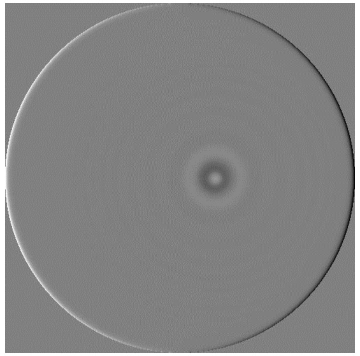
Region 4: Start Zero State ⟶ Depression A1 ⟶ Depression A2

Output

[P2,P2, A1,A2] ⟶ input([P2,P2, A1,A2]) = 0000 to 1111



Summary of Experiments

	What are the different forms of skyrmion arrangement?	**How can one develop a spin wave-mediated spiking neuron?**	**How can one develop a spin-wave mediated spiking neural network?**
Experiments	**Investigating skyrmion arrangement and spin-wave phenomenon**	**Develop spin-wave mediated spiking neuron using ring configuration**	**Develop spin-wave mediated spiking neural network using individual spiking neurons**
Results			

Objective

How can spin-wave mediated skyrmionics overcome the limitations faced by current skyrmionics synaptic devices?

Conclusion

Considerations

Current artificial synaptic devices that use displacement **are limited by device size**

Current artificial synaptic devices that store weights are **limited by the number of the skyrmions**

The resolution of firing is often not analogue, but **dependent on the number of skyrmions**

Objective

How can spin-wave mediated skyrmionics overcome the limitations faced by current skyrmionics synaptic devices?

Proposal

Introducing Spin-wave mediated Skyrmionics for Spiking Neurons

Using the arrangement of skyrmions to mediate the interfering waves offers promise in developing a spin-wave mediated spiking neuron which can overcome limitations of size and dependencies on the number of skyrmions

Results

Investigating skyrmion arrangement and spin-wave phenomenon → Develop spin-wave mediated spiking neuron using ring configuration → Develop spin-wave mediated spiking neural network using individual spiking neurons

Future Works

- Verify results using BRIAN2 neural simulator
  - BRIAN2 unable to simulate below ms threshold
  - BRIAN2 unable to be used for learning (working on updating the library)
- Further explore the complex interference phenomenon of *Double Skyrmion*
- Explore different neural network architectures in hardware
- Optimize the proposed implementation as well as investigate different fundamentally different methods of using spin waves as synaptic neurons

Thank you for your time.
Q&A

Appendix A. BRIAN 2

- BRIAN 2 unable to simulate at nanosecond level
- Timing function TBD in Brian2, but the proof of concept holds
- Training/Learning integration code for BRIAN2 with pytorch not existent