Quantum excitations, real and simulated

Leon Balents,
KITP

Recent Progress in Quantum Materials 2023

Collaborators

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Outline

- Quantum Ising chain: flat bands and soliton interactions
- Computing excitations on a quantum computer

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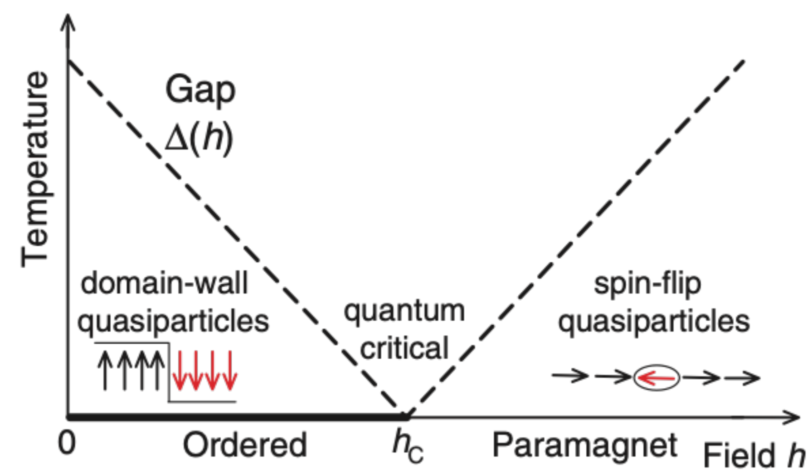
Quantum Ising chain

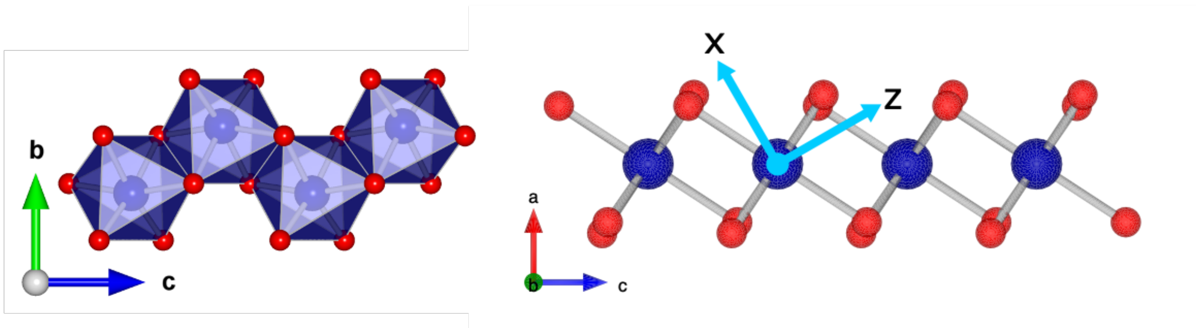
$$H = \sum_i - J_z S_i^z S_{i+1}^z - h_y S_i^y$$

Solitons = the simplest example of non-local excitations

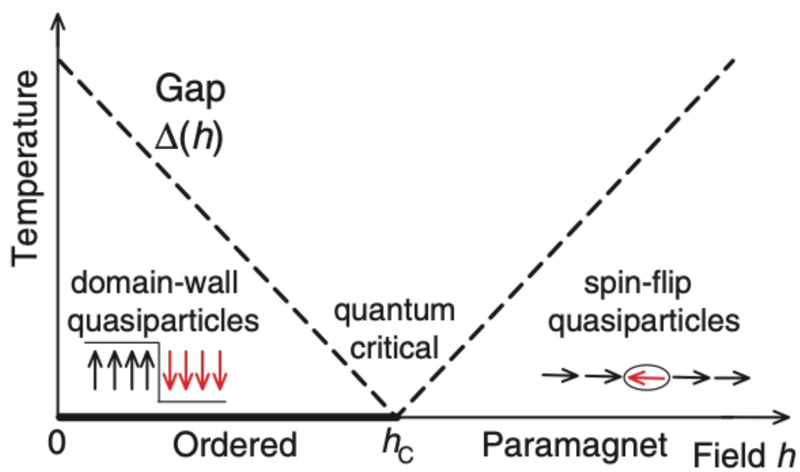


S^z=1 excitations are soliton pairs and form a continuum

$CoNb_2O_6$

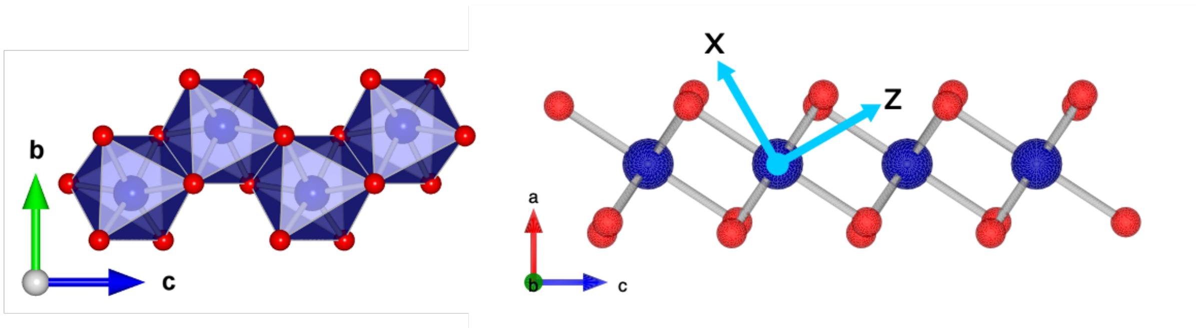


R. Coldea *et al*, Science **327**, 117 (2010)

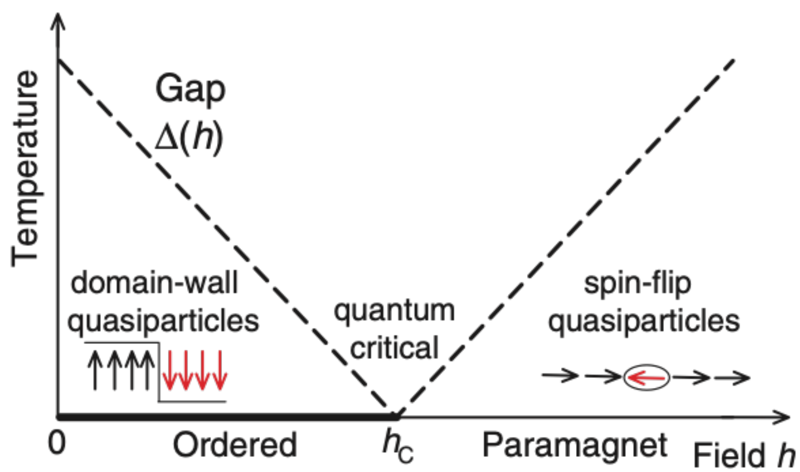


~5.5T

$CoNb_2O_6$



R. Coldea *et al*, Science **327**, 117 (2010)



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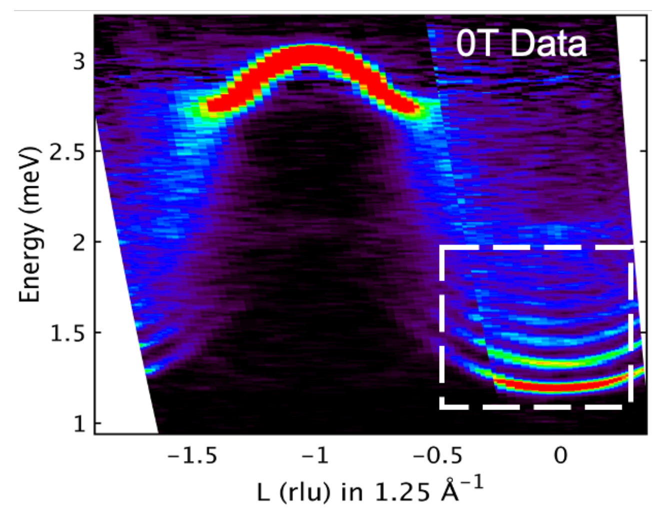
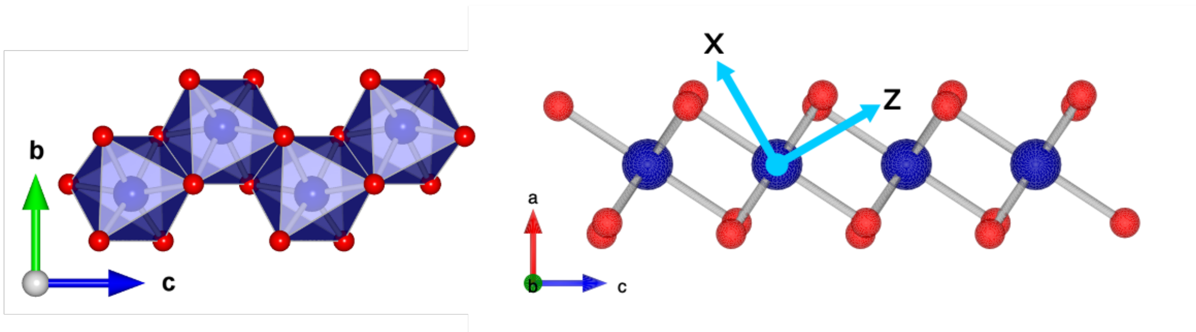
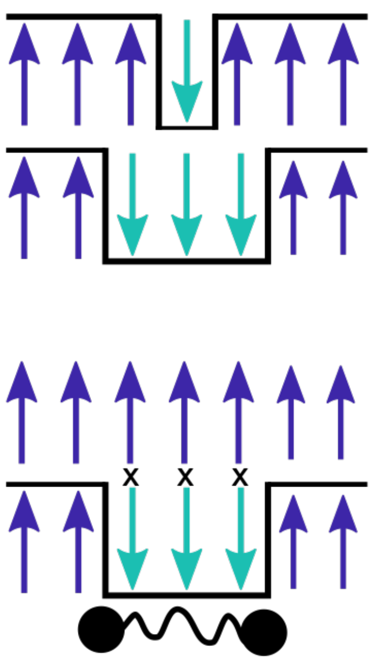


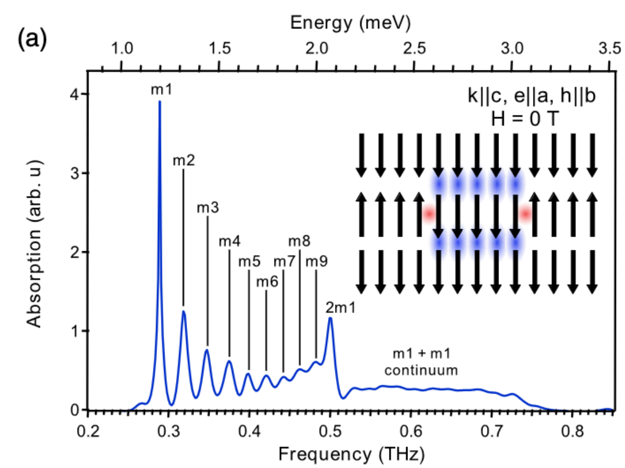
$CoNb_2O_6$



R. Coldea *et al*, Science **327**, 117 (2010)

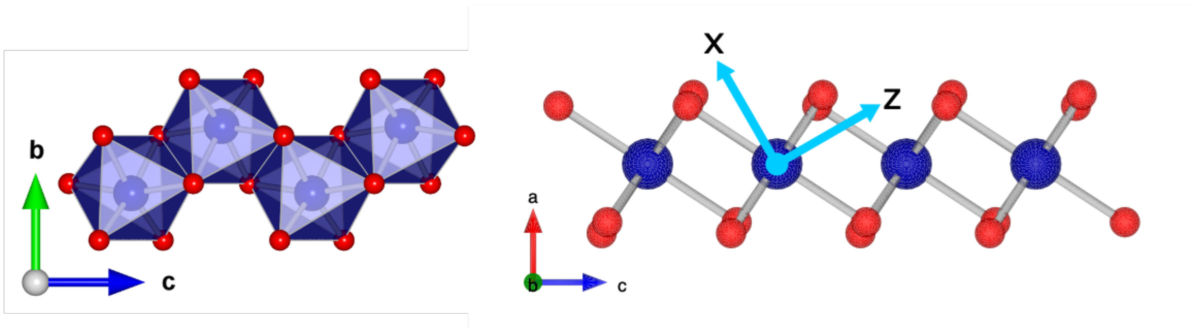


Continuum splits into tower of weakly bound states, due to weak *longitudinal* field from neighboring chains

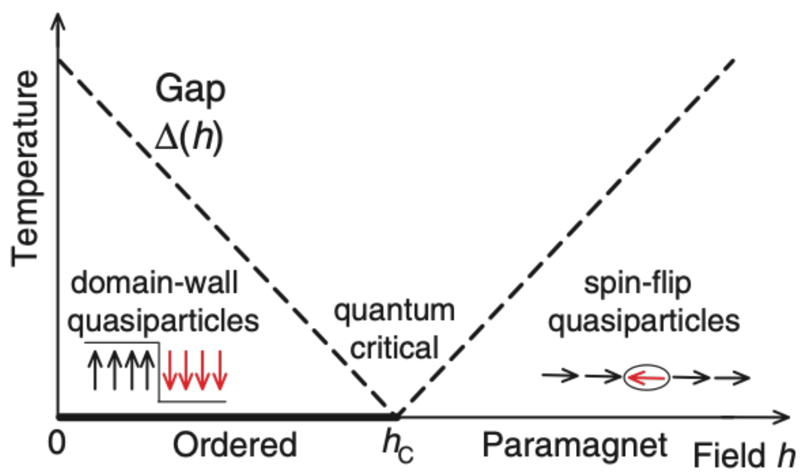


C. Morris *et al*, 2014

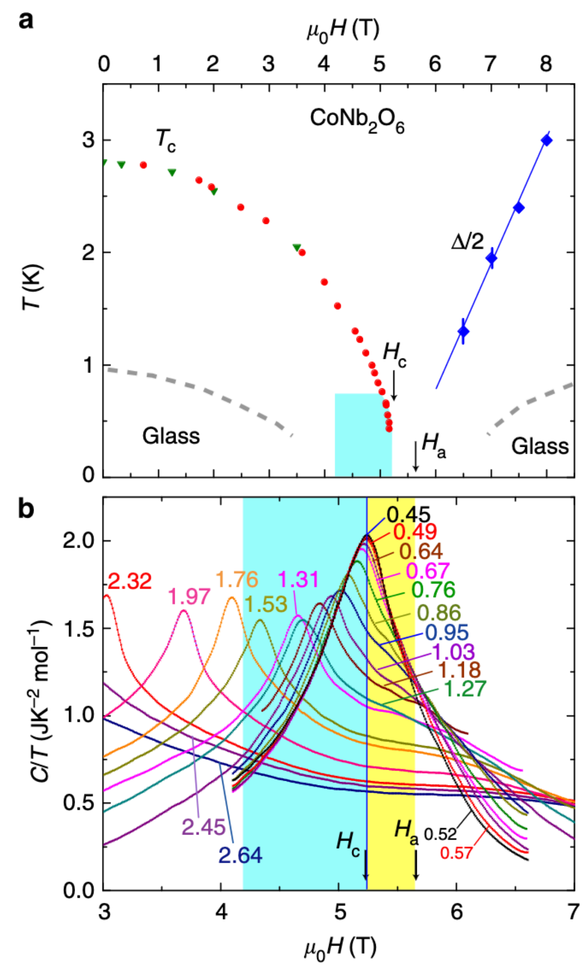
$CoNb_2O_6$



R. Coldea *et al*, Science **327**, 117 (2010)

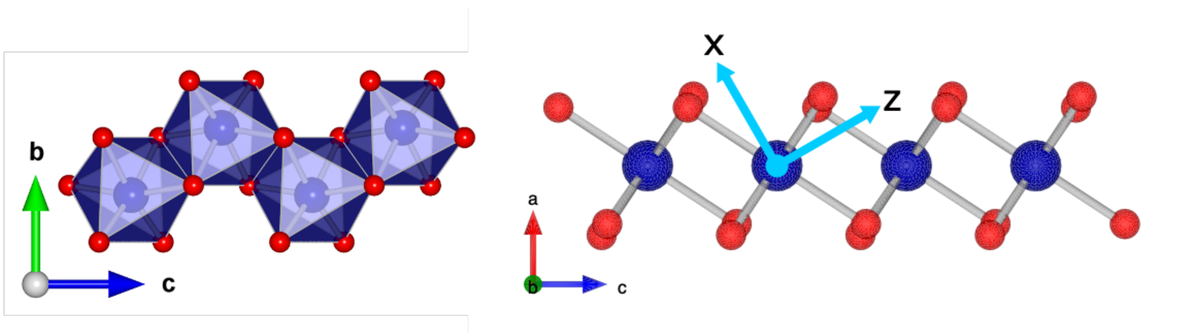


~5.5T

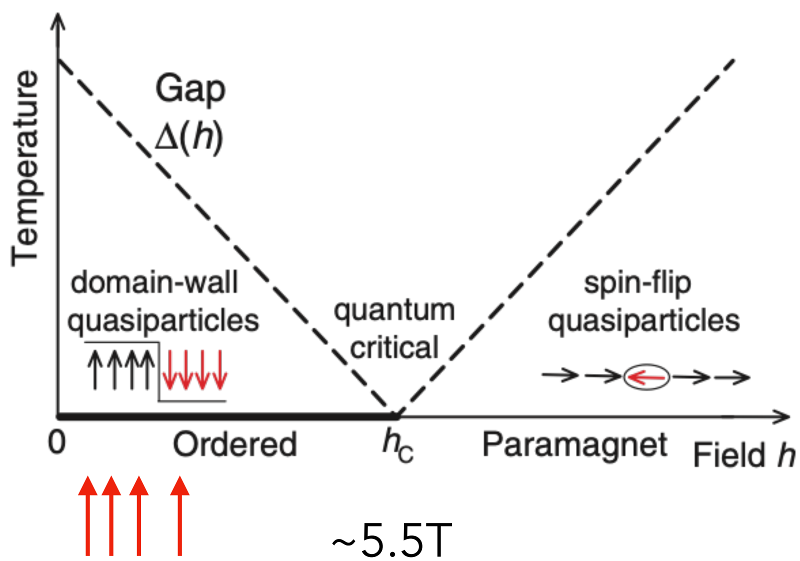


T. Liang *et al*, 2015

$CoNb_2O_6$

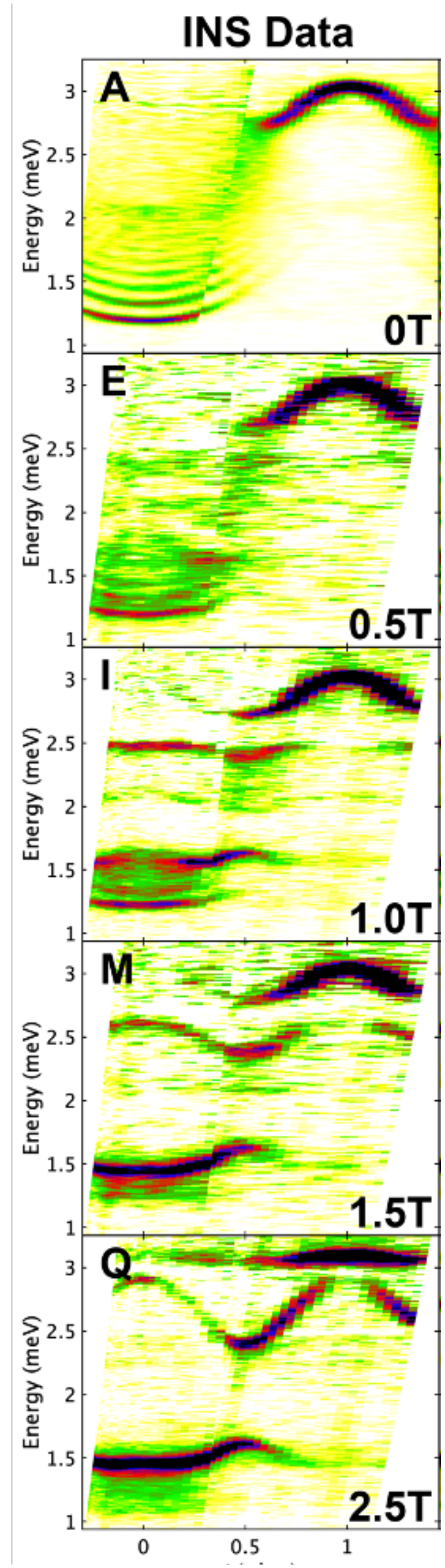


L. Woodland *et al*, arXiv:2306.01948



~5.5T

Surprising complex behavior in between!



A refined model

$$\mathcal{H} = \mathcal{H}_1 + \mathcal{H}_2 + \mathcal{H}_3$$

where

$$\mathcal{H}_1 = J \sum_j \left[-S_j^z S_{j+1}^z - \lambda_S \left(S_j^x S_{j+1}^x + S_j^y S_{j+1}^y \right) + (-1)^j \lambda_{yz} \left(S_j^y S_{j+1}^z + S_j^z S_{j+1}^y \right) \right] + \sum_j h_y S_j^y,$$

$$\mathcal{H}_2 = J \sum_j \left[-\lambda_A \left(S_j^x S_{j+1}^x - S_j^y S_{j+1}^y \right) + \lambda_{\mathrm{AF}} S_j^z S_{j+2}^z + \lambda_{\mathrm{AF}}^{xy} \left(S_j^x S_{j+2}^x + S_j^y S_{j+2}^y \right) \right],$$

XY

Staggered anisotropy

M. Fava *et al*, 2020; L. Woodland *et al*, arXiv 2308.07699

A refined model

$$\mathcal{H} = \mathcal{H}_1 + \mathcal{H}_2 + \mathcal{H}_3$$

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$$\mathcal{H}_1 = J \sum_j \left[-S_j^z S_{j+1}^z - \lambda_S \left(S_j^x S_{j+1}^x + S_j^y S_{j+1}^y \right) + (-1)^j \lambda_{yz} \left(S_j^y S_{j+1}^z + S_j^z S_{j+1}^y \right) \right] + \sum_j h_y S_j^y,$$

$$\mathcal{H}_2 = J \sum_j \left[-\lambda_A \left(S_j^x S_{j+1}^x - S_j^y S_{j+1}^y \right) + \lambda_{\mathrm{AF}} S_j^z S_{j+2}^z + \lambda_{\mathrm{AF}}^{xy} \left(S_j^x S_{j+2}^x + S_j^y S_{j+2}^y \right) \right],$$

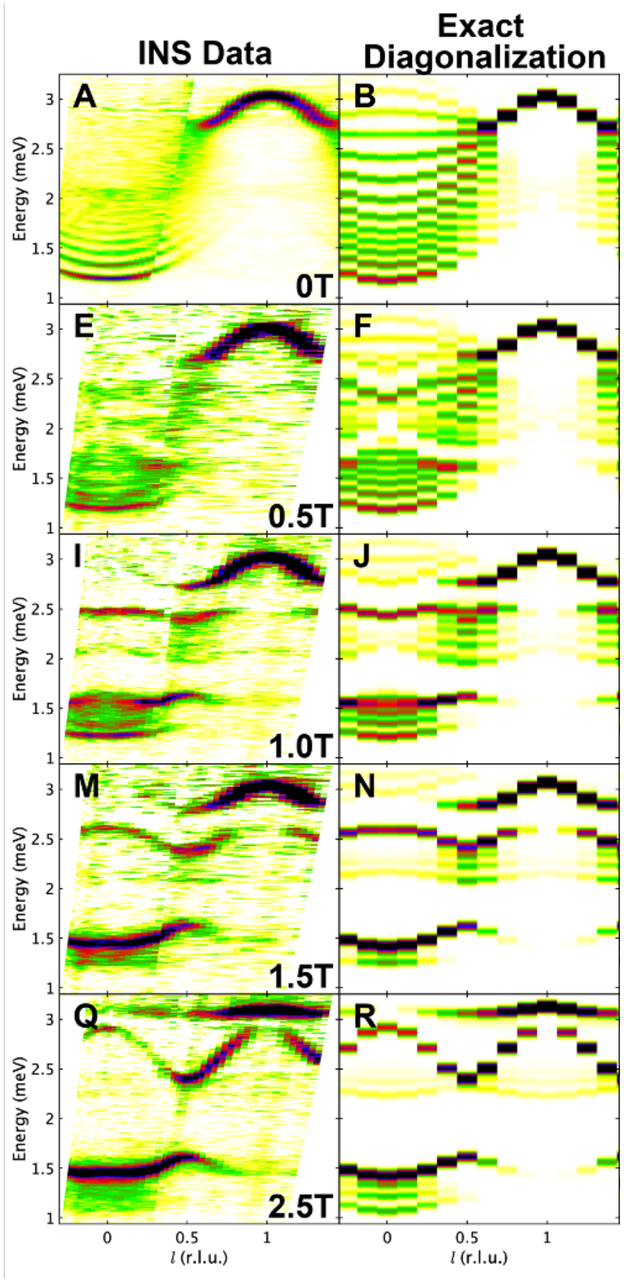
M. Fava *et al*, 2020; L. Woodland *et al*, arXiv 2308.07699

J	2.48(2) meV
λ_S	0.251(6)
λ_{yz}	0.226(3)
g_y	3.32(2)
λ_A	−0.021(1)
λ_{AF}	0.077(3)
λ_{AF}^{xy}	0.031(1)
λ_{MF}	0.0158(2)

(These are fit from different experiments)

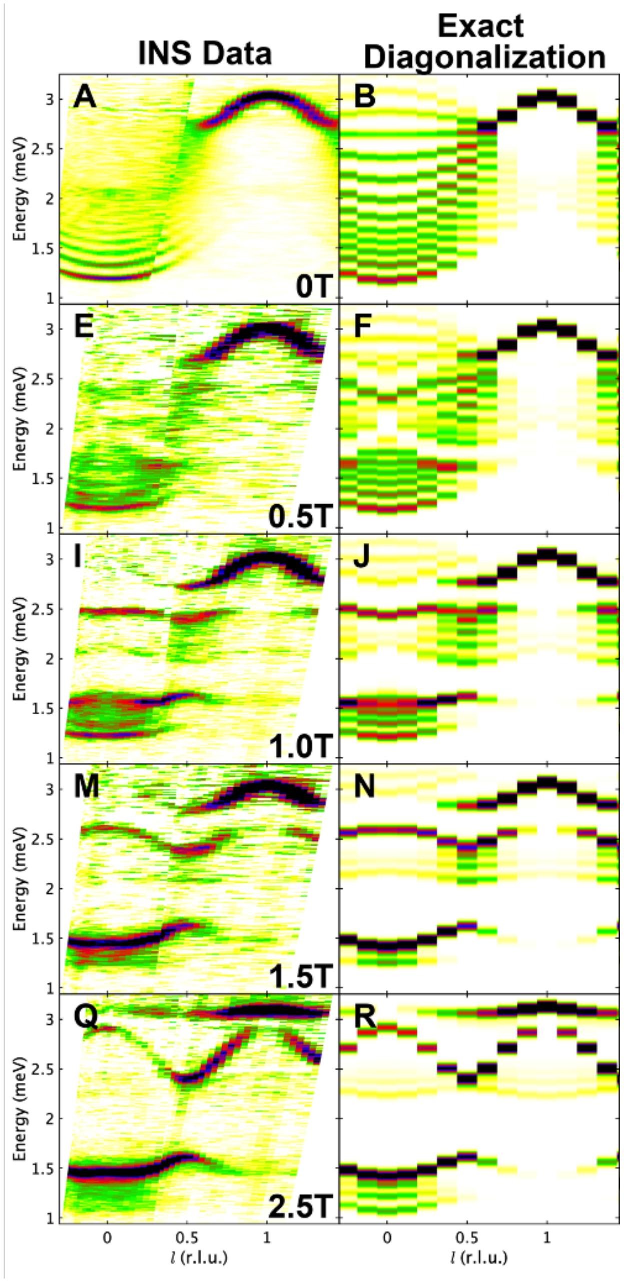
Smallness of perturbations implies we should be able to understand this!

The model works



I think this speaks for itself

The model works

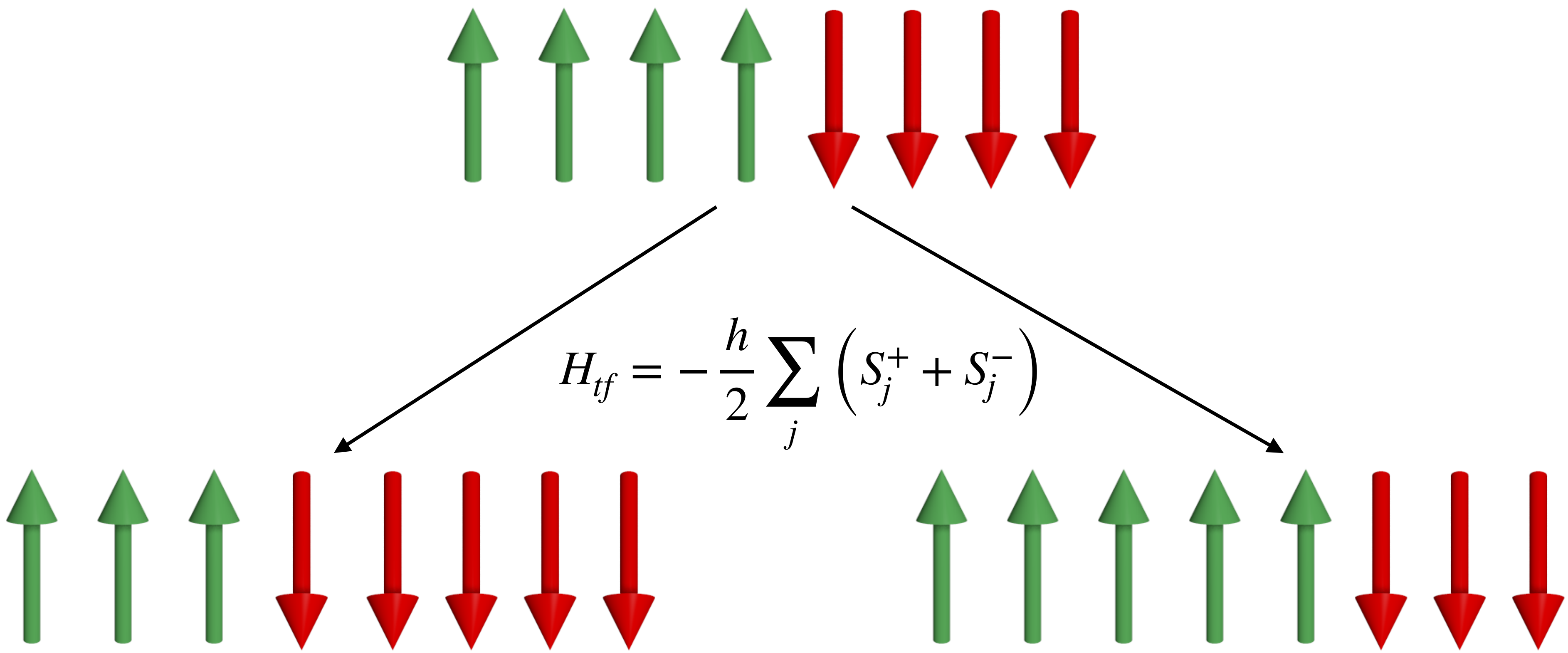


I think this speaks for itself

But let's try to understand it

One soliton

Start with one soliton:

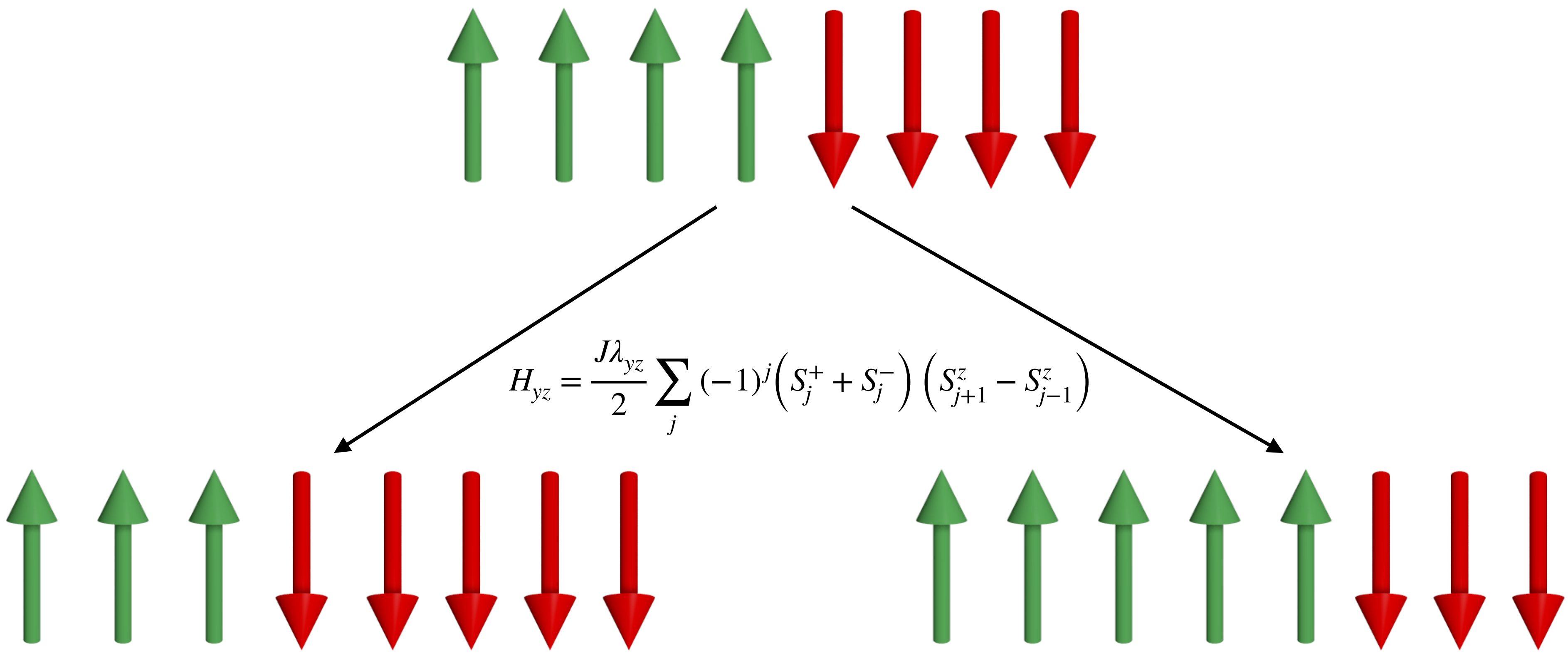


$$H_{tf} = -\frac{h}{2}\sum_j \left(S_j^+ + S_j^-\right)$$

Hopping amplitude h/2

One soliton

Start with one soliton:

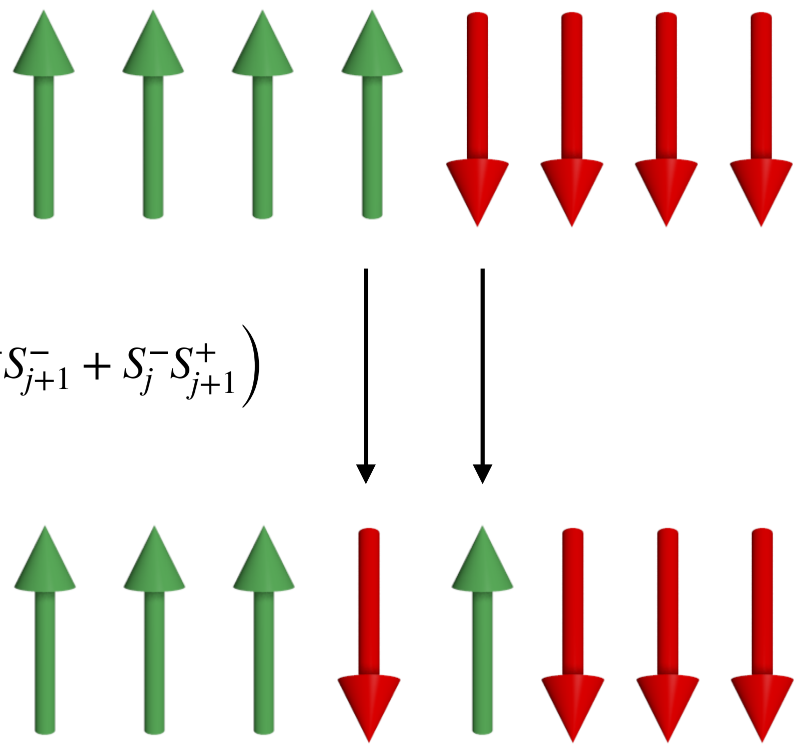


$$H_{yz} = \frac{J\lambda_{yz}}{2} \sum_j (-1)^j \left(S_j^+ + S_j^-\right)\left(S_{j+1}^z - S_{j-1}^z\right)$$

Hopping amplitude $\pm J\lambda_{yz}/2$

One soliton

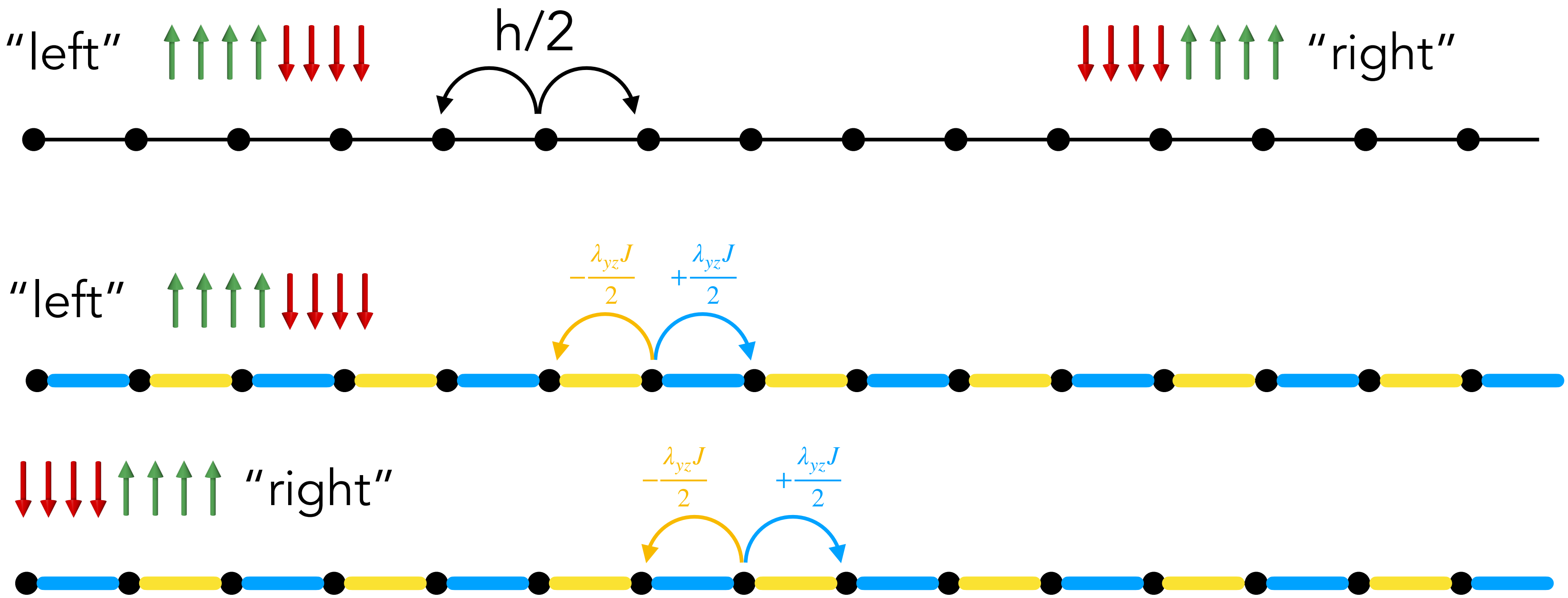
Start with one soliton:



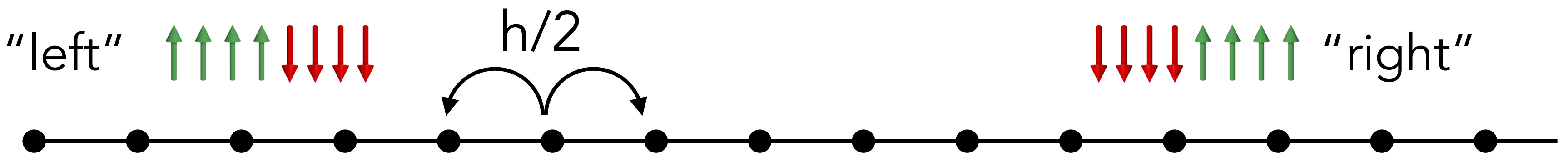
$$H_{xy} = \frac{J\lambda_S}{2}\sum_j \left(S_j^+ S_{j+1}^- + S_j^- S_{j+1}^+ \right)$$

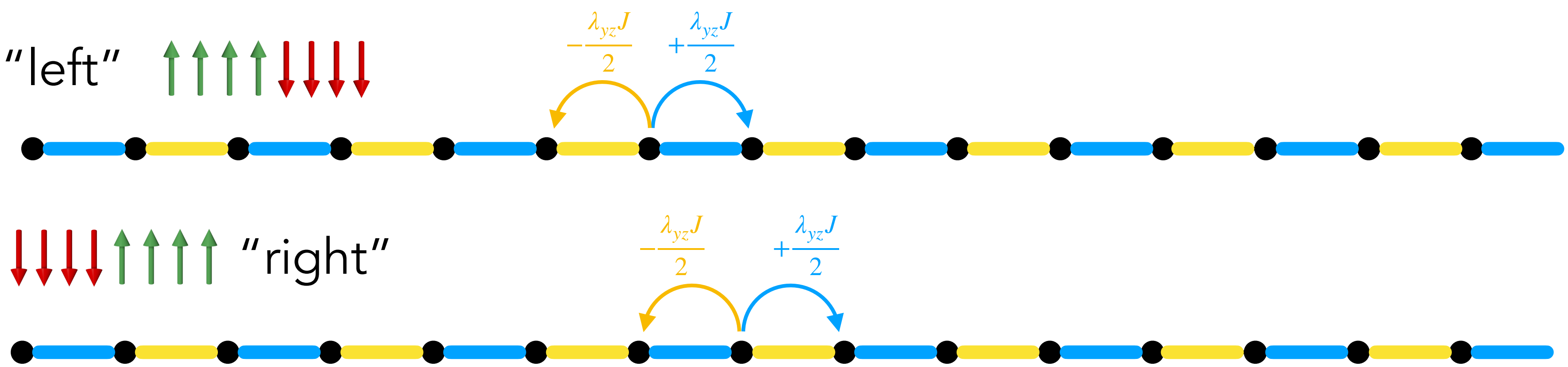
3 soliton state: high energy

Hopping picture

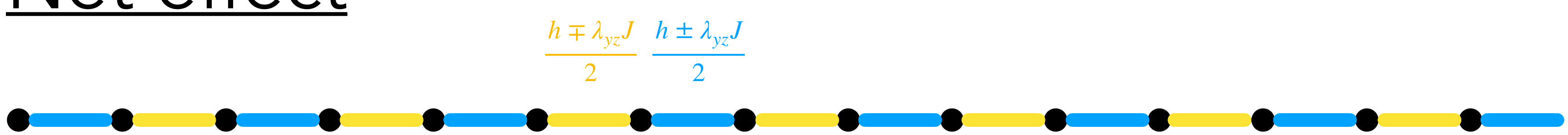


Hopping picture



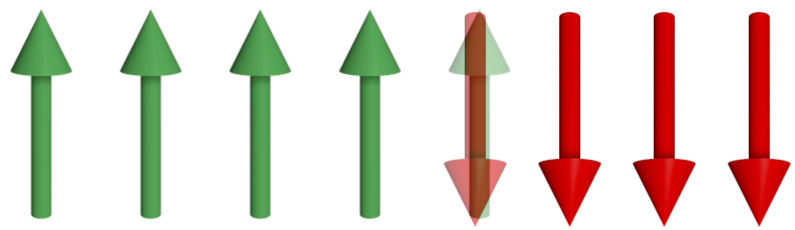


Net effect



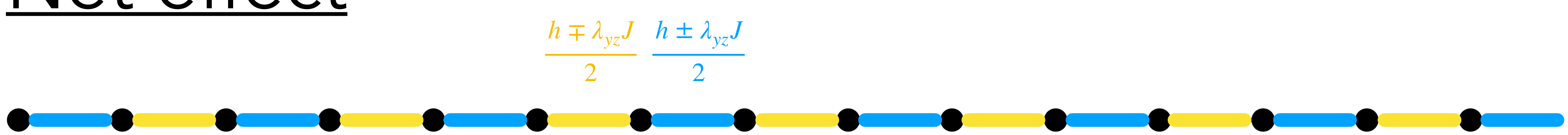
$h = \lambda_{yz}J$: localized solitons!

Hopping picture



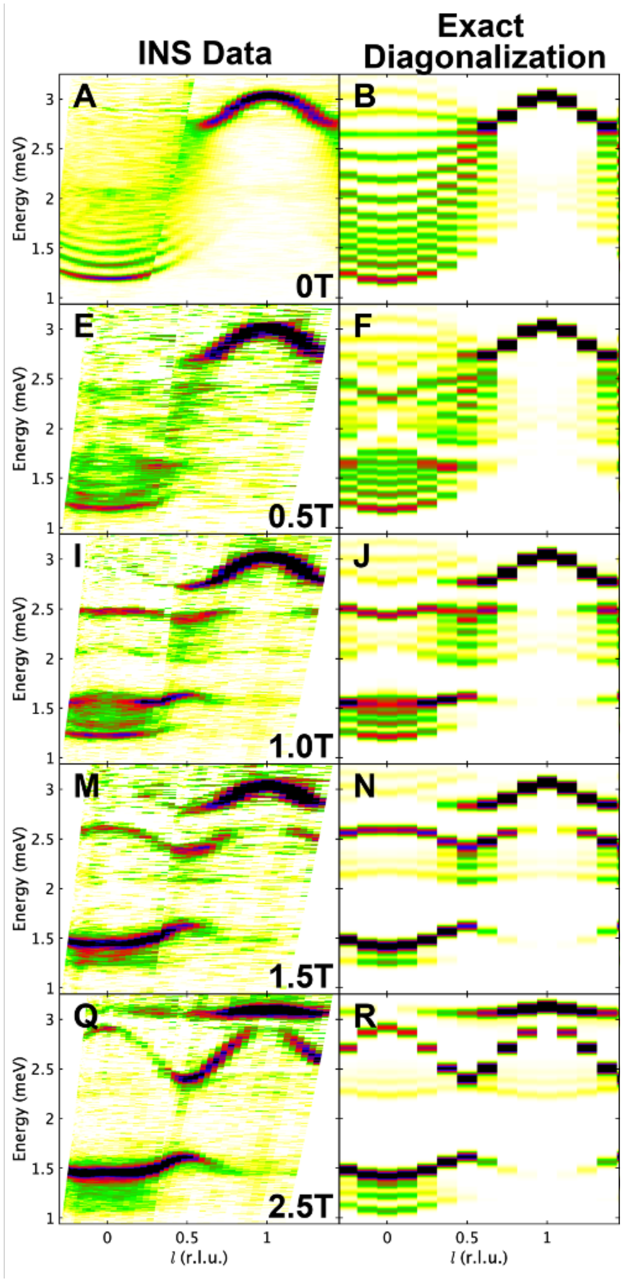
Another view of a localized soliton

Net effect



$h = \lambda_{yz} J$: localized solitons!

Back to experiment



This is around the flat band condition

$$h = \lambda_{yz} J$$

Two solitons

We expect that flat band solitons interact strongly when nearby.

$$|j_L, j_R\rangle = |\cdots \uparrow\uparrow_{j_L-1}\downarrow_{j_L} \cdots \downarrow_{j_R-1}\uparrow_{j_R}\uparrow \cdots\rangle$$

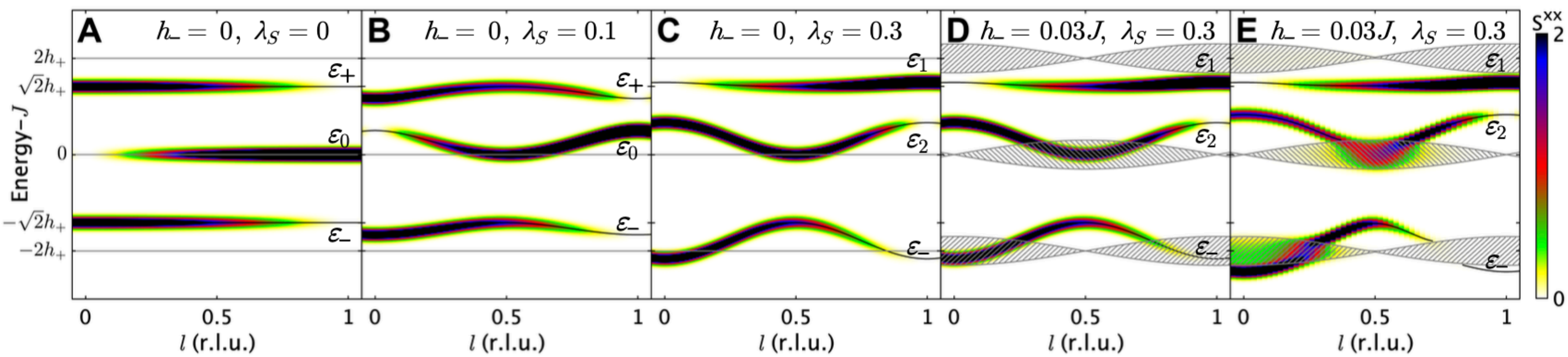
$$|\Psi\rangle = \sum_{j_L<j_R} \Psi(j_L, j_R)|j_L, j_R\rangle.$$

Obeys a 2-particle Schrödinger equation

Two solitons

3 bound state modes

2 symmetric
1 antisymmetric



Exactly flat

Small XY coupling

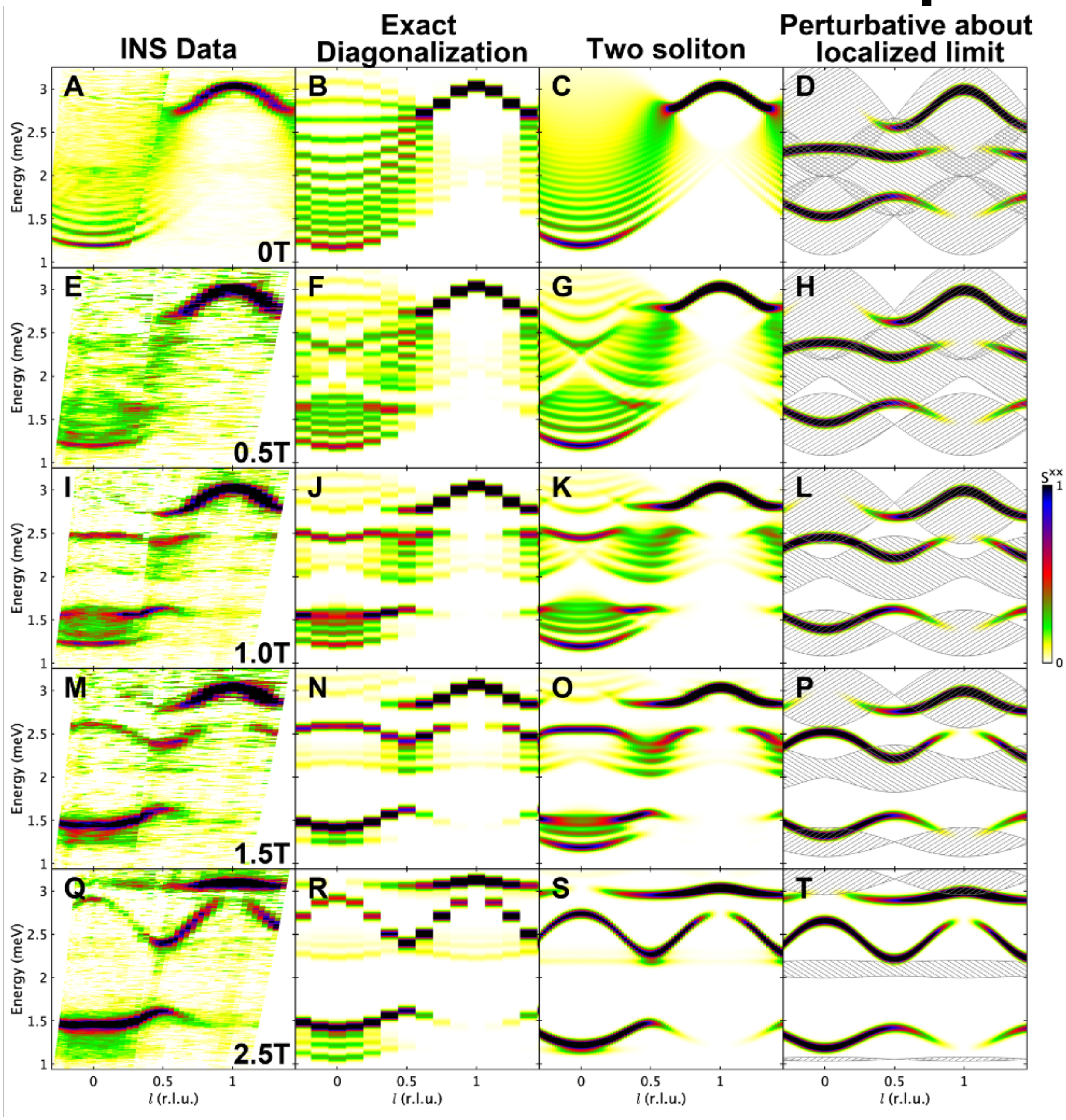
Experimental XY coupling

Tuning away (approx)

Tuning away (full)

Band inversion

Full comparison



- 2 soliton states highly accurate
- Localized soliton approximation quantitative near 2.5T as expected
- Visible features of band inversion

Outline

- Quantum Ising chain: flat bands and soliton interactions
- Computing excitations on a quantum computer

Quantum science

- $$:
  - Microsoft Quantum: probably > $300M per year.
  - Many others!

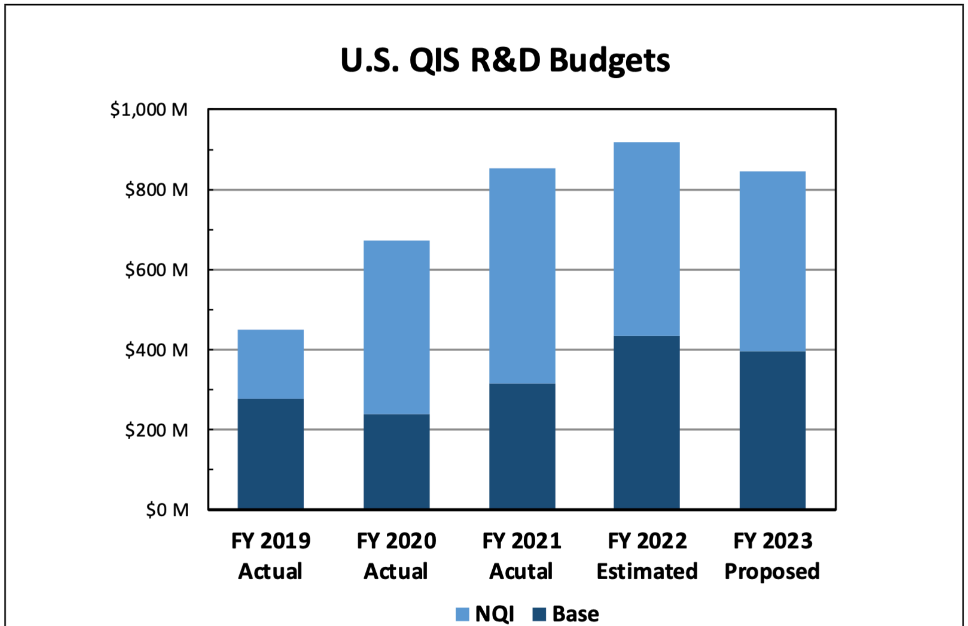


Figure 2.1: U.S. R&D budgets for QIS since the inception of the NQI Act. The bar heights represent the total budget for each fiscal year (FY 2019 – FY 2021 actual expenditures, FY 2022 estimated expenditures, and FY 2023 requested budgets). The portion of each bar marked "NQI" identifies funding allocated for NQI Act-authorized activities; this additional funding is on top of the budgets for baseline QIS R&D activities.

Quantum science

- People:
    - Compare arXiv “new” listings:
        - 172 CM vs 131 Quantum
- Experimentalists going to private sector
- Theorists mass movement to QI:
    - Let’s look at UCSB faculty

1. arXiv:2306.00058 [pdf, other] quant-ph cond-mat.stat-mech
   Universality of the cross entropy in $\mathbb{Z}_2$ symmetric monitored quantum circuits
   Authors: Maria Tikhanovskaya, Ali Lavasani, Matthew P. A. Fisher, Sagar Vijay
   Submitted 14 August, 2023; **v1** submitted 31 May, 2023; **originally announced** June 2023.
   Comments: 12+6 pages, 16 figures. V2: References added
2. arXiv:2304.13198 [pdf, other] quant-ph cond-mat.stat-mech
   Continuous symmetry breaking in adaptive quantum dynamics
   Authors: Jacob Hauser, Yaodong Li, Sagar Vijay, Matthew P. A. Fisher
   Submitted 25 April, 2023; **originally announced** April 2023.
   Comments: 17 pages, 10 figures
3. arXiv:2303.01533 [pdf, other] quant-ph cond-mat.stat-mech
   Measurement-induced Floquet enriched topological order
   Authors: DinhDuy Vu, Ali Lavasani, Jong Yeon Lee, Matthew P. A. Fisher
   Submitted 2 March, 2023; **originally announced** March 2023.
   Comments: 6+7 pages, 12 figures
4. arXiv:2210.11547 [pdf, other] quant-ph cond-mat.dis-nn cond-mat.stat-mech
   Coherence requirements for quantum communication from hybrid circuit dynamics
   Authors: Shane P. Kelly, Ulrich Poschinger, Ferdinand Schmidt-Kaler, Matthew P. A. Fisher, Jamir Marino
   Submitted 23 May, 2023; **v1** submitted 20 October, 2022; **originally announced** October 2022.
   Comments: 19 pages, 12 figures
5. arXiv:2209.00609 [pdf, other] quant-ph cond-mat.stat-mech doi 10.1103/PhysRevLett.130.220404
   Cross Entropy Benchmark for Measurement-Induced Phase Transitions
   Authors: Yaodong Li, Yijian Zou, Paolo Glorioso, Ehud Altman, Matthew P. A. Fisher
   Submitted 7 June, 2023; **v1** submitted 1 September, 2022; **originally announced** September 2022.
   Comments: 7+8 pages, 6 figures. v2: 7+9 pages, 3+3 figures. Updated discussions on sample size (Fig. 2d, 2e), and new results from ra

1. arXiv:2306.00058 [pdf, other] quant-ph cond-mat.stat-mech
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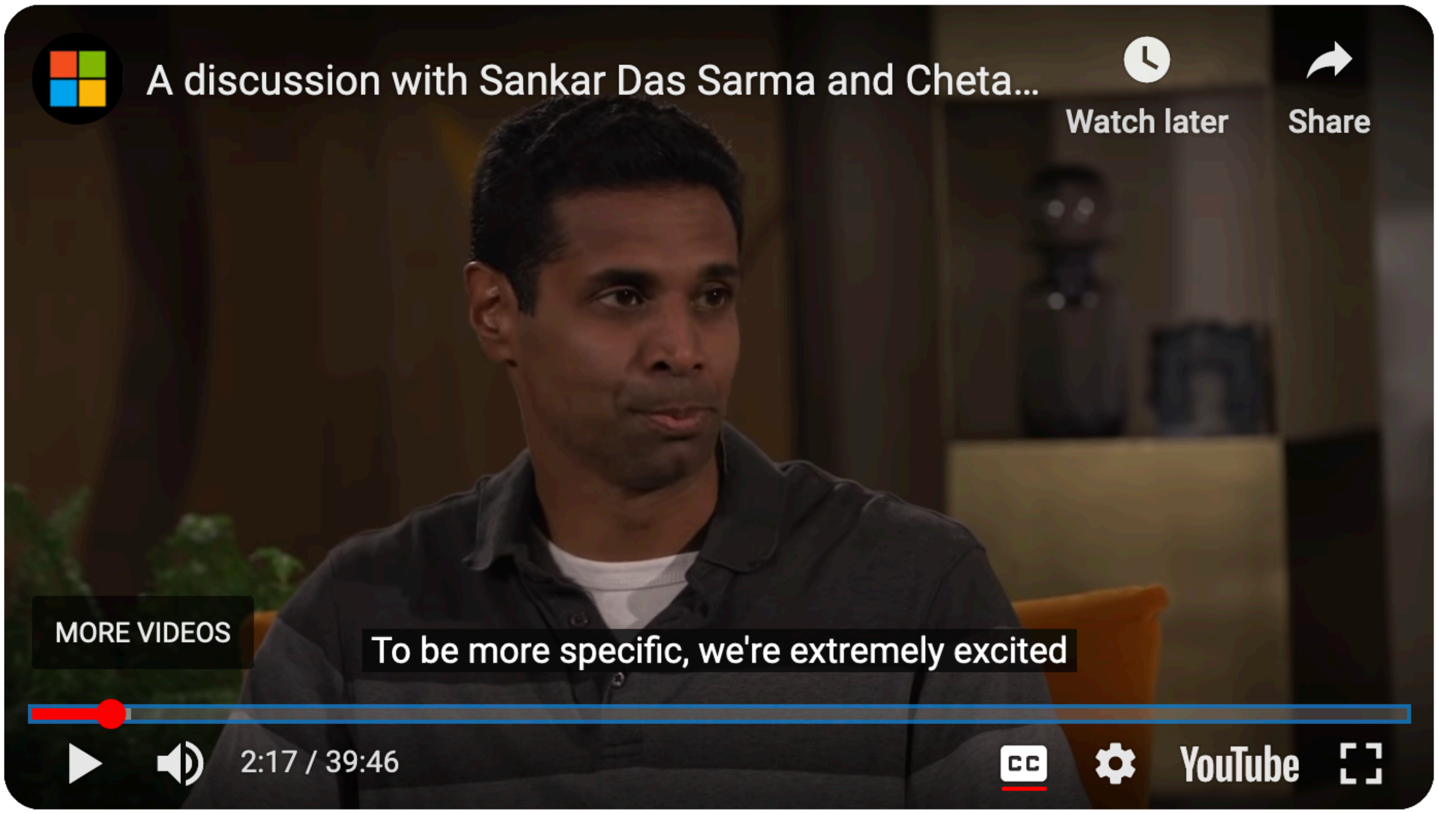
   Comments: 12+6 pages, 16 figures. V2: References added
2. arXiv:2304.13198 [pdf, other] quant-ph cond-mat.stat-mech
   Continuous symmetry breaking in adaptive quantum dynamics
   Authors: Jacob Hauser, Yaodong Li, Sagar Vijay, Matthew P. A. Fisher
   Submitted 25 April, 2023; **originally announced** April 2023.
   Comments: 17 pages, 10 figures
3. arXiv:2304.02664 [pdf, other] quant-ph cond-mat.dis-nn cond-mat.stat-mech
   Quantum Coding Transitions in the Presence of Boundary Dissipation
   Authors: Izabella Lovas, Utkarsh Agrawal, Sagar Vijay
   Submitted 5 April, 2023; **originally announced** April 2023.
   Comments: 21 pages, 14 figures
4. arXiv:2303.15507 [pdf, other] cond-mat.str-el cond-mat.stat-mech quant-ph doi 10.1103/PRXQuantum
   Mixed-state long-range order and criticality from measurement and feedback
   Authors: Tsung-Cheng Lu, Zhehao Zhang, Sagar Vijay, Timothy H. Hsieh
   Submitted 13 September, 2023; **v1** submitted 27 March, 2023; **originally announced** March 2023.
   Comments: 25 pages, 11 figures; updated to the published version
   Journal ref: PRX Quantum 4, 030318 (2023)
5. arXiv:2211.05784 [pdf, other] quant-ph cond-mat.str-el
   The X-Cube Floquet Code
   Authors: Zhehao Zhang, David Aasen, Sagar Vijay
   Submitted 10 November, 2022; **originally announced** November 2022.
   Comments: Main Text (6 pages, 5 figures), Appendices (4 pages, 5 figures)

1. arXiv:2305.13240 [pdf, other] cond-mat.str-el cond-mat.stat-mech quant-ph
   Entanglement Spectrum as a diagnostic of chirality of Topological Spin Liquids: Analysis of an $\mathbf{SU(3)}$ PEPS
   Authors: Mark J. Arildsen, Ji-Yao Chen, Norbert Schuch, Andreas W. W. Ludwig
   Submitted 22 May, 2023; **originally announced** May 2023.
   Comments: 49 pages, 14 figures, 8 tables
2. arXiv:2302.09094 [pdf, other] cond-mat.stat-mech cond-mat.dis-nn cond-mat.str-el quant-ph
   Measurement-induced entanglement transitions in quantum circuits of non-interacting fermions: Born-rule versus forced measurements
   Authors: Chao-Ming Jian, Hassan Shapourian, Bela Bauer, Andreas W. W. Ludwig
   Submitted 17 February, 2023; **originally announced** February 2023.
   Comments: 16+5 pages, 6 figures
3. arXiv:2207.03246 [pdf, other] cond-mat.str-el cond-mat.stat-mech quant-ph
   Entanglement spectra of non-chiral topological (2+1)-dimensional phases with strong time-reversal breaking, Li-Haldane state counting, and PEPS
   Authors: Mark J. Arildsen, Norbert Schuch, Andreas W. W. Ludwig
   Submitted 7 July, 2022; **originally announced** July 2022.
   Comments: 45 pages, 9 figures, 5 tables
4. arXiv:2110.02988 [pdf, other] cond-mat.stat-mech cond-mat.dis-nn cond-mat.str-el quant-ph
   Statistical Mechanics Model for Clifford Random Tensor Networks and Monitored Quantum Circuits
   Authors: Yaodong Li, Romain Vasseur, Matthew P. A. Fisher, Andreas W. W. Ludwig
   Submitted 6 October, 2021; **originally announced** October 2021.
   Comments: 23 pages, 5 figures. Abstract shortened to meet arxiv requirements, see pdf for full abstract
5. arXiv:2107.03393 [pdf, other] cond-mat.dis-nn cond-mat.stat-mech cond-mat.str-el quant-ph doi 10.1103/PhysRevLett.128.050602
   Operator scaling dimensions and multifractality at measurement-induced transitions
   Authors: Aidan Zabalo, Michael J. Gullans, Justin H. Wilson, Romain Vasseur, Andreas W. W. Ludwig, Sarang Gopalakrishnan, David A. Huse, J. H. Pixley
   Submitted 11 February, 2022; **v1** submitted 7 July, 2021; **originally announced** July 2021.
   Comments: (6 + 12) pages, (2 + 12) figures, (1 + 2) tables (Updated with published version)
   Journal ref: Phys. Rev. Lett. 128, 050602 (2022)

Not QI

1. arXiv:2309.03946 [pdf, other] cond-mat.str-el hep-th
   Nonlinear Lifshitz Photon Theory in Condensed Matter Systems
   Authors: Yi-Hsien Du, Cenke Xu, Dam Thanh Son
   Submitted 7 September, 2023; **originally announced** September 2023.
2. arXiv:2308.07380 [pdf, other] cond-mat.str-el
   Disorder Operator and Rényi Entanglement Entropy of Symmetric Mass Generation
   Authors: Zi Hong Liu, Yuan Da Liao, Gaopei Pan, Menghan Song, Jiarui Zhao, Weilun Jiang, Chao-Ming Jian, Yi-Zhuang Yo Cenke Xu
   Submitted 8 September, 2023; **v1** submitted 14 August, 2023; **originally announced** August 2023.
   Comments: 16 pages, 12 figures
3. arXiv:2306.10105 [pdf, other] cond-mat.str-el hep-th
   A no-go result for implementing chiral symmetries by locality-preserving unitaries in a 3 dim model of fermions
   Authors: Lukasz Fidkowski, Cenke Xu
   Submitted 13 July, 2023; **v1** submitted 16 June, 2023; **originally announced** June 2023.
   Comments: 3 figures, v3 typo fixed
4. arXiv:2305.13410 [pdf, other] cond-mat.str-el hep-th quant-ph
   Conformal Field Theories generated by Chern Insulators under Quantum Decoherence
   Authors: Kaixiang Su, Nayan Myerson-Jain, Cenke Xu
   Submitted 22 May, 2023; **originally announced** May 2023.
   Comments: 8.5 pages, including references
5. arXiv:2304.14433 [pdf, other] cond-mat.str-el hep-th quant-ph
   Higher-form Symmetries under Weak Measurement
   Authors: Kaixiang Su, Nayan Myerson-Jain, Chong Wang, Chao-Ming Jian, Cenke Xu
   Submitted 27 April, 2023; **originally announced** April 2023.
   Comments: 9 pages, 1 figure
6. arXiv:2301.05238 [pdf, other] cond-mat.stat-mech cond-mat.str-el quant-ph doi 10.1103/PRXQuantum.4.0303
   Quantum criticality under decoherence or weak measurement
   Authors: Jong Yeon Lee, Chao-Ming Jian, Cenke Xu
   Submitted 26 July, 2023; **v1** submitted 12 January, 2023; **originally announced** January 2023.
   Comments: 18 pages, 5 figures (Accepted to PRX Quantum)

What is it good for?



What is it good for?

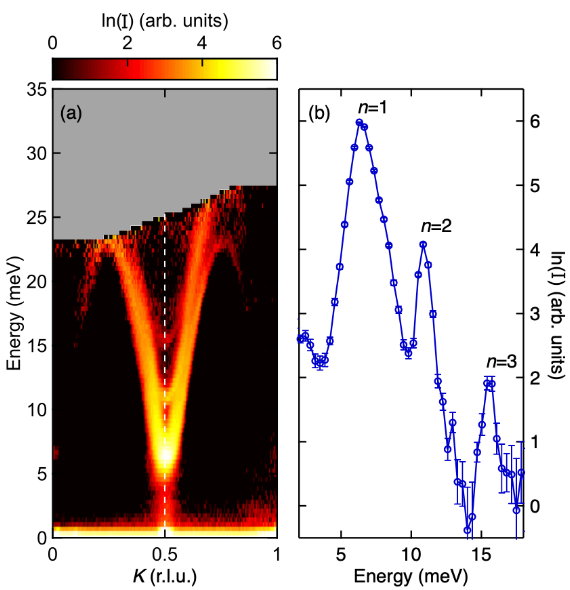
What is it good for?

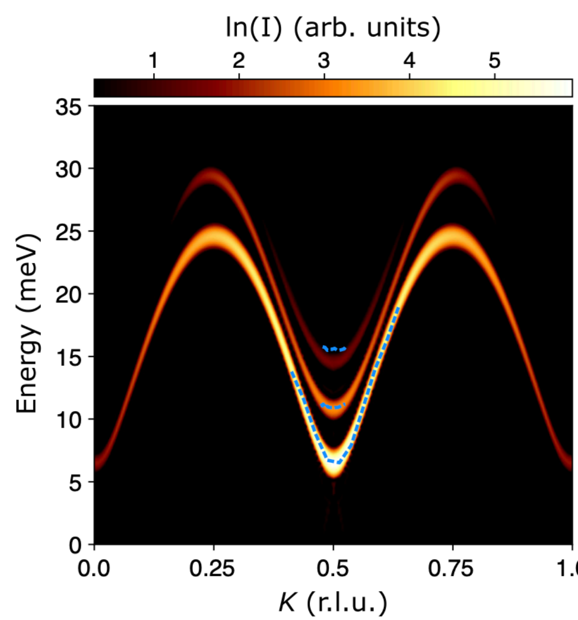
What is it good for?

Application to quantum materials?

- Try to *apply* quantum algorithms to actual quantum problems

- For example: how would we obtain S(k,ω) on a quantum computer?





R. Dally *et al*, PRL (2020).

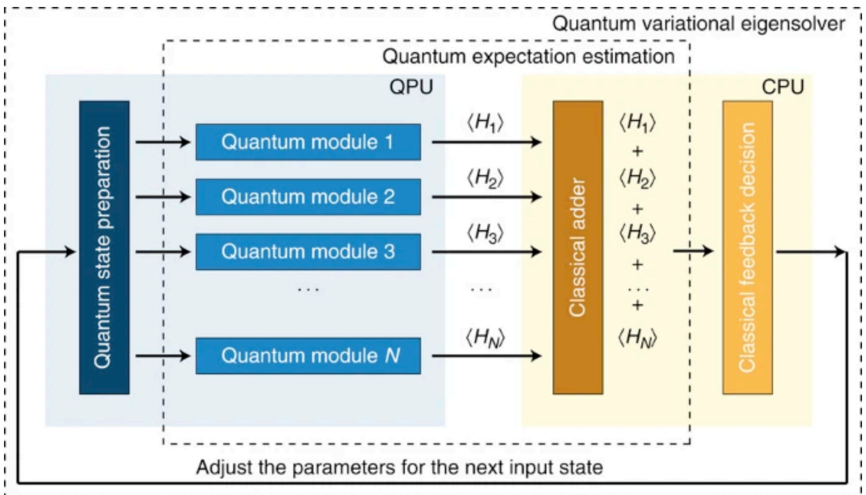
Possible approaches

- Direct time evolution? Q: Isn't that what a quantum computer is good at?
  - A: Maybe a special purpose simulator, but a digital quantum computer like google machines can't. They apply controlled 1 and 2 qubit gates
  - You can Trotterize but this introduces substantial errors that can only be improved by scaling to many gates.
- Instead we will try to use a variational approach to obtain eigenstates.

VQE

- Variational quantum eigensolver:

Peruzzo *et al*, 2014



quantum circuit

$$|\Psi(\{\theta_i\})\rangle = U(\{\theta_i\})|\Psi_0\rangle$$

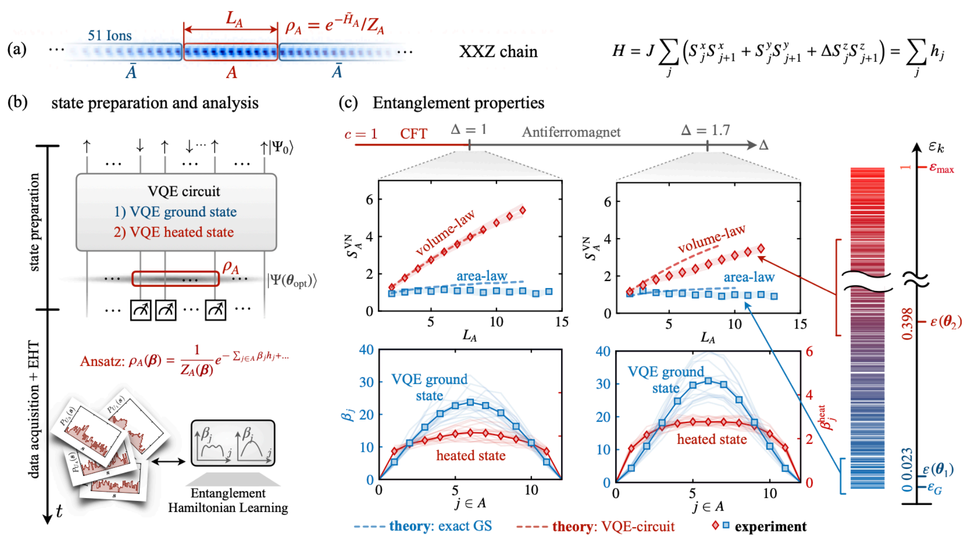
$$E_{\mathrm{var}} = \langle\Psi|H|\Psi\rangle \geq E_0$$

measure

Ground state

Exploring Large-Scale Entanglement in Quantum Simulation

Manoj K. Joshi,[1,2,*] Christian Kokail,[1,3,*] Rick van Bijnen,[1,3,*] Florian Kranzl,[1,2]
Torsten V. Zache,[1,3] Rainer Blatt,[1,2] Christian F. Roos,[1,2] and Peter Zoller[1,3]



PHYSICAL REVIEW B **105**, 094409 (2022)

Probing ground-state properties of the kagome antiferromagnetic Heisenberg model using the variational quantum eigensolver

Jan Lukas Bosse[1,2,*] and Ashley Montanaro[2,1,†]
[1]*School of Mathematics, University of Bristol, Bristol, BS8 1QU, United Kingdom*
[2]*Phasecraft Ltd, Bristol, BS1 5DD, United Kingdom*

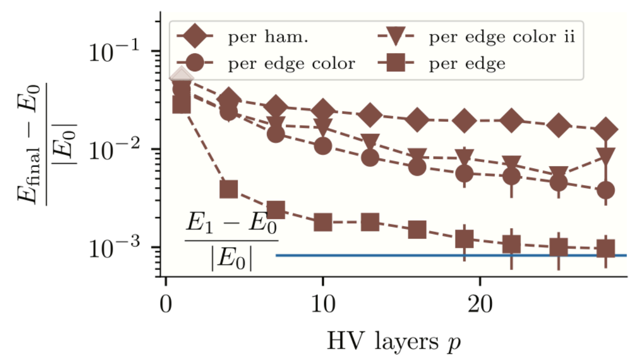


FIG. 12. Scaling of the relative energy error as a function of p for the 3×8 lattice with different ansatz circuits. Results are shown for three runs per data point and with the initial parameters chosen uniformly random within $[0, \frac{1}{p}]$. The error bars reflect the standard deviation between the different runs.

PHYSICAL REVIEW B **106**, 214429 (2022)

Variational quantum eigensolver for the Heisenberg antiferromagnet on the kagome lattice

Joris Kattemölle[1,2,3] and Jasper van Wezel[1,2]

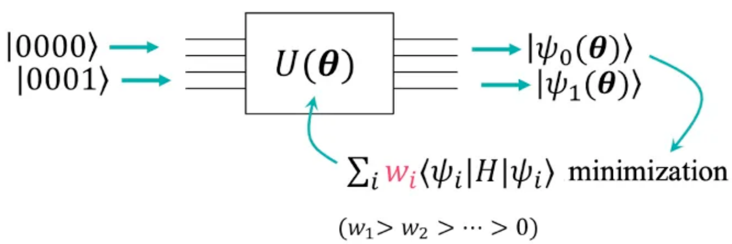
SS VQE

- Subspace Search VQE: for excited states

K. Nakanishi *et al*, 2019

$$|\Psi_n(\{\theta_i\})\rangle = U(\{\theta_i\})|\Psi_{n,0}\rangle$$

Choose N orthogonal initial states



$$\langle\Psi_{n'}|\Psi_n\rangle = \langle\Psi_{n',0}|\Psi_{n,0}\rangle$$

$$E_{\text{var}} = \sum_n w_n\langle\Psi_n|H|\Psi_n\rangle$$

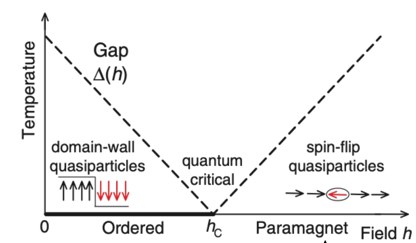
$w_n > 0$

Just repeat the VQE *with the same circuit* on N initial orthogonal states and minimize (weighted) energy sum.

Elementary excitations

- Transverse field Ising chain

$$H_T = -J\sum_{i=1}^{L} Z_i Z_{i+1} - h\sum_{i=1}^{L} X_i$$



- Excitations at J<<h:

$$|-_i\rangle = |++\cdots -_i + \cdots +\rangle$$

$$|k\rangle = \frac{1}{\sqrt{N}}\sum_i e^{ikx_i}|-_i\rangle$$

Momentum eigenstates

Exact energy $\epsilon_k = 2\sqrt{h^2 + J^2 - 2hJ\cos k}$

? Can we get this from (SS) VQE?

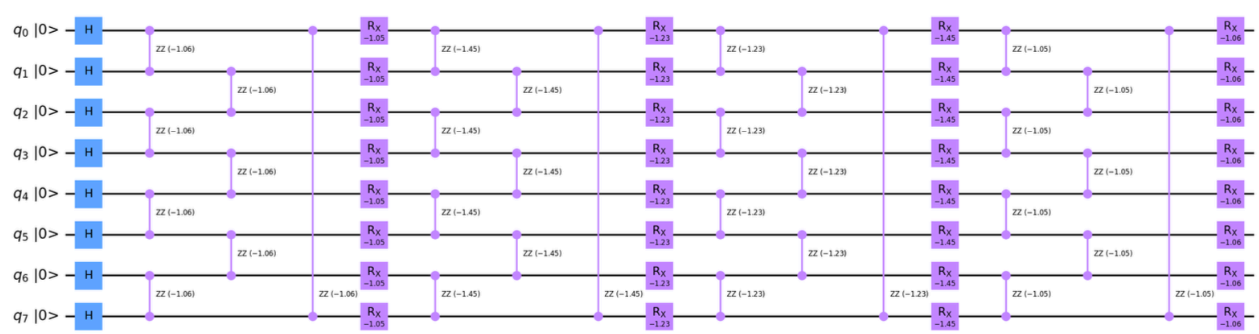
VQE for Ising chain

- Natural circuit: preserve translational symmetry

$$H_T = -J \underbrace{\sum_{i=1}^{L} Z_i Z_{i+1}}_{H_1} - h \underbrace{\sum_{i=1}^{L} X_i}_{H_2}$$

$$|\psi_P(\gamma, \beta)\rangle = e^{-i\beta_p H_1} e^{-i\gamma_p H_2} \cdots e^{-i\beta_1 H_1} e^{-i\gamma_1 H_2} |\psi_1\rangle$$

Example circuit



VQE for Ising chain

SciPost Phys. 6, 029 (2019)

Efficient variational simulation of non-trivial quantum states

Wen Wei Ho[1*] and Timothy H. Hsieh[2,3]

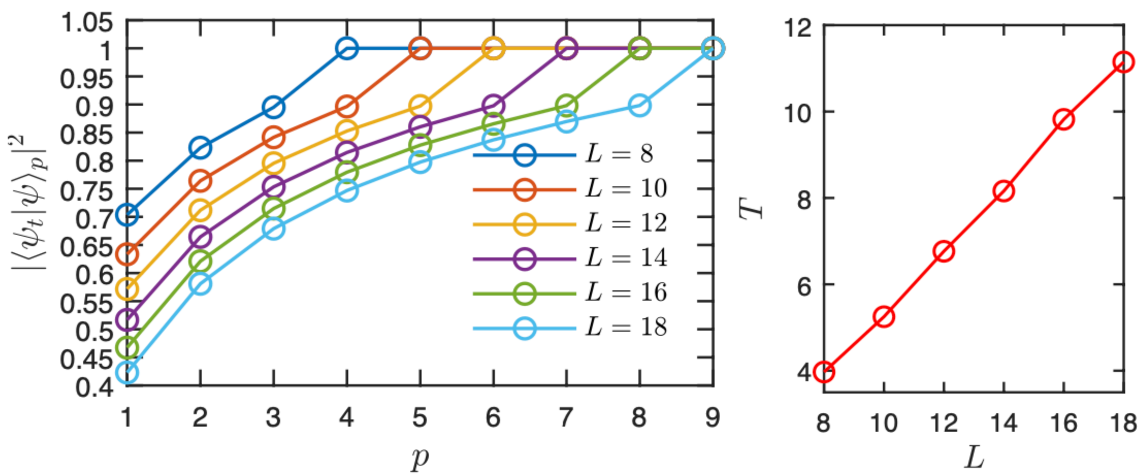


Figure 4: Preparation of critical state. (Left) Many-body overlap $|\langle\psi_t|\psi\rangle_p|^2$ of the prepared state with the target ground state of (9) found by exact diagonalization. Ones sees perfect fidelity for $p \geq L/2$. (Right) Total minimum time $T = \min_{(\gamma,\beta)}\left[\sum_i^{p=L/2}(\gamma_i + \beta_i)\right]$ required for the VQCS to produce the critical state with perfect fidelity using $\text{VQCS}_{p=L/2}$. One sees a linear trend $T \sim L$.

VQE for excited states?

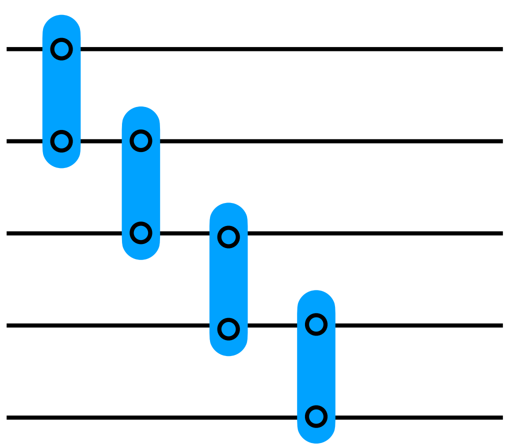
$$|-_i\rangle = |++\cdots -_i + \cdots +\rangle$$

$$|k\rangle = \frac{1}{\sqrt{N}} \sum_i e^{ikx_i} |-_i\rangle$$

For J/h << 1

$$\epsilon_k = 2\sqrt{h^2 + J^2 - 2hJ\cos k}$$

Issue: *translation operator T* cannot be generated with a finite depth circuit (depth proportional to L).



c.f D. Gross *et al*, 2012

Amount of translation is a "topological index" for 1d quantum cellular automata

VQE Attempt 1

- Let's not worry about it and just initialize a momentum state.

$$|\psi_0(k)\rangle = \frac{1}{\sqrt{N}} \sum_i e^{ikx_i} |-_i\rangle$$

- Generate

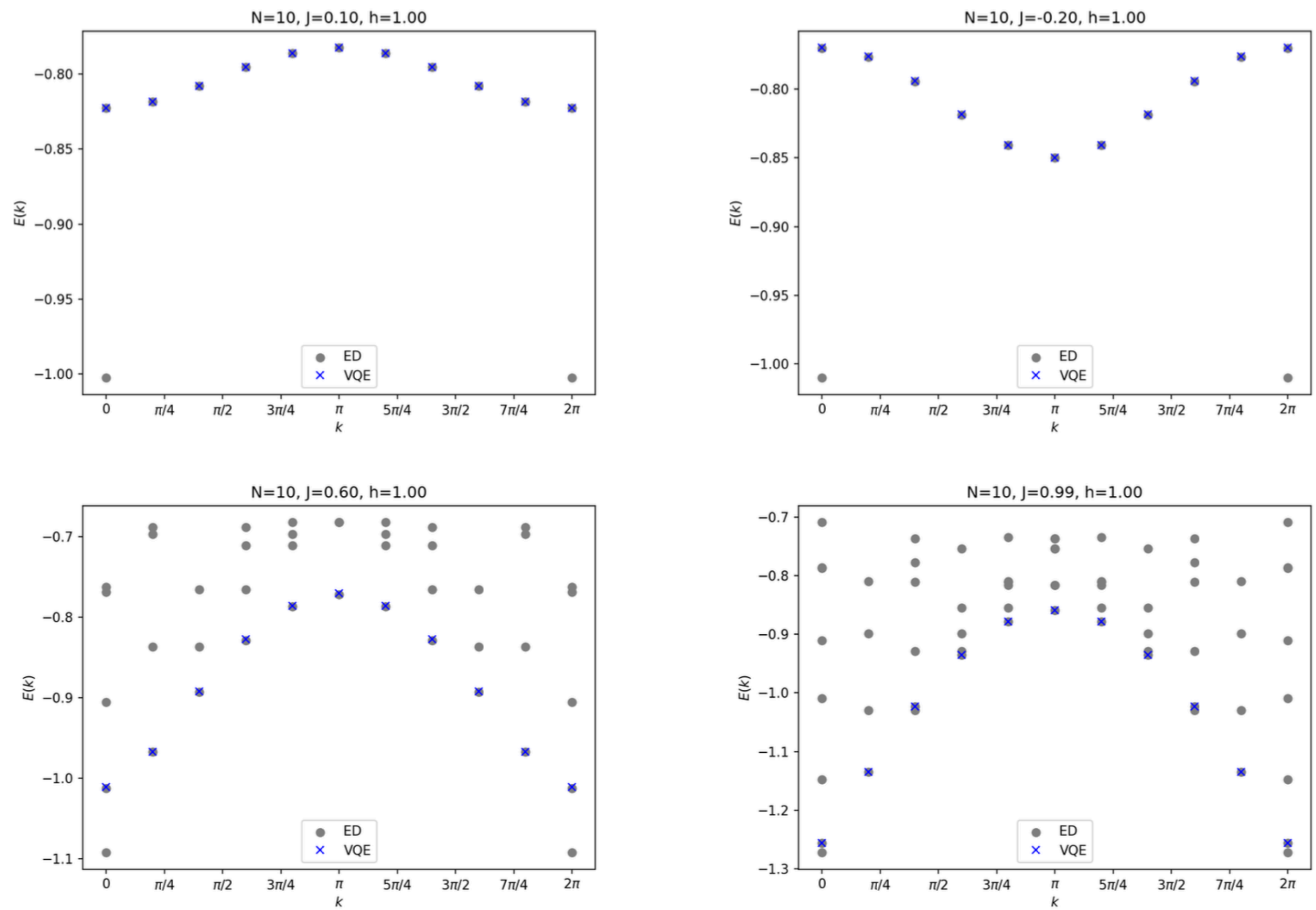
$$|\psi(k)\rangle = U(\{\beta_i\}) |\psi_0(k)\rangle$$

- Momentum conservation helps: k is conserved as is $P = \bigotimes_i X_i$

VQE Attempt 1

Simulations with QISkit

Works!



VQE attempt 2

- Make the system generate k state
  - Trick 1: Parity conservation $P = \otimes_i X_i$.

Ground state P=+1, k=0 $|GS\rangle = U_+ | + + \cdots + \rangle$

Excited state P=(-1)^N, k=0 $|k = 0\rangle = U_- | - - \cdots - \rangle$

Generates quasiparticle state if N odd!

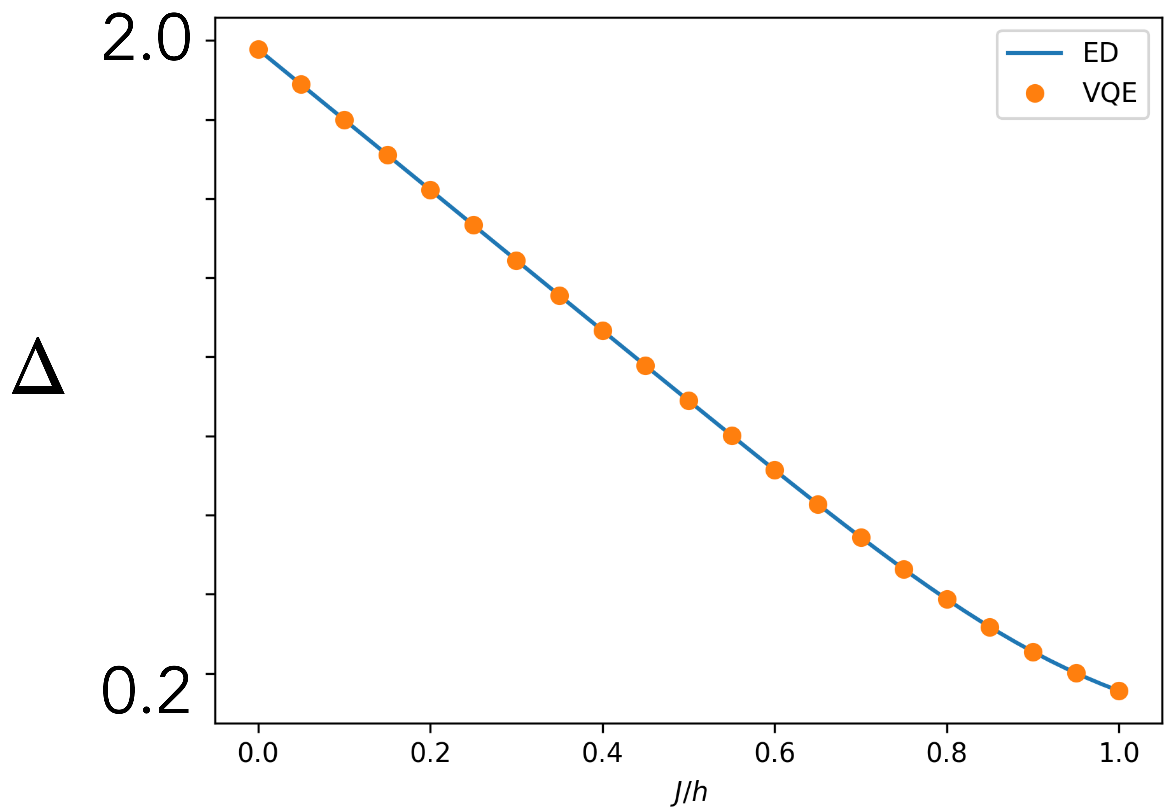
- In general this U depends on J/h (and is non-trivial even for J/h=0).

VQE attempt 2

- It works!

$$|GS\rangle = U_+|++\cdots+\rangle$$

$$|k=0\rangle = U_-|--\cdots-\rangle$$



VQE attempt 2

- Generate other k values?

- Trick 2: for *ideal* single spin-flip state, can *change* k via local unitary

$$|k\rangle_0 = U_k |k=0\rangle_0$$

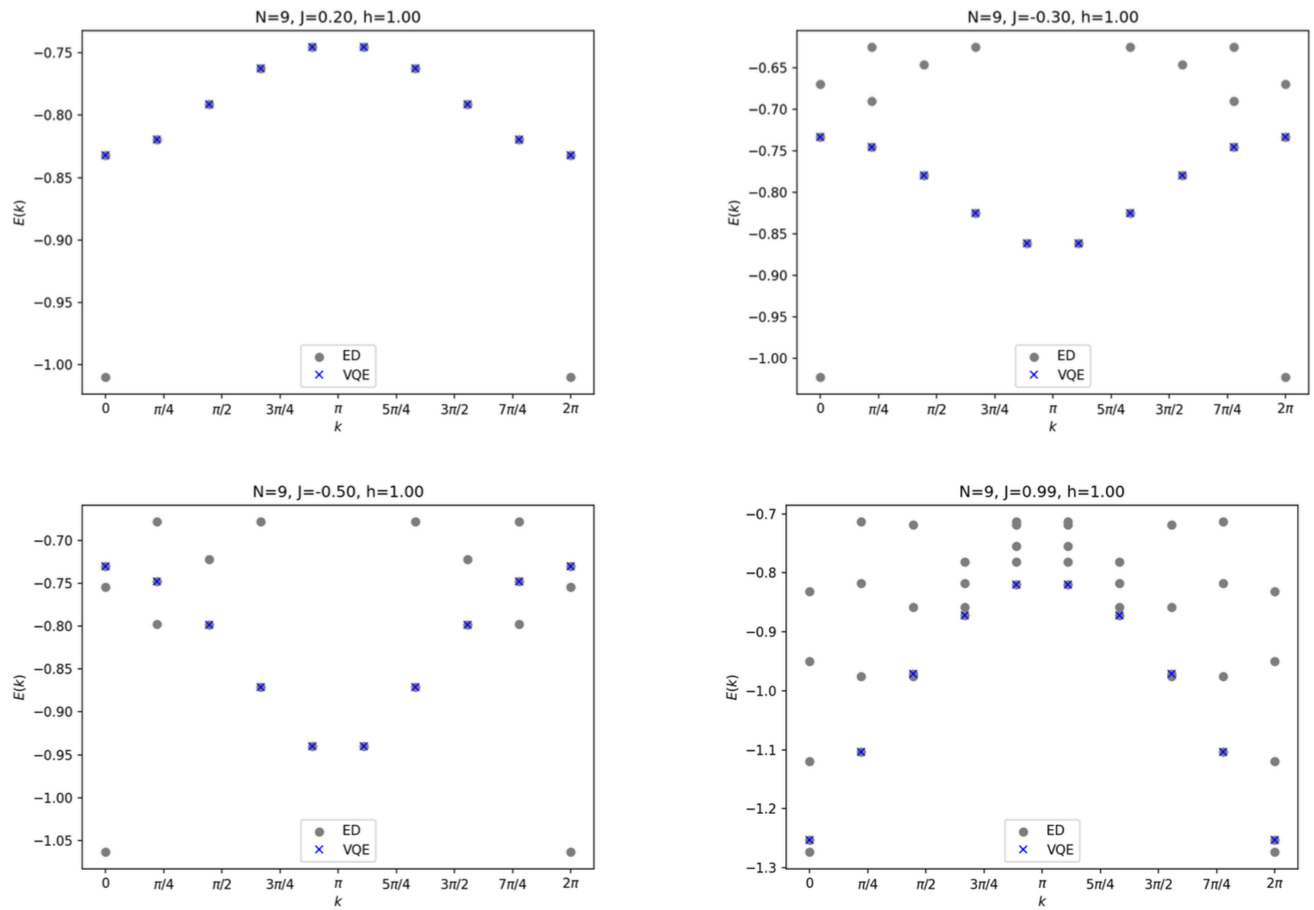
$$|k=0\rangle_0 = \frac{1}{\sqrt{N}} \sum_i |-_i\rangle$$

$$U_k = \prod_j e^{ikx_j(\frac{1}{2} - \frac{X_j}{2})}$$

- So we have a protocol

$$|k\rangle = U_{\text{int}} |k\rangle_0 = U_{\text{int}} U_k U^0_- |- - \cdots -\rangle$$

VQE attempt 2



This also works!

VQE attempt 3

- Can we work in *real* space instead of k space?
- What if we initialize to a *localized* excitation?

$$|x=0\rangle_0 = |++\cdots -_{x=0} + \cdots + \rangle = Z_0 \prod_i |+\rangle_i$$

- Evolved state

$$|x=0\rangle = U[\{\beta_i\}]\,|x=0\rangle_0$$

- Since U is translationally invariant and parity conserving, we have

$$|x=0\rangle = \frac{1}{\sqrt{N}} \sum_k U|k\rangle_0 = \frac{1}{\sqrt{N}} \sum_k |k\rangle$$

VQE attempt 3

- Variational energy

$$\langle x=0|H|x=0\rangle = \frac{1}{N}\sum_{k,k'}\langle k'|H|k\rangle = \frac{1}{N}\sum_{k}\langle k|H|k\rangle$$

  - ⋆ Minimum is reached only if it is reached for each k state individually!

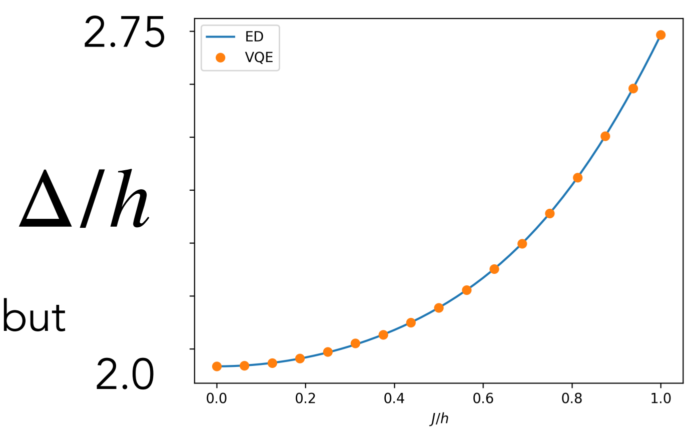
- Quantum parallelism! Just running VQE on this single state encodes the entire band of excited states!

VQE attempt 3

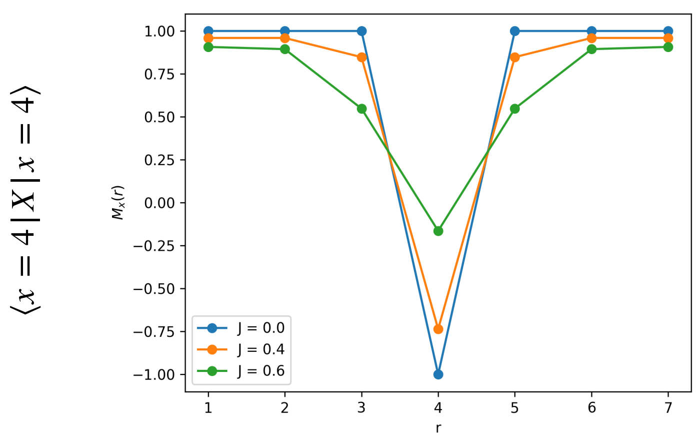
- Variational energy of this state gives the mean energy of the band

$$E_{x=0} - E_{GS} = \frac{1}{N}\sum_{k} \epsilon_k$$

With some work we can extract the entire band, but we're still trying to make it efficient



- We can also look at the state itself

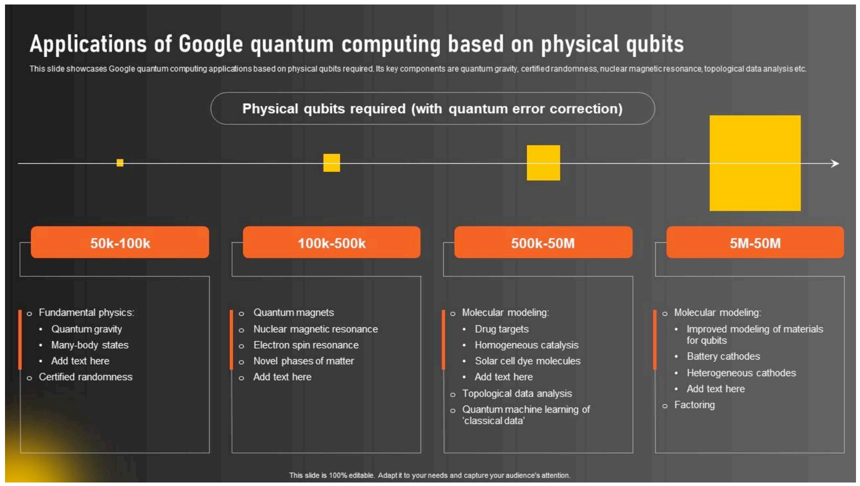


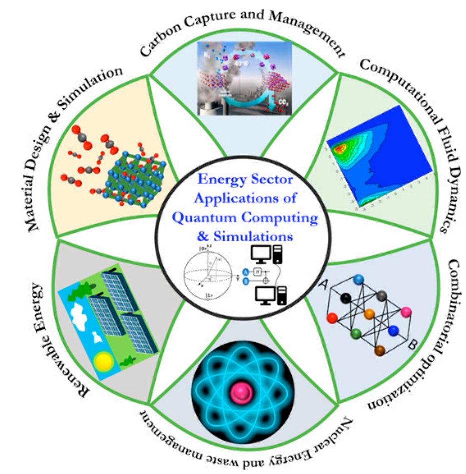
- Physically, we are generating the interacting analog of a Wannier state.

"The quasiparticle"

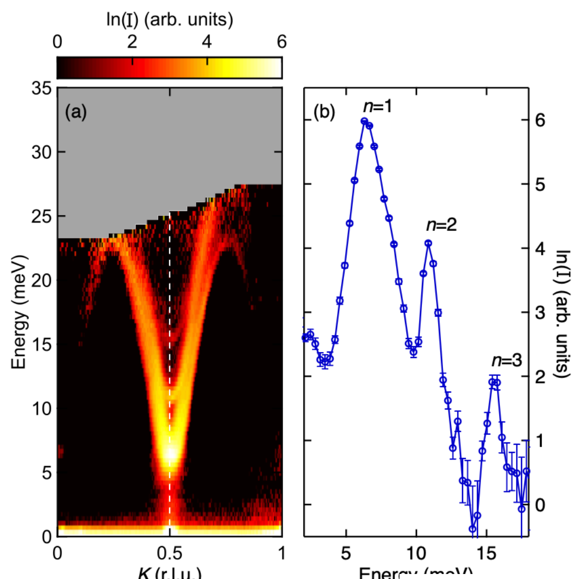
Is a QC useful for us?

I’m still not sure about this





But maybe this.



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Simons Collaboration on Ultra-Quantum Matter