CHIRON workshop on hybrid spin-wave computing, Heraklion, April 27, 2022

# Spin-wave Reservoir Computing in Artificial Spin Systems: Conventional, Deep & Parallel Architectures

**Jack C. Gartside[1,†], Kilian D. Stenning[1,†],** Alex Vanstone[1,†], Holly H. Holder[1], Daan M. Arroo[3,4], Troy Dion[5,2], Francesco Caravelli[6], Hidekazu Kurebayashi[2], Will R. Branford[1,4]

[1] *Blackett Laboratory, Imperial College London, London SW7 2AZ, UK*
[2]*London Centre for Nanotechnology, University College London, London WC1H 0AH, UK*
[3]*Department of Materials, Imperial College London, London SW7 2AZ, UK*
[4]*London Centre for Nanotechnology, Imperial College London, London SW7 2AZ, UK*
[5]*Solid State Physics Lab., Kyushu University, 744 Motooka, Nishi-ku, Fukuoka, 819-0395, Japan*
[6]*Theoretical Division (T4), Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[†]*These authors contributed equally*

Strongly-interacting artificial spin systems are moving beyond mimicking naturally-occurring materials to emerge as versatile functional platforms, from reconfigurable magnonics[1,2] to neuromorphic computing[3]. Typically, artificial spin systems comprise nanomagnets with a single magnetisation texture: collinear macrospins or chiral vortices. By tuning nanoarray dimensions we achieve macrospin/vortex bistability and demonstrate a four-state metamaterial spin-system ‘Artificial Spin-Vortex Ice’ (ASVI). ASVI can host Ising-like macrospins with strong ice-like vertex interactions, and weakly-coupled vortices with low stray dipolar-field. Vortices and macrospins exhibit starkly-differing spin-wave spectra with analogue mode-amplitude control and mode-frequency shifts of $\Delta f = 3.8$ GHz.

The enhanced bi-textural microstate space gives rise to emergent physical memory phenomena & nonlinear spectral response, ideal for computation. We employ spin-wave microstate fingerprinting for rapid, scaleable readout of vortex and macrospin populations and leverage this for spin-wave reservoir computation. ASVI performs non-linear mapping transformations of diverse input and target signals in addition to chaotic time-series forecasting[3].

However, the computing performance of single nanoarrays breaks down when attempting harder tasks. Theoretical work suggests combining multiple reservoirs (nanoarrays) together in parallel and series can enhance performance[4,5]. We implement this physically by fabricating three distinct nanoarrays tuned for differing memory capacity & nonlinearity, and confirm substantially improved computational power when combining arrays in series (deep) and parallel.

---

[1]Gartside, Jack C., et al. "Reconfigurable magnonic mode-hybridisation and spectral control in a bicomponent artificial spin ice." *Nature Communications* 12.1 (2021): 1-9.

[2]Stenning, Kilian D., et al. "Magnonic bending, phase shifting and interferometry in a 2d reconfigurable nanodisk crystal." *ACS nano* (2020).

[3]Gartside, Jack C., Stenning, Kilian D. et al. “Reconfigurable Training, Vortex Writing and Spin-Wave Fingerprinting in an Artificial Spin-Vortex Ice.” *Nature Nanotechnology* (2022)

[4]Gallicchio, Claudio, Alessio Micheli, and Luca Pedrelli. "Deep reservoir computing: A critical experimental analysis." *Neurocomputing* 268 (2017): 87-99.

[5] Manneschi, Luca, et al. "Exploiting multiple timescales in hierarchical echo state networks." *Frontiers in Applied Mathematics and Statistics* 6 (2021): 76.