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Quantum Phase of Matter: A Qutrit Perspective and Novel Order Parameter Discovery

Enrique Rico Ortega

Friday, 22/11/2024

Academia-Industry Matching Event (AIME24)

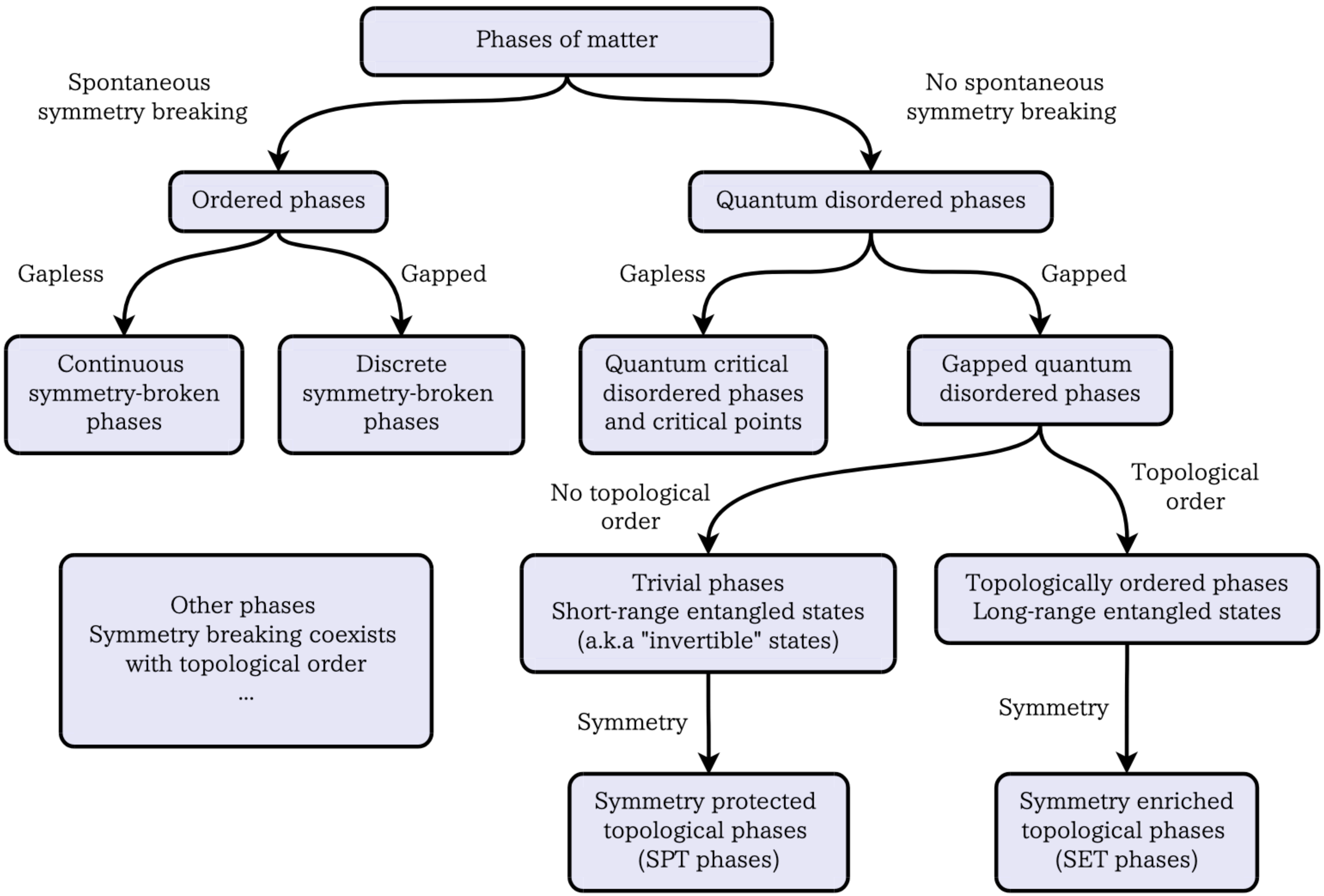
Nov 21 – 22, 2024
Mercure Budapest Castle Hill Hotel
Europe/Budapest timezone

Quantum Phase Transitions: A Qutrit Perspective and Novel Order Parameter Discovery — *Enrique Rico Ortega*

Mercure Budapest Castle Hill Hotel — 09:45 - 10:30

HUN-REN Wigner Research Centre for Physics
MTA Centre of Excellence
HUN-REN Hungarian Research Network

Phases of matter



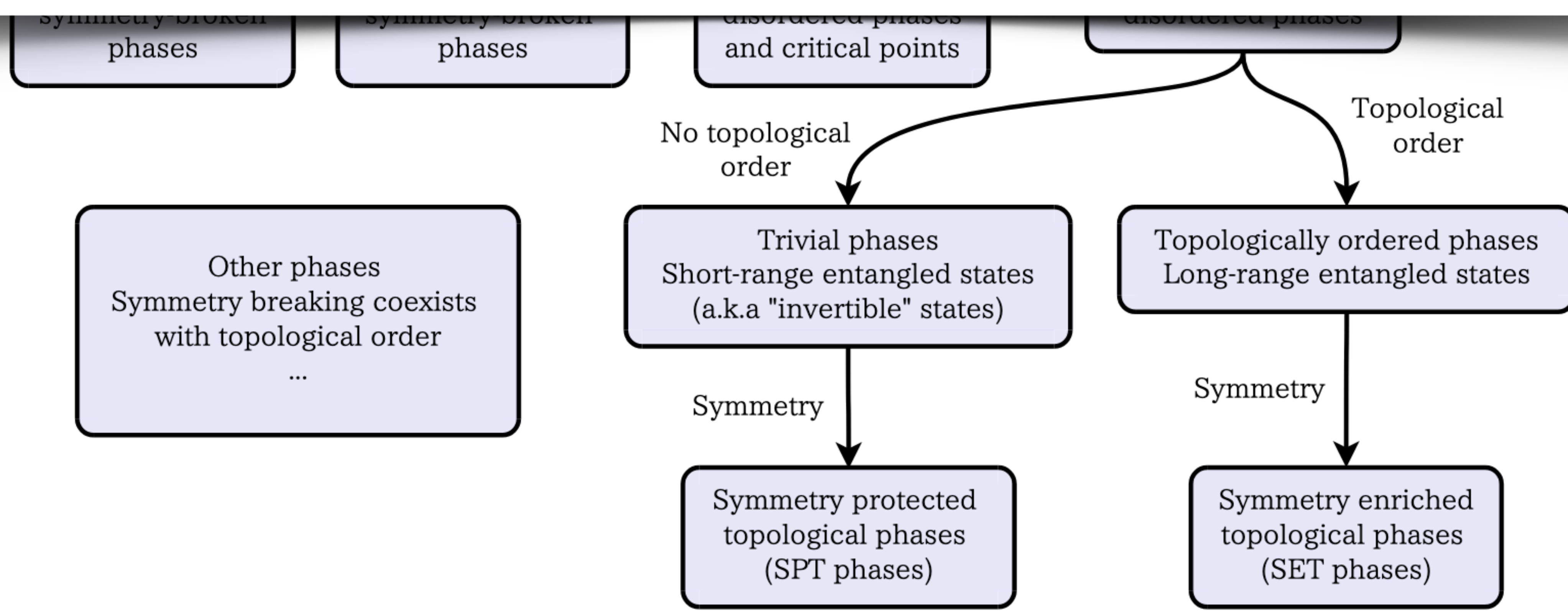
Talk given on August 23, 2021 at GGI.
"Topological phases of matter and quantum entanglement”
Shinsei Ryu (Princeton University)

Phases of matter

<u>Two main questions:</u>

How to engineer in the lab new Quantum Phases of Matter

How to characterise these new Quantum Phases



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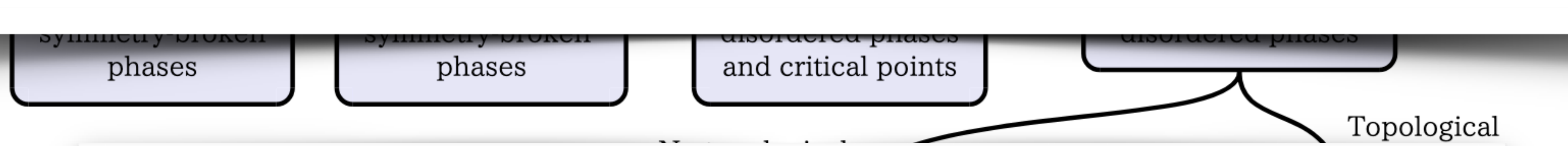

New tools from Quantum Technologies:

Quantum Simulators and Quantum Computers

Quantum Information ideas and measures

Talk given on August 23, 2021 at GGI.
"Topological phases of matter and quantum entanglement"
Shinsei Ryu (Princeton University)

Constructing the spin-1 Haldane phase on a qudit quantum processor

C. L. Edmunds,[1,*] E. Rico,[2,3,4,†] I. Arrazola,[5] G. K. Brennen,[6] M. Meth,[1] R. Blatt,[1,7,8] and M. Ringbauer[1]

arXiv > quant-ph > arXiv:2408.04702

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Order Parameter Discovery for Quantum Many-Body Systems

Nicola Mariella+,[1,*] Tara Murphy+,[1,2,†] Francesco Di Marcantonio,[3,‡] Khadijeh Najafi,[4,§] Sofia Vallecorsa,[5,¶] Sergiy Zhuk,[1,**] and Enrique Rico[3,6,7,††]

arXiv > quant-ph > arXiv:2408.01400

What is the Haldane phase?

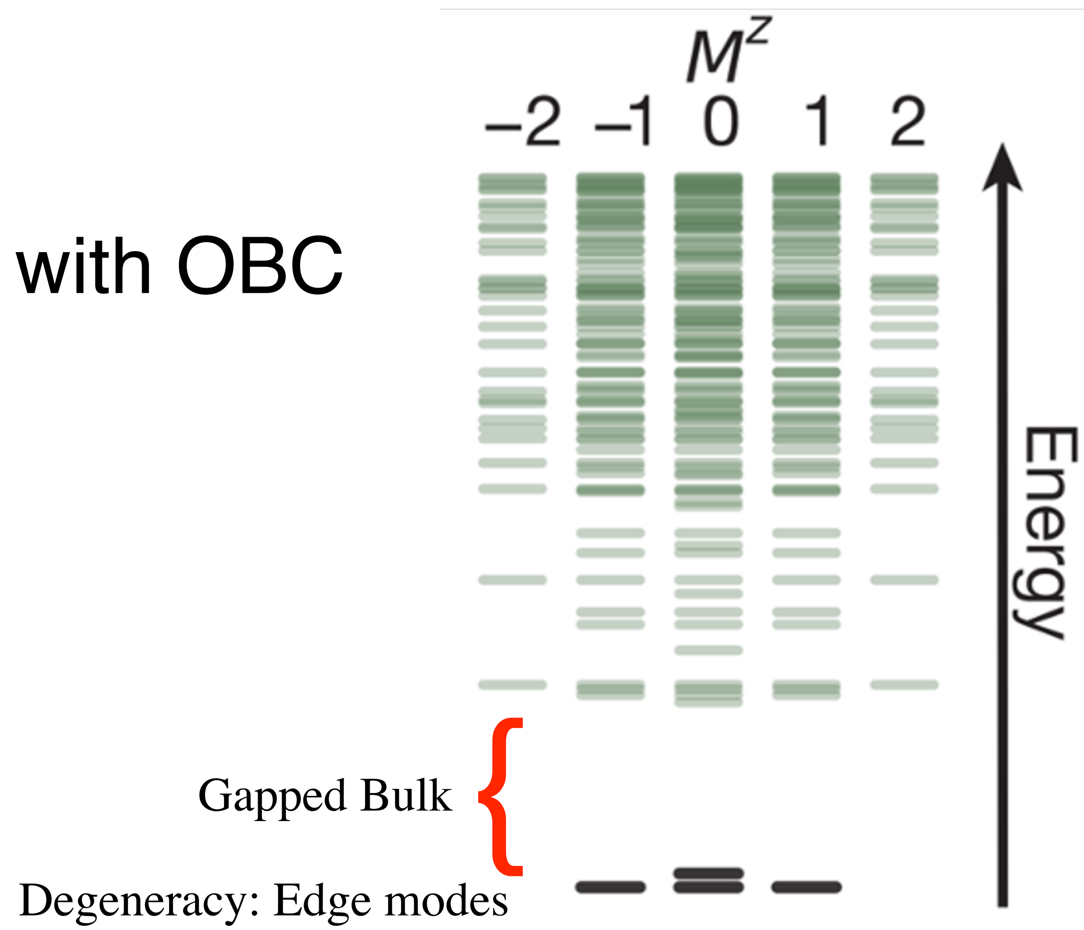
Symmetry Protected Topological Phases

$$\hat{H} = + \sum_i \vec{S}_i \vec{S}_{i+1}$$

- Gapped spectrum to next excited state
- Four-fold (nearly) degenerate ground state with OBC
- Protected by a Z_2 x Z_2 spin symmetry

➔First example of a SPT phase

➔Against all known evidence at the time



Haldane, F. D. M. (1981a), ILL preprint SP81/95,
arXiv:1612.00076

What is the Haldane phase?

Emerging experimental evidence

- Prior heuristic experimental evidence seemed to suggest that isotropic (rotationally symmetric) Hamiltonians were always gapless

- “Natural” spin-one crystals were made, and all evidence controversially pointed towards an energy gap

CsNiC13 (1985)
Ni(C2H8N2)2NO2(ClO4) (1990)

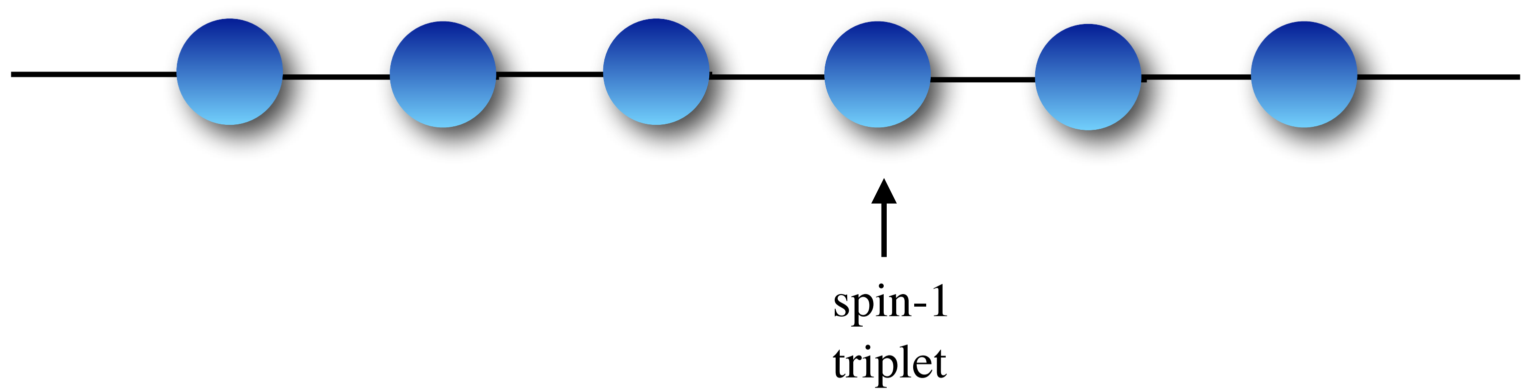
- Analog simulation in an ultra-cold atom Fermi-Hubbard ladder (2021)

- We are now performing the first digital simulation of Haldane using trapped ions

Haldane, F. D. M. (1981a), ILL preprint SP81/95,
arXiv:1612.00076

Simulating the Haldane phase ground state

$$\hat{H}_{\mathrm{AKLT}} = \sum_i \left[\vec{S}_i \vec{S}_{i+1} + \frac{1}{3} \left(\vec{S}_i \vec{S}_{i+1} \right)^2 \right] \propto \sum_i P_{S=2} \left(\vec{S}_i + \vec{S}_{i+1} \right)$$



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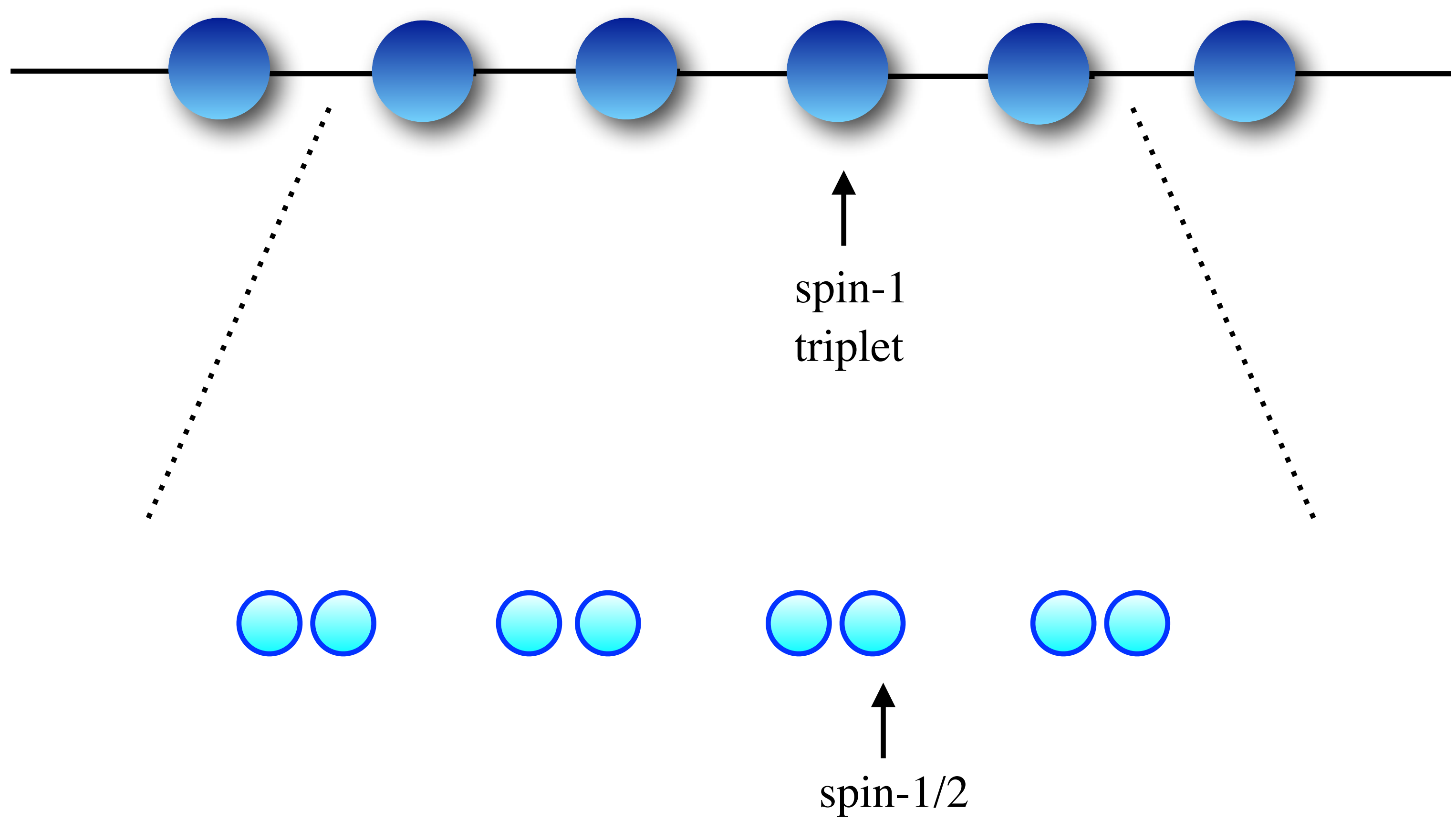

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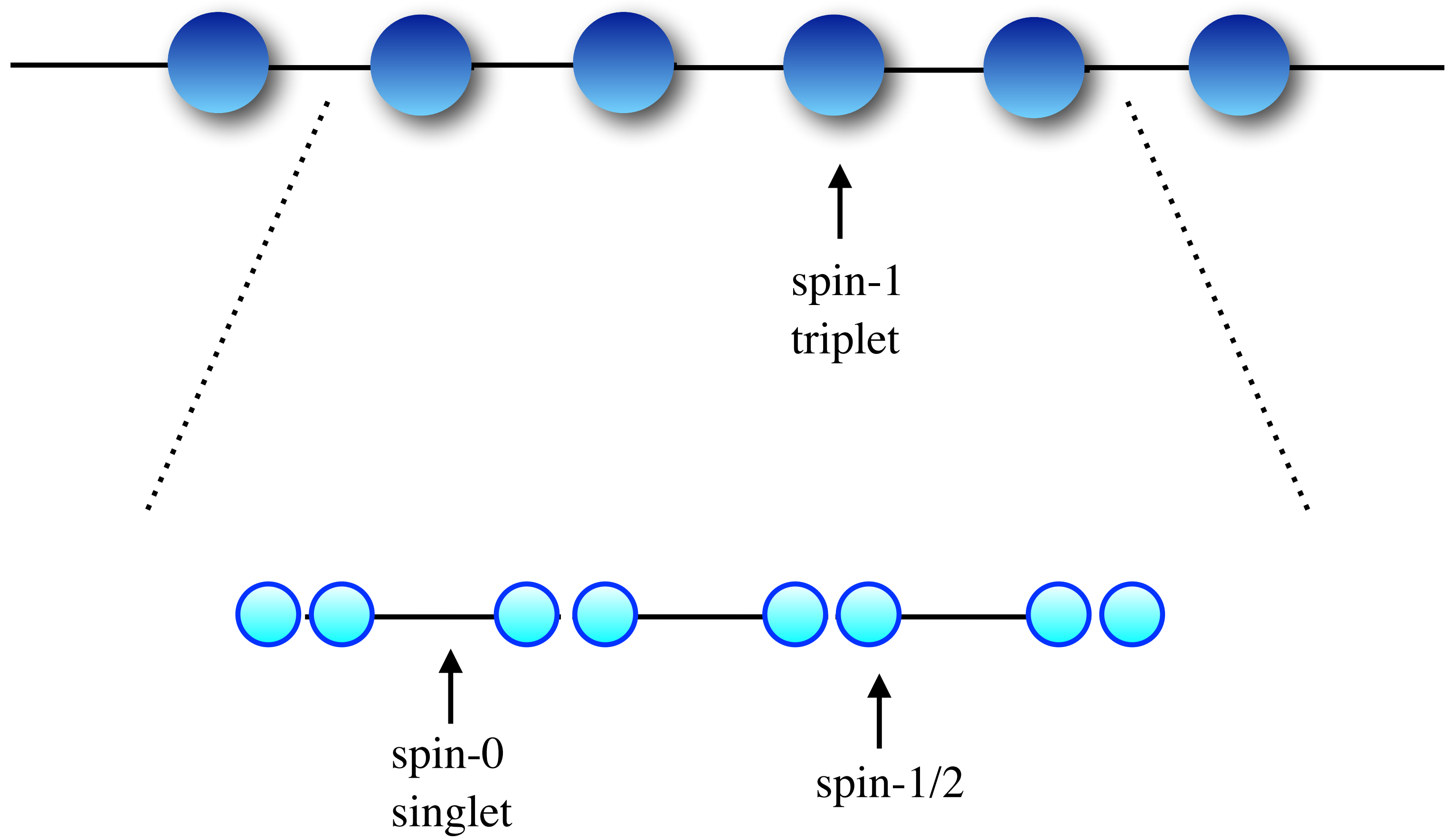

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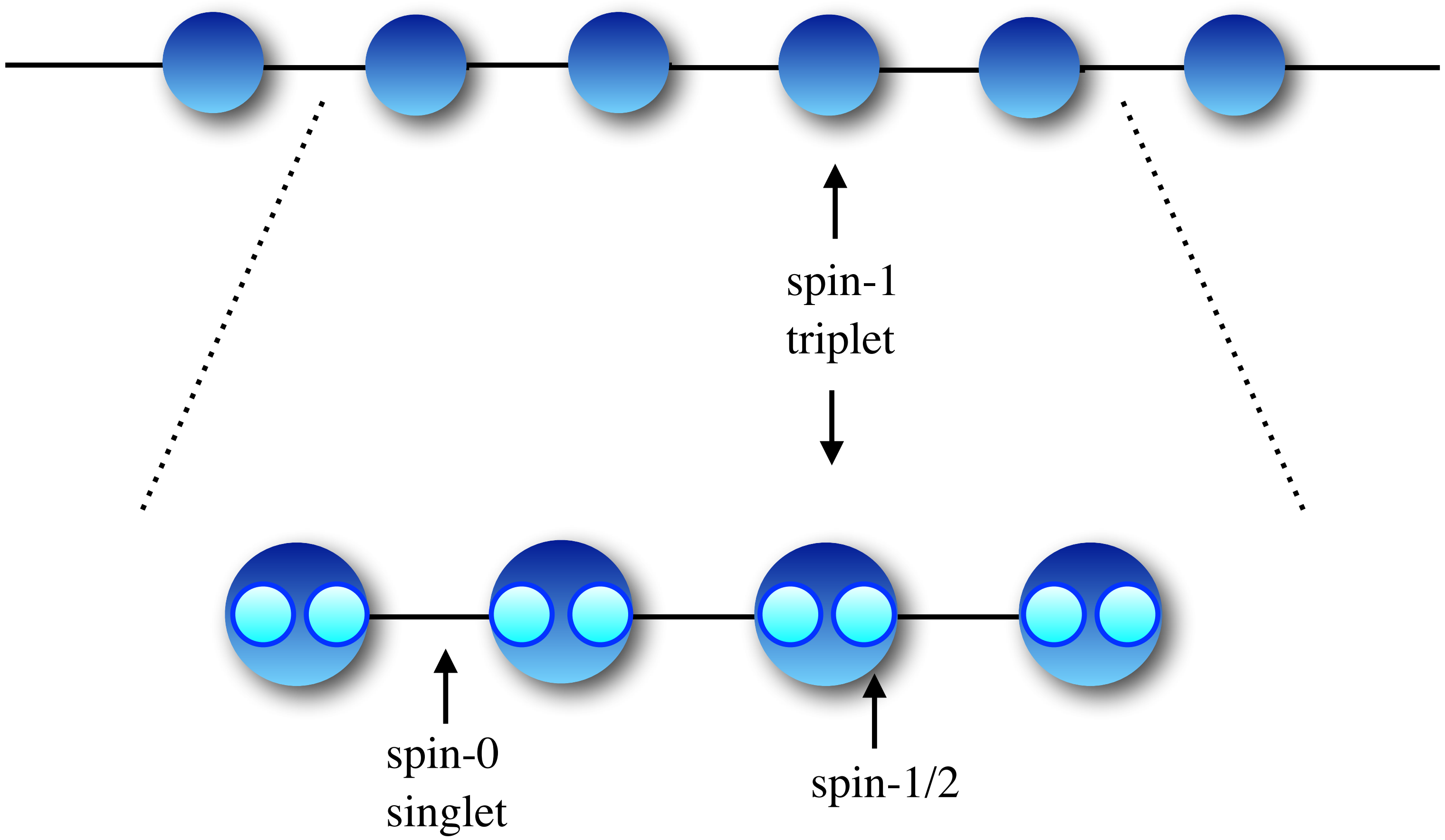
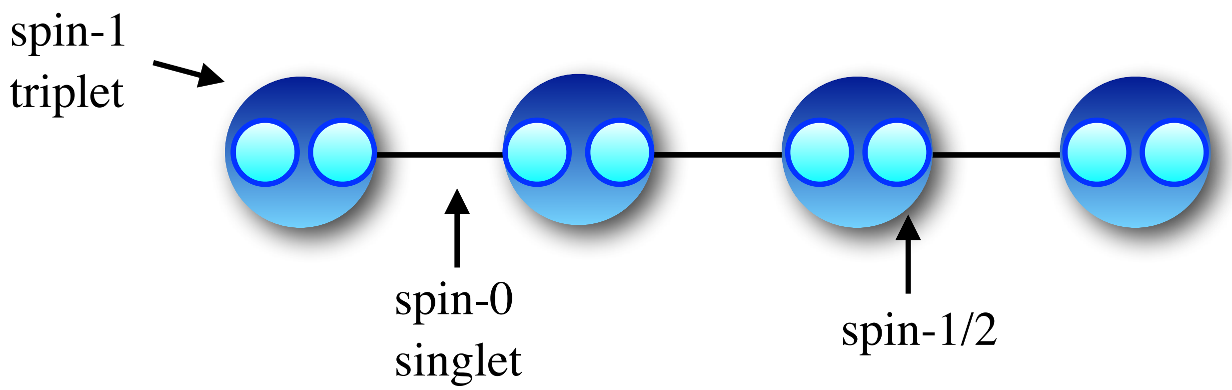


Simulating the Haldane phase ground state

Translationally invariant



Singlet state: $\langle \hat{S}_i^{\alpha} \rangle = 0$

Simulating the Haldane phase ground state

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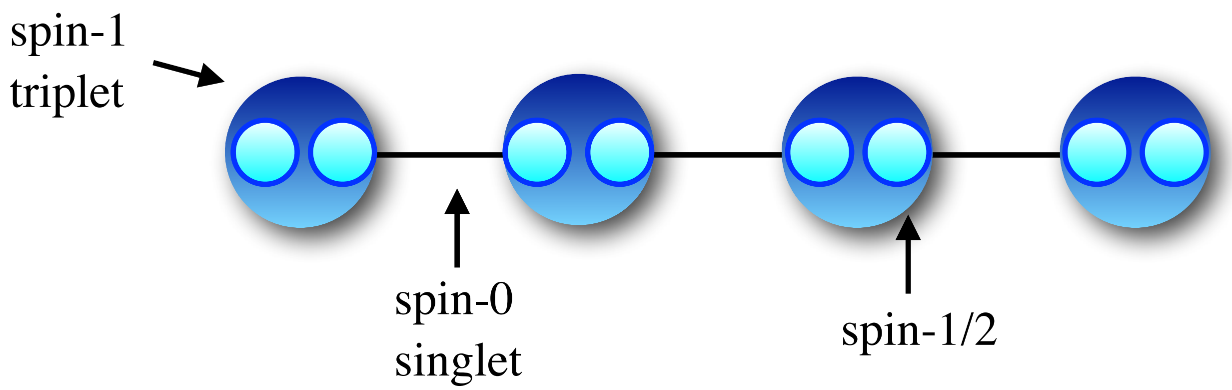


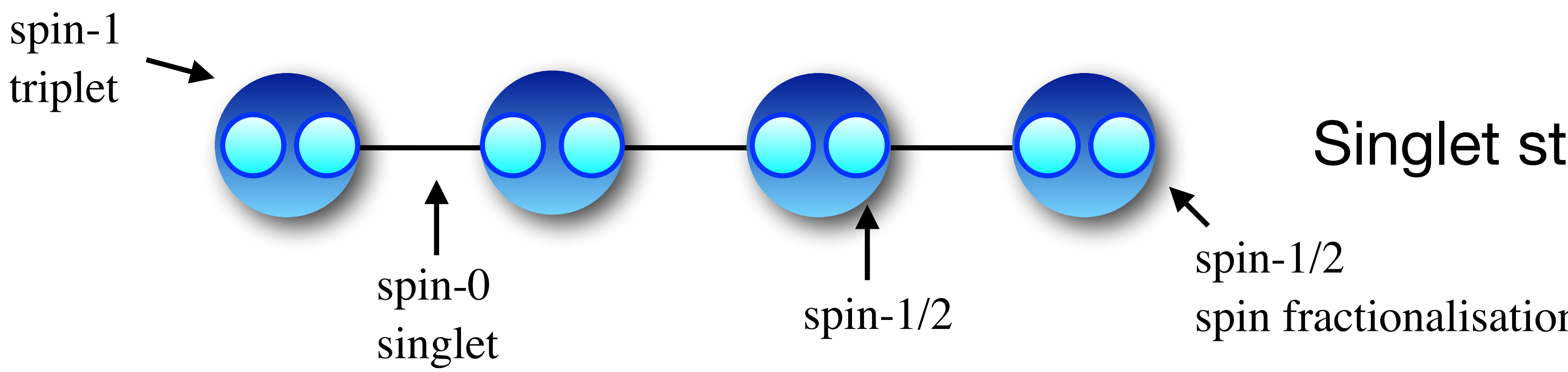
Singlet state: $\langle \hat{S}_i^\alpha \rangle = 0$

No long-range order: Finite correlation length.
Exponential decay of two point correlation function.

$$\langle \hat{S}_i^\alpha \hat{S}_j^\beta \rangle = \delta_{\alpha\beta} (-1)^{i+j} e^{-|i-j|/\xi}$$

Simulating the Haldane phase ground state

Translationally invariant



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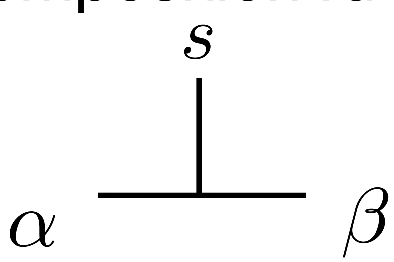
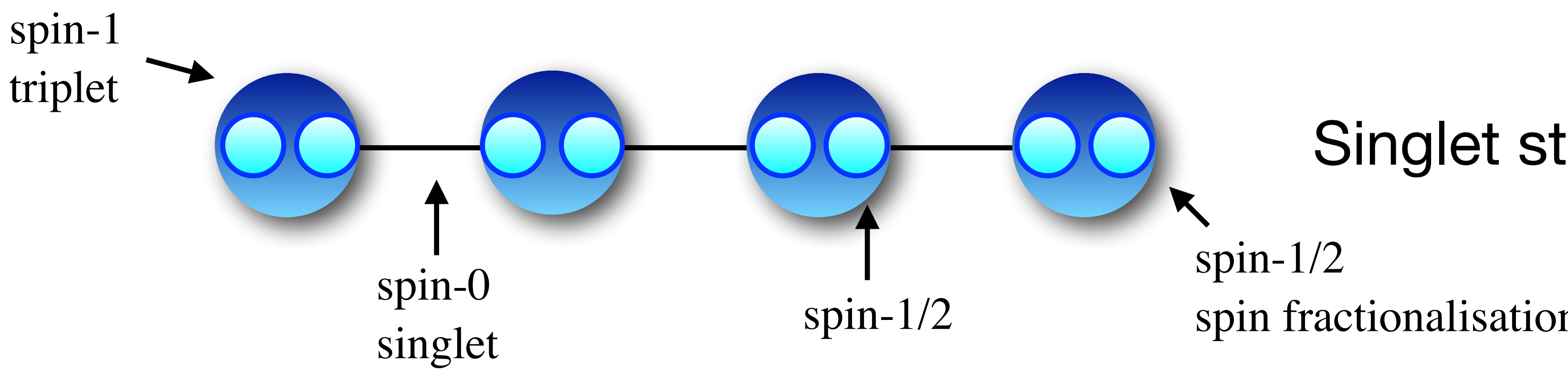
Composition rules: PBC = Unique state; OBC = 4-fold degeneracy



$$\frac{1}{2} \otimes \frac{1}{2} = 0 \oplus 1 \qquad 0 \otimes \frac{1}{2} = \frac{1}{2} \qquad \frac{1}{2} \otimes 1 = \frac{1}{2} \quad \Rightarrow SU(2)_2$$

Simulating the Haldane phase ground state

Translationally invariant



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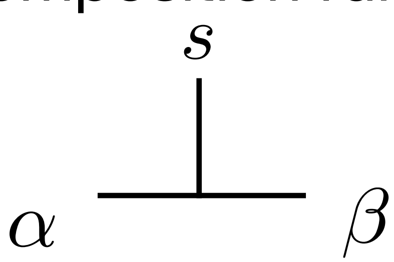

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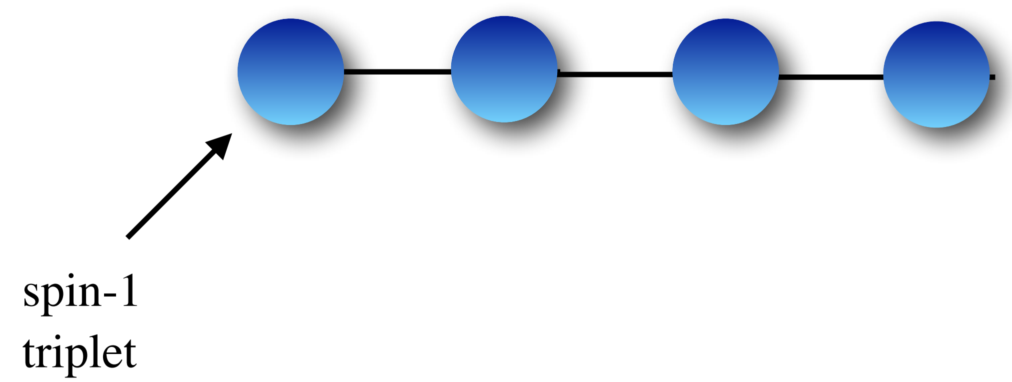
Non-local order parameter.- String order parameter and entanglement length
den Nijs, Rommelse (1989)
Cirac, Martin-Delgado, Popp, Verstraete (2005)

$$O_{\text{str}}^\alpha = lim_{|i-j| \to \infty} \langle \hat{S}_i^\alpha e^{i\pi \sum_{i+1}^{k=j+1} \hat{S}_k^\alpha} \hat{S}_j^\alpha \rangle$$

Simulating the Haldane phase ground state

Non-local order parameter.- Entanglement length

$$|\mathrm{AKLT}\rangle = \sum_{\{s\}} A^{s_1} A^{s_s} \cdots A^{s_N} | s_1, s_2, \cdots, s_N \rangle$$



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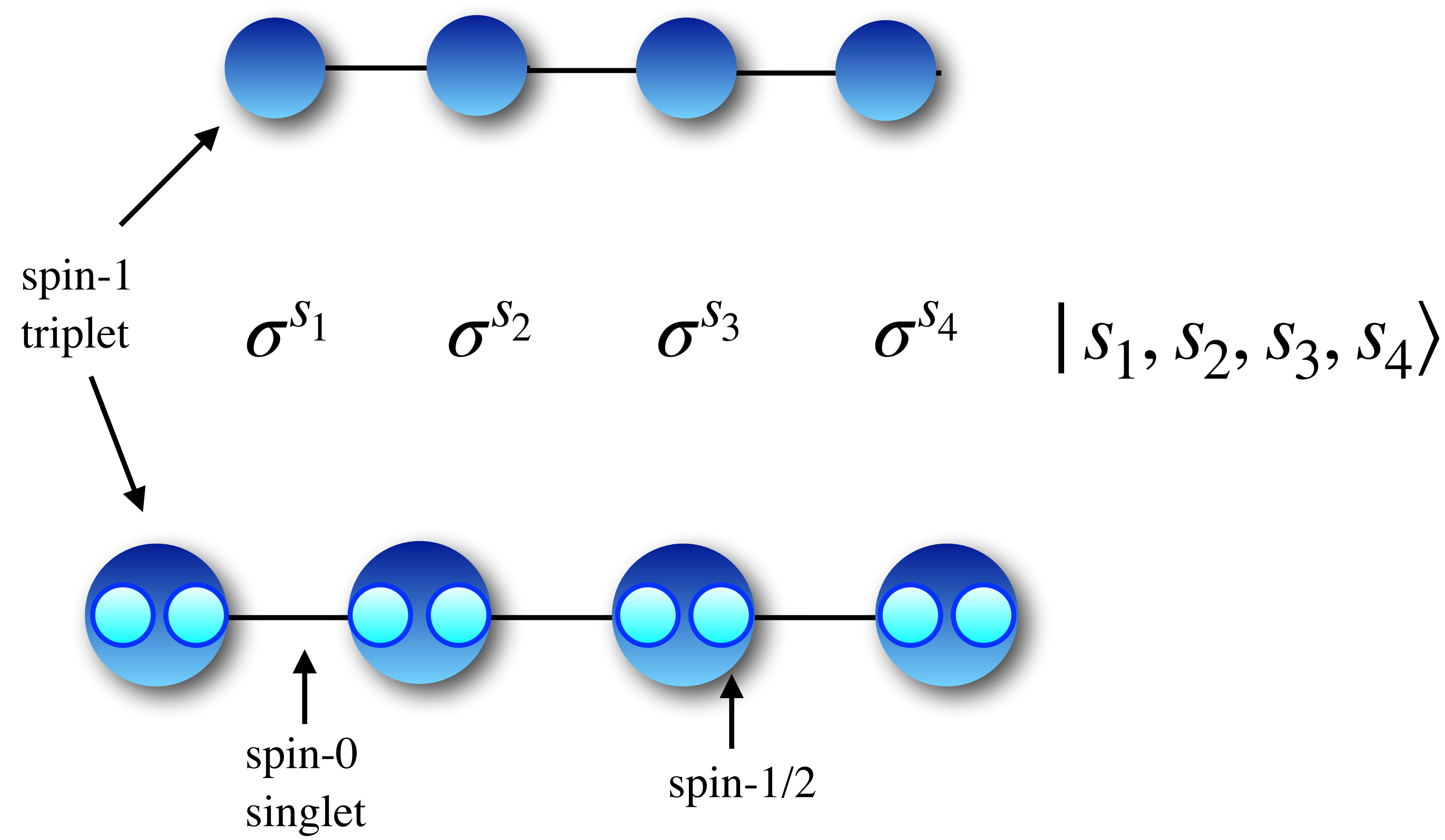
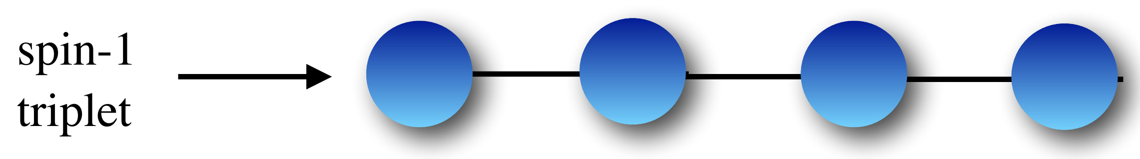


Simulating the Haldane phase ground state

Non-local order parameter.- String order parameter

$$e^{i\theta S^{\alpha}_{\rm tot}} = e^{i\theta S^{\alpha}_1} e^{i\theta S^{\alpha}_2} e^{i\theta S^{\alpha}_3} e^{i\theta S^{\alpha}_4}$$



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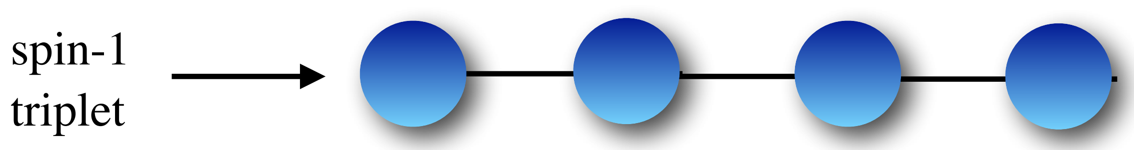
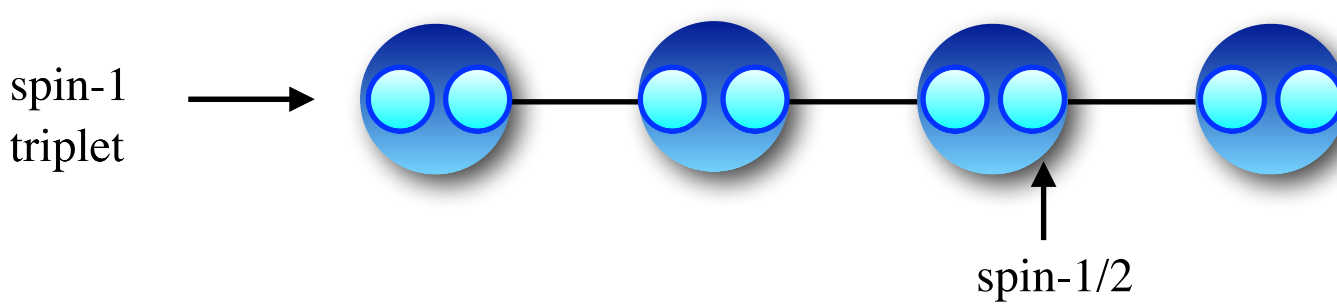


$$e^{i\theta S^{\alpha}_{\text{tot}}} \sim e^{i\theta \sigma^{\alpha}_1/2} e^{i\theta \sigma^{\alpha}_2/2} e^{i\theta \sigma^{\alpha}_3/2} e^{i\theta \sigma^{\alpha}_4/2} e^{i\theta \sigma^{\alpha}_5/2} e^{i\theta \sigma^{\alpha}_6/2} e^{i\theta \sigma^{\alpha}_7/2} e^{i\theta \sigma^{\alpha}_8/2}$$



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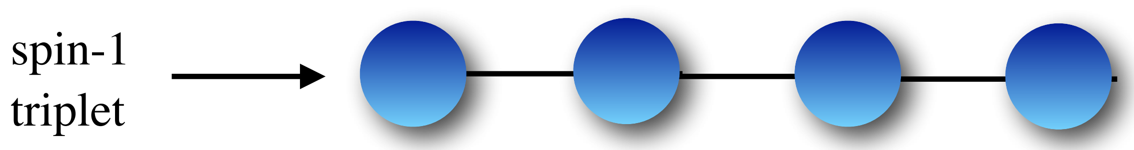

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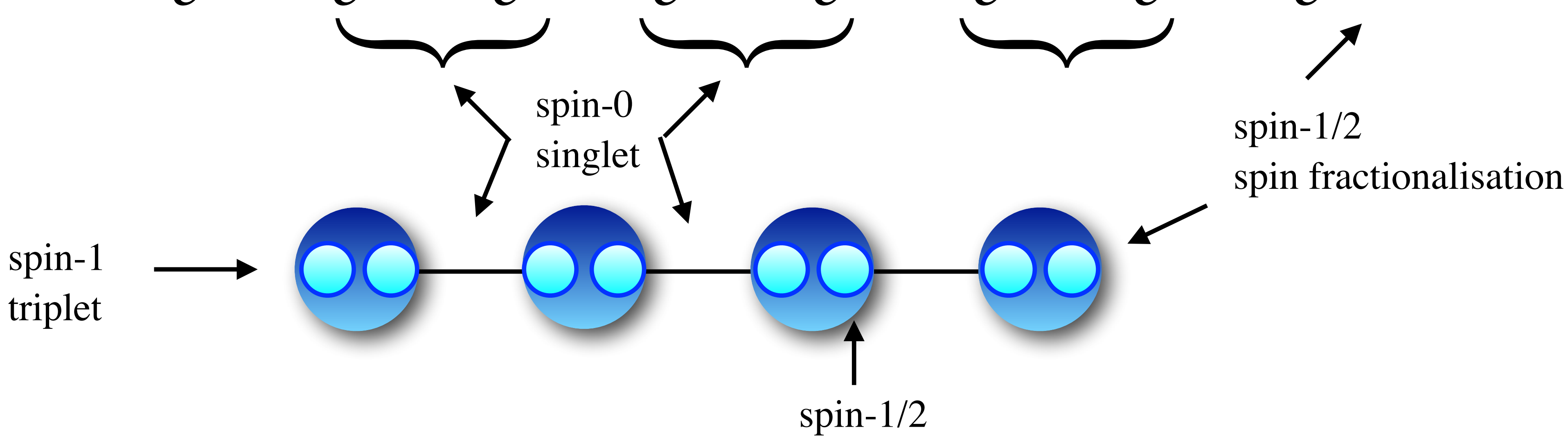

Simulating the Haldane phase ground state

Non-local order parameter.- String order parameter

$$\hat{H}_{\text{cluster}} = -\sum_i \hat{\sigma}^z_{i-1}\hat{\sigma}^x_i\hat{\sigma}^z_{i+1}$$

$$[\hat{\sigma}^z_{i-1}\hat{\sigma}^x_i\hat{\sigma}^z_{i+1}, \hat{\sigma}^z_{j-1}\hat{\sigma}^x_j\hat{\sigma}^z_{j+1}] = 0 \qquad \hat{\sigma}^z_{i-1}\hat{\sigma}^x_i\hat{\sigma}^z_{i+1}\,|\,\text{gs}\rangle = |\,\text{gs}\rangle$$ Stabiliser-State

Z_2 x Z_2 symmetry: $\hat{X}_{\text{even}} = \hat{\sigma}^x_2\hat{\sigma}^x_4\cdots\hat{\sigma}^x_{2N}$ $\qquad \hat{X}_{\text{odd}} = \hat{\sigma}^x_1\hat{\sigma}^x_3\cdots\hat{\sigma}^x_{2N-1}$

F. Pollmann and A. M. Turner, Phys. Rev. B 86, 125441 (2012)
A. Smith, B. Jobst, A.G. Green, F. Pollmann, PRReseach 4, L022020 (2022)

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$$\left(\hat{\sigma}^z_{2N}\right)\left(\hat{\sigma}^x_1\hat{\sigma}^z_2\right)\Big|_{\text{g.s.}} = \hat{X}_{\text{odd}} \qquad \left(\hat{\sigma}^z_{2N-1}\hat{\sigma}^x_{2N}\right)\left(\hat{\sigma}^z_1\right)\Big|_{\text{g.s.}} = \hat{X}_{\text{even}}$$

Projective symmetry representation at the boundary: $\{\hat{\sigma}^x_1\hat{\sigma}^z_2, \hat{\sigma}^z_1\} = 0$

F. Pollmann and A. M. Turner, Phys. Rev. B 86, 125441 (2012)
A. Smith, B. Jobst, A.G. Green, F. Pollmann, PRReseach 4, L022020 (2022)

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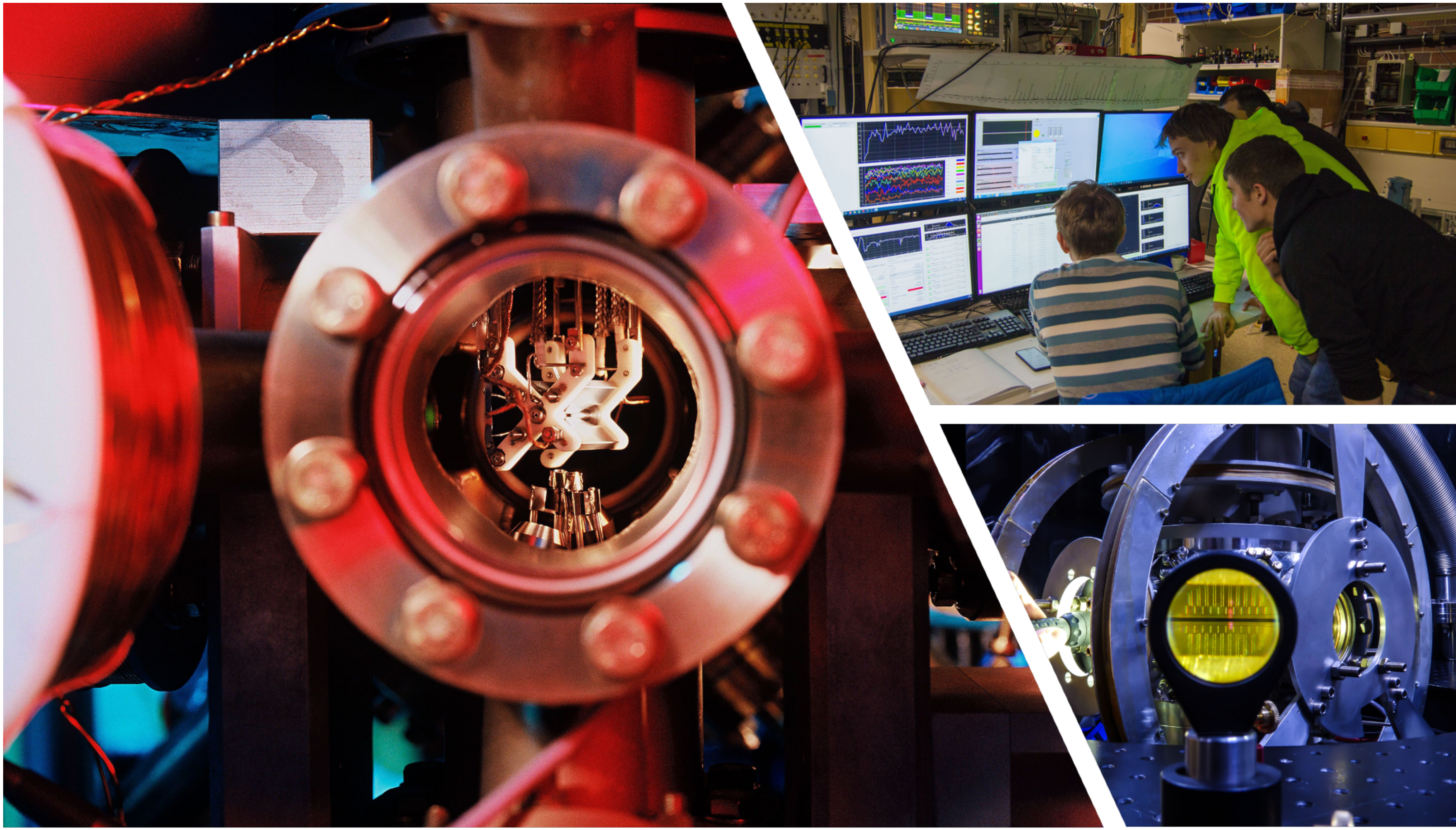
Trapped $^{40}Ca^{+}$ ion “qudits”



M. Ringbauer et al., arxiv:2109.06903 (2021)

Y. Chi et al., Nature Communications 13, 1166 (2022)

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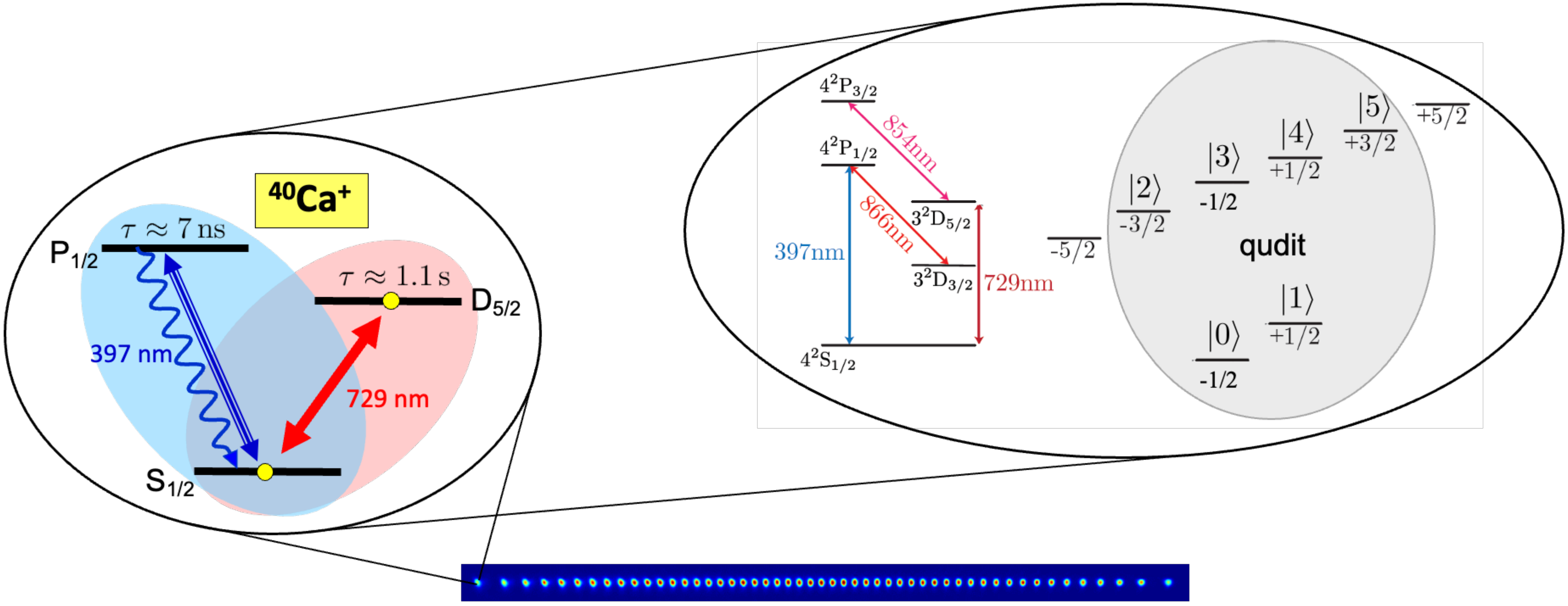


Directly simulate non-spin-½ systems in nature by utilising extra levels in ions

M. Ringbauer et al., arxiv:2109.06903 (2021)
Y. Chi et al., Nature Communications 13, 1166 (2022)

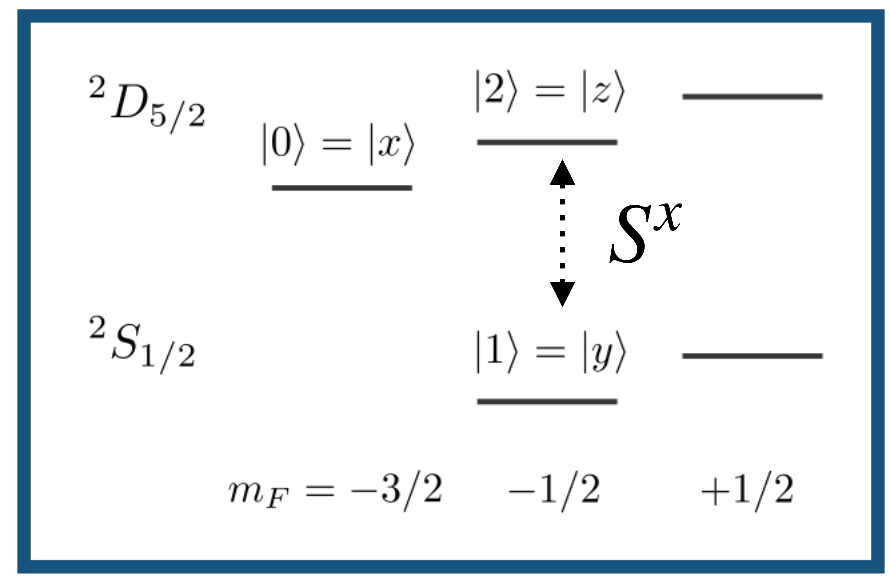
Creating the Spin-1 AKLT chain

AKLT Spin-1 Basis Definition

$$\hat{H}_{\mathrm{AKLT}} = \sum_i \left[\vec{S}_i \vec{S}_{i+1} + \frac{1}{3} \left(\vec{S}_i \vec{S}_{i+1} \right)^2 \right]$$

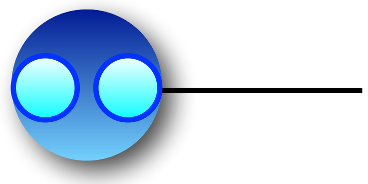
$$S^\alpha \,|\, \beta \rangle = i\epsilon^{\alpha\beta\gamma} \,|\, \gamma \rangle, \qquad S^x = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}$$

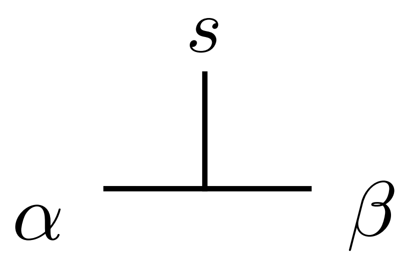
$^{40}Ca^+$ energy level encoding



The state $|\,\alpha\rangle$ is the zero-projection eigenvectors of the operator S^α

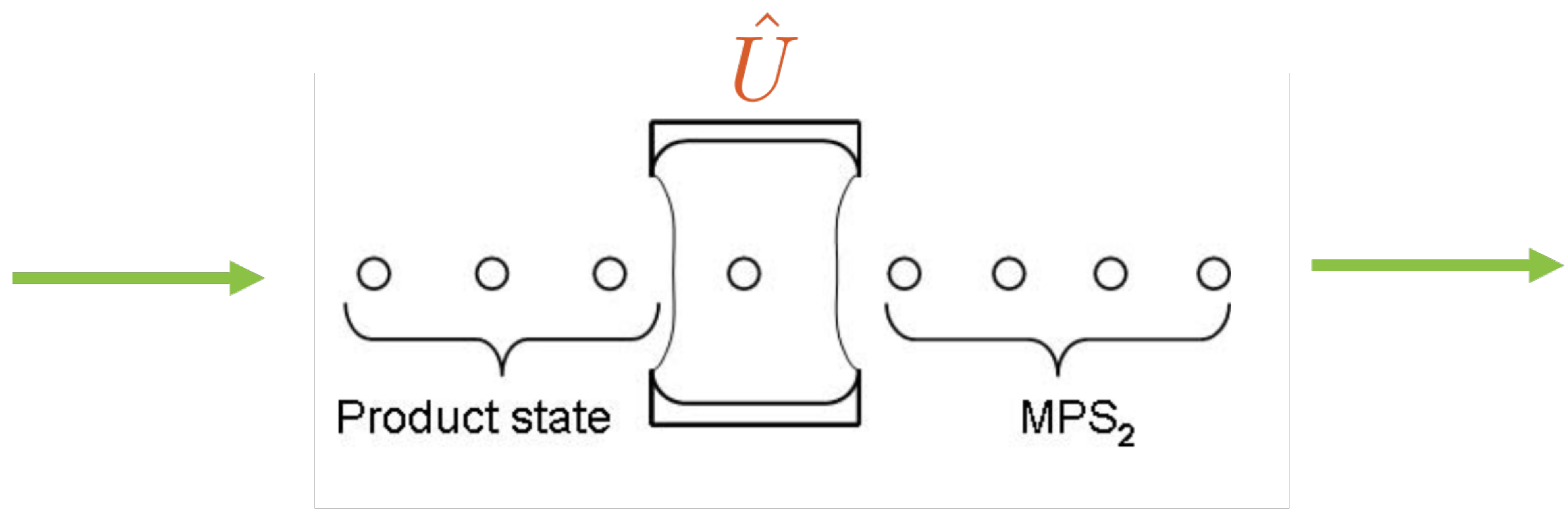
Sequential Preparation of the AKLT ground state





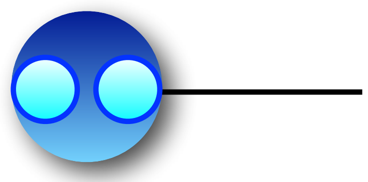
$$|\alpha\rangle = \sum_{s,\beta} \sigma^{s}_{\alpha\beta} |s,\beta\rangle$$

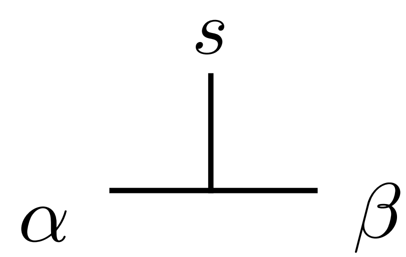
- The AKLT ground state is a matrix product state → equivalent to a sequentially generated state
- Uncorrelated atoms pass sequentially through a “cavity” and couple to the cavity mode
- Choosing an appropriate coupling unitary will generate the AKLT state



C. Schön, et al., Phys. Rev. Lett. 95, 110503 (2005),
C. Schön et al., Phys. Rev. A 75, 032311 (2007)

MPS Coupling Gate

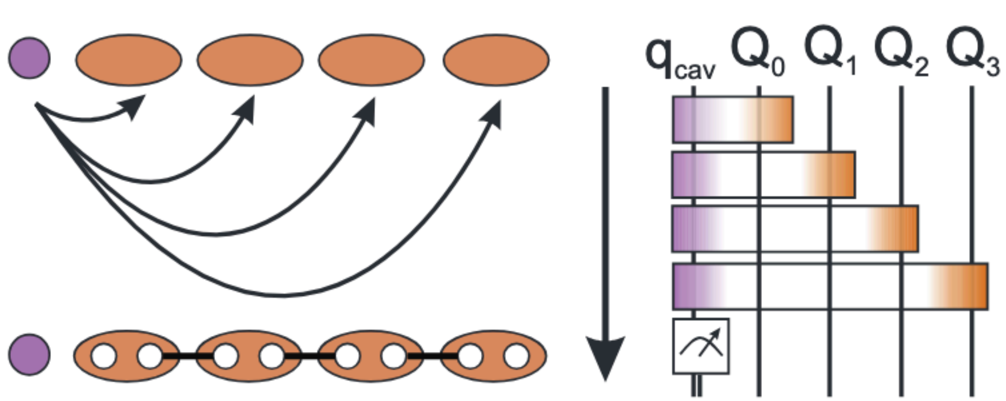




$$|\alpha\rangle = \sum_{s,\beta} \sigma^{s}_{\alpha\beta} |s, \beta\rangle$$

Control-unitary: spin-1/2 unitary controlled by spin-1

$$|\beta\rangle \sum_{s} |s\rangle \mapsto |\alpha\rangle = \sum_{s,\beta} \sigma^{s}_{\alpha\beta} |s, \beta\rangle$$

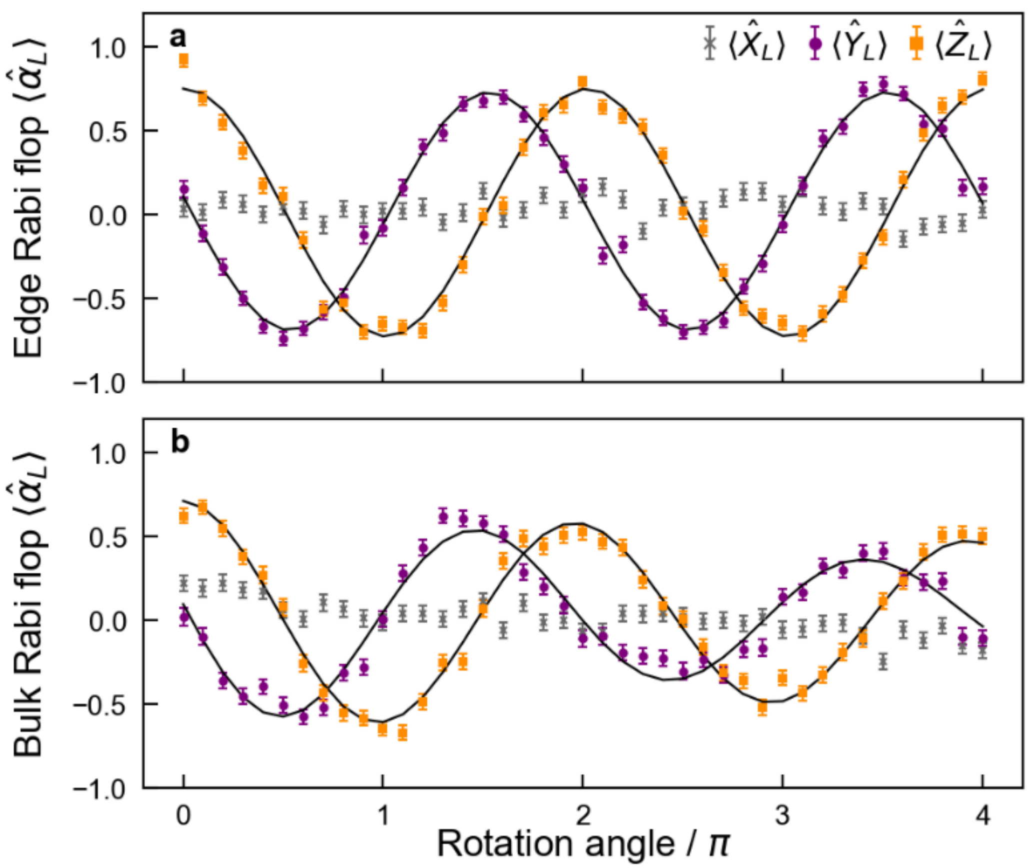


45 local gates (fidelity ~ 0.999)
2 entangling gate (fidelity ~ 0.985)

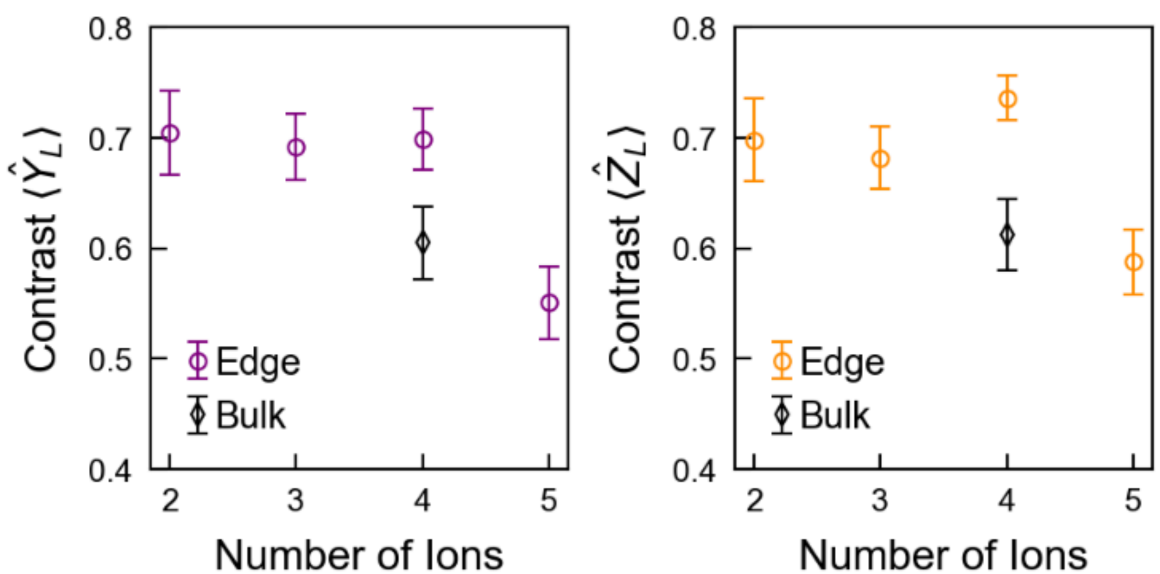
Fidelity ~ (0.99945 * 0.9852)N
= {0.86, 0.80, 0.74, 0.69} for N = {2, 3, 4, 5}

Bulk - edge correspondence

Rabi flops of the Fractionalized edge qubit



Rabi flop contrast



Summary and outlook

- Using qutrits, we can directly create the ground state of a spin-1 AKLT chain
- We observe the critical features of an SPT, in particular, spin fractionalisation of the spin-1 chain into two qubits on the boundaries
- The AKLT state is a perfect quantum repeater and has interesting properties for one-way quantum computation
- Looking at ways to explore more complex SPTs, such as higher dimensional spin-1 lattices using qudits

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EHU QC EHU Quantum Center

ikerbasque Basque Foundation for Science

The Team

BasQ Basque Quantum



Federal Ministry Republic of Austria Education, Science and Research



ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

universität innsbruck

I. Arrazola.- PostDoc researcher at IFT-UAM

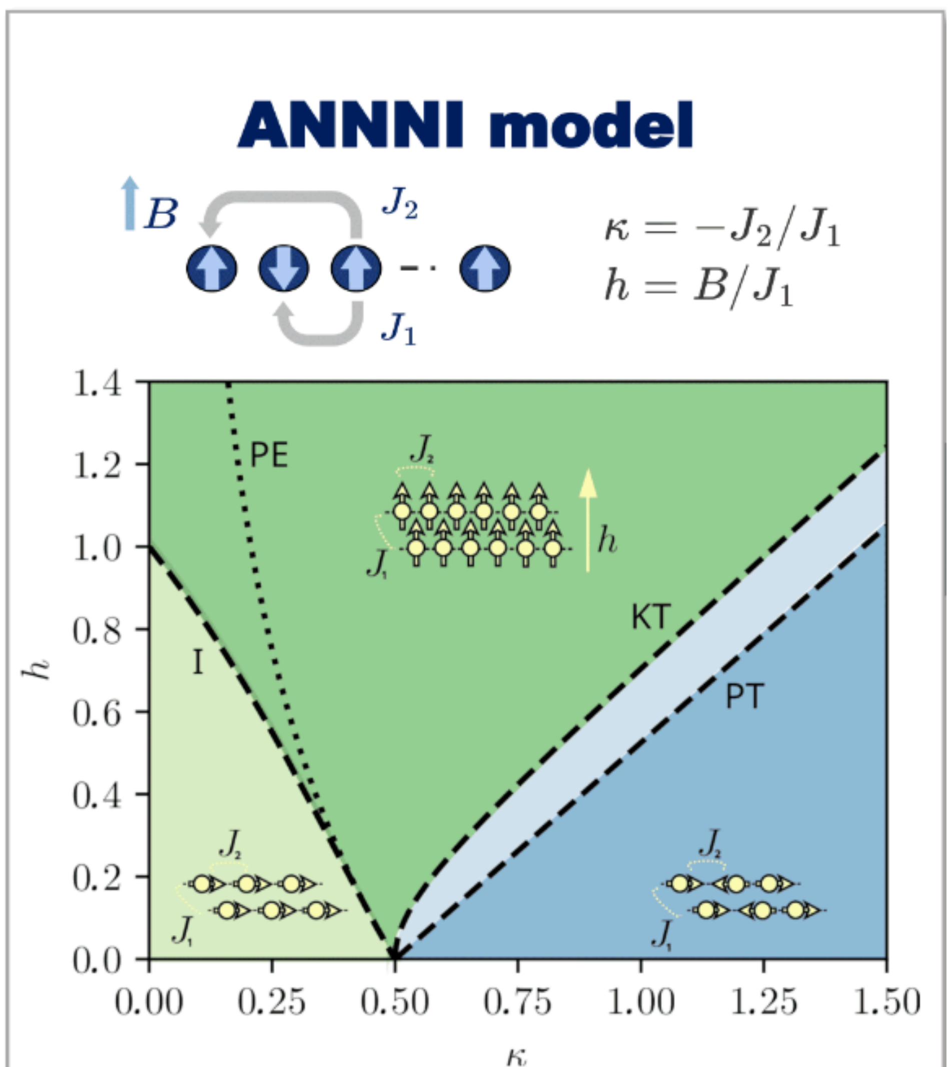
G. K. Brennen.- Professor at Macquarie University

C. L. Edmunds, M. Meth, R. Blatt, M. Ringbauer.- Qudit group at trapped ion experiments in Innsbruck

The problem:

Consider some Hamiltonian depending on some coupling parameters

$$H(\kappa, h) = -\sum_i S_i^x S_{i+1}^x + \kappa \sum_i S_i^x S_{i+2}^x + h \sum_i S_i^z$$



Objective: design a mathematical tool

for classifying different phases of matter (classification)

for detecting the phase transitions (anomaly detection)

The problem:

Phase transition happens when a “smooth variation” of a Hamiltonian as a function of coupling parameters leads to an abrupt “change” of a ground state.

Phases of matter are usually classified using so called order parameters: e.g. averaged magnetisation is the order parameter for transverse field Ising model.

With the general behaviour: ordered phase (order parameter is different from zero) and disordered phase (order parameter equals to zero). Phase transition at the boundary between phases.

How to classify phases and detect phase transitions of a quantum system without tailored “order parameters”?

Visualisation of the uses of the reduced fidelity susceptibility

Possible way-out fidelity susceptibility: $\langle \psi(\lambda) | \psi(\lambda + v) \rangle$ untrainable in a many-body situation: diagonal dominance, orthogonality catastrophe

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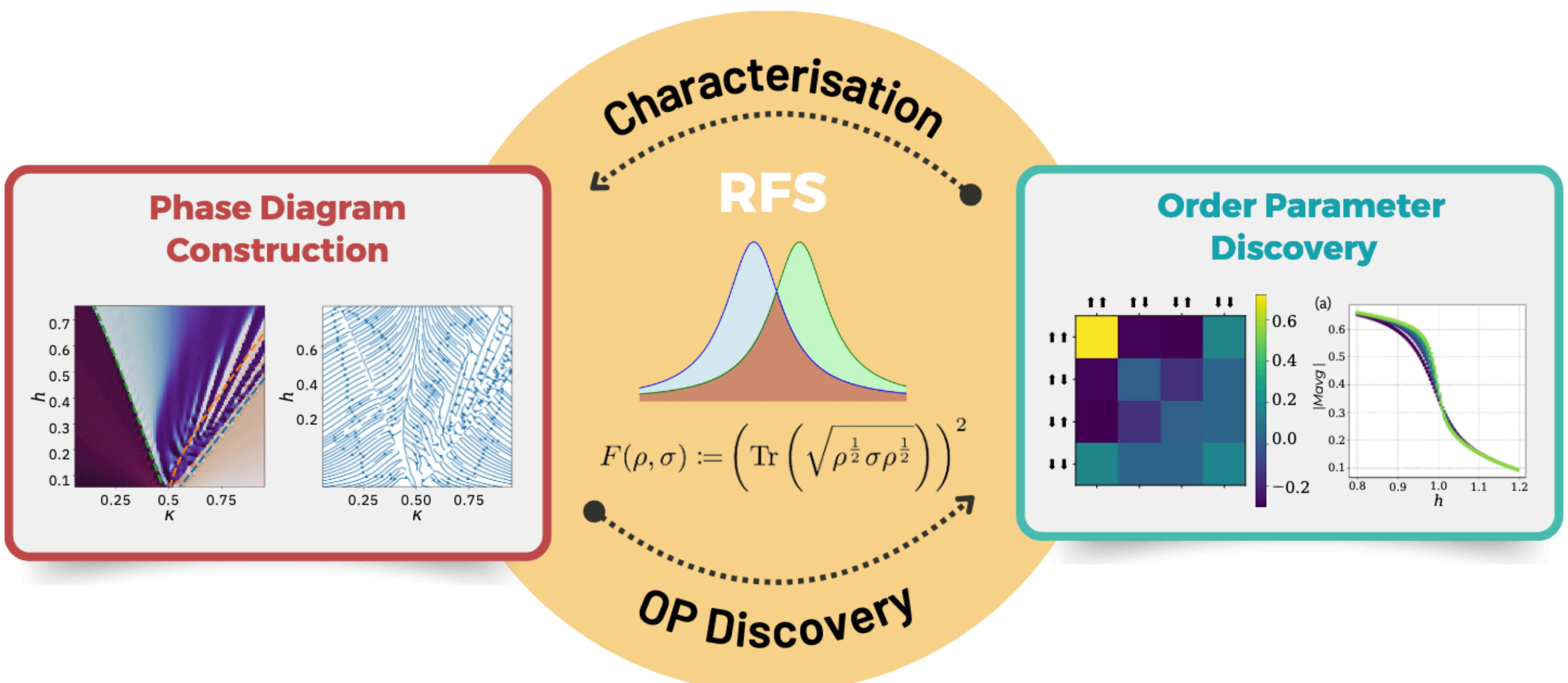

$$F(\rho, \sigma) = \left[\mathrm{Tr}\left(\sqrt{\rho^{1/2} \sigma \rho^{1/2}} \right) \right]^2$$

The tools:

The Uhlmann-Jozsa fidelity for density matrices:

$$F(\rho, \sigma) = \left[\mathrm{Tr} \left(\sqrt{\rho^{1/2} \sigma \rho^{1/2}} \right) \right]^2$$

and let:

$$f(\lambda, v) = \sqrt{F(\rho(\lambda), \rho(\lambda + v))} \rightarrow 1 - \frac{\partial^2}{\partial v^2} f \bigg|_{v=0} \frac{v^2}{2}$$

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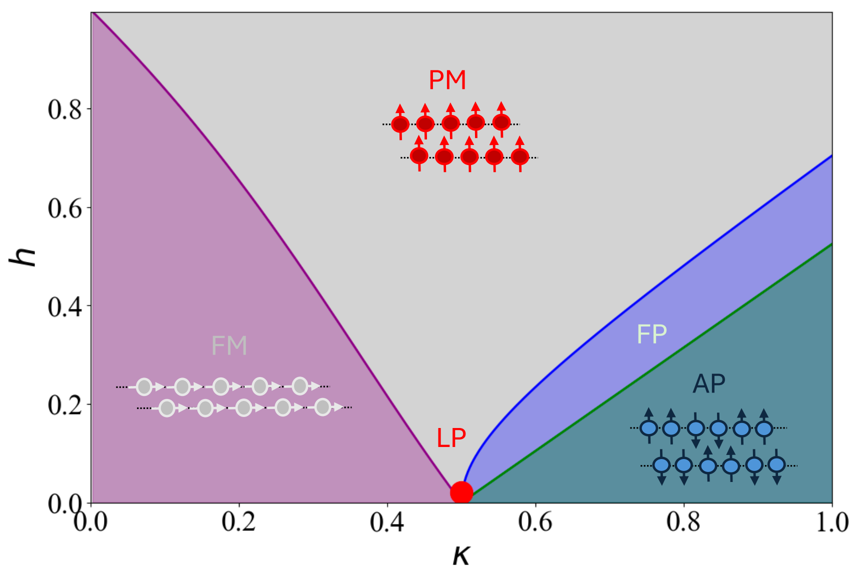
we define:

$$g(\lambda) = -\sum_i \frac{\partial^2}{\partial v_i^2} f\Big|_{v=0}$$

and the gradient field:

$$P_i(\lambda) = \frac{\partial}{\partial \lambda_i} g(\lambda)$$

First results:



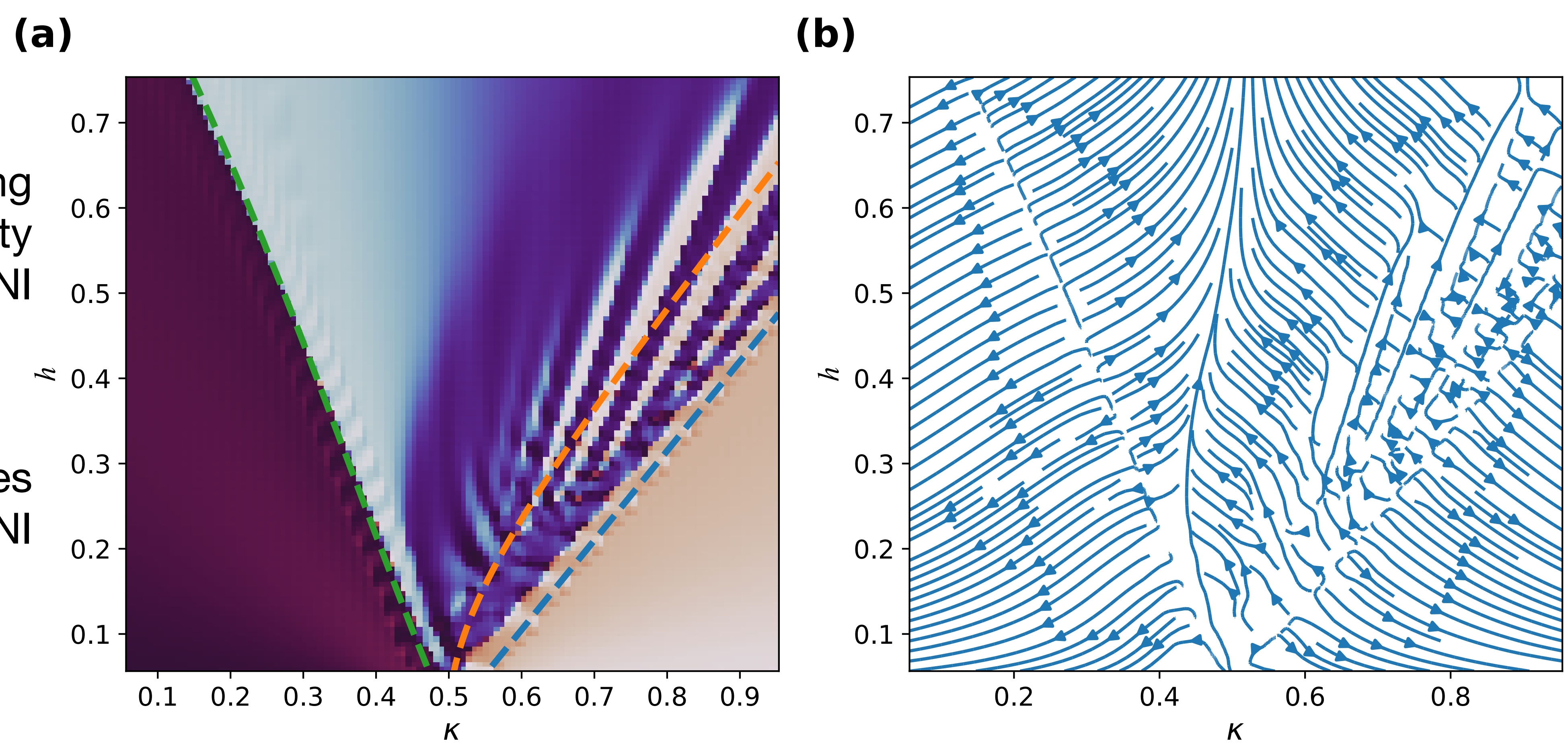
In the reduced fidelity susceptibility vector field:

Sources are phase transitions and

Sinks are representative ground states for the corresponding phase.

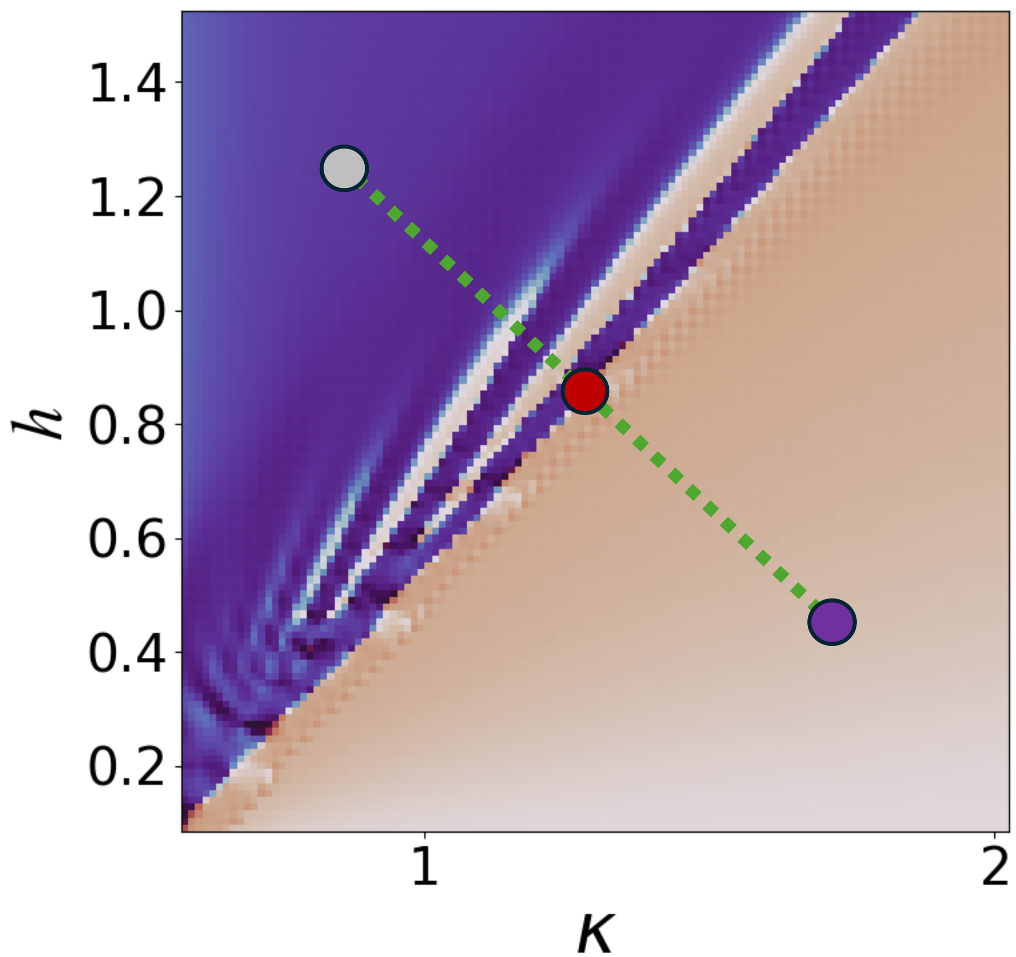
Phase Diagram obtained using the reduced fidelity susceptibility of the one-dimensional ANNNI Model

The plots are given by the angles of the vector field for the ANNNI model with 50 spins (DMRG)



Order parameter discovery:

The order parameter for a given system is not unique; any thermodynamic variable that is zero in the un-ordered phase and non-zero in an adjacent (on the phase diagram), usually ordered phase, is a possible choice for an order parameter.



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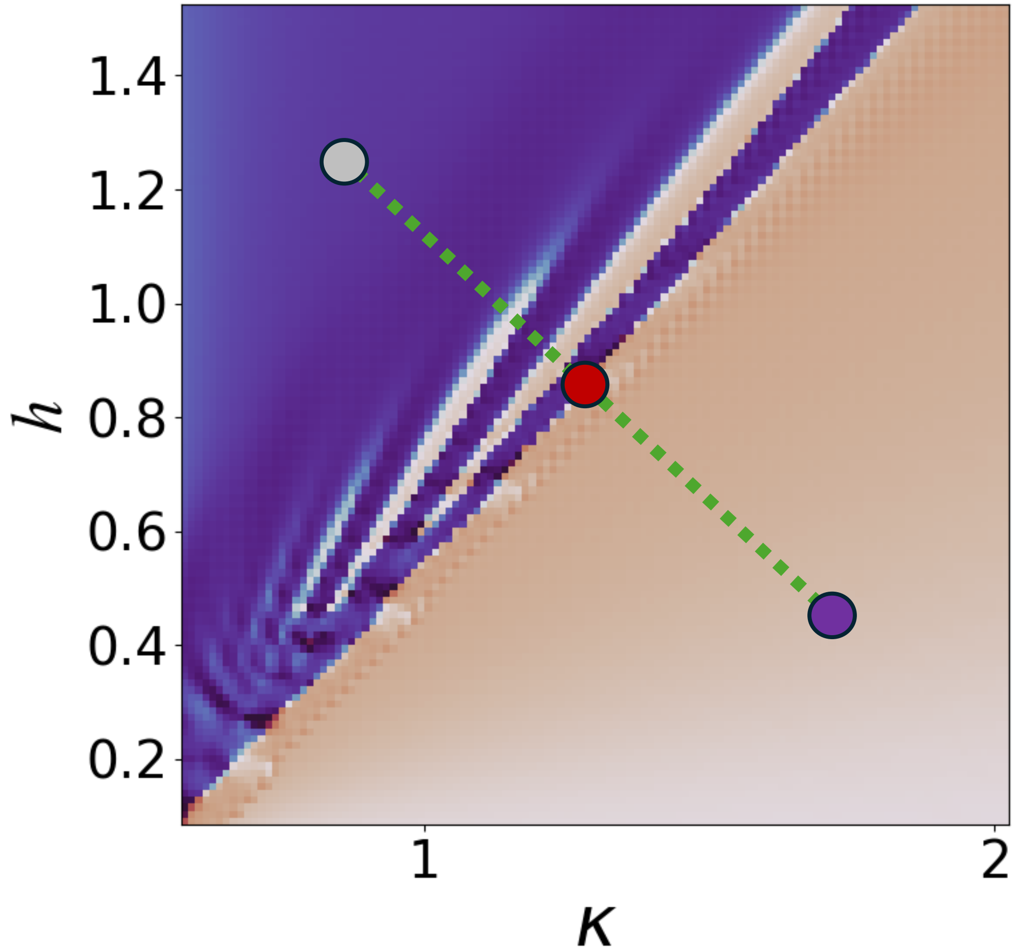

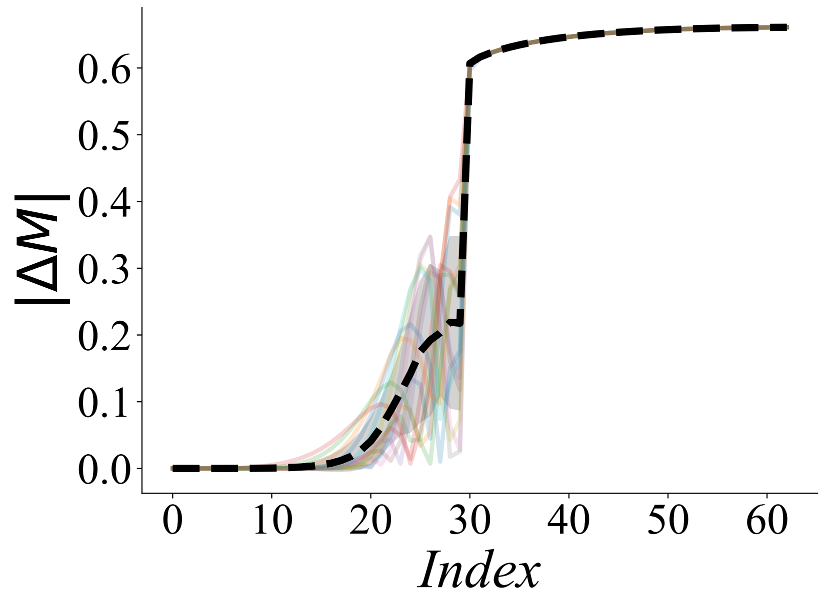

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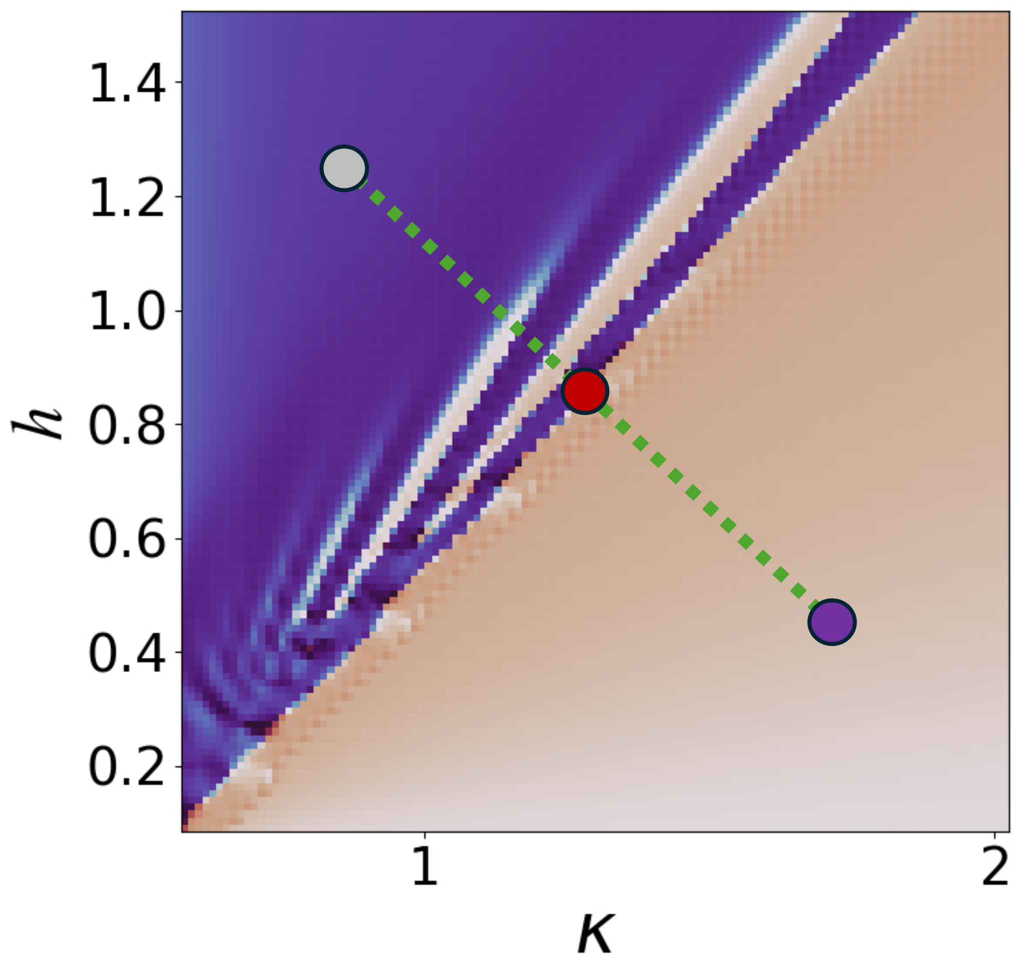

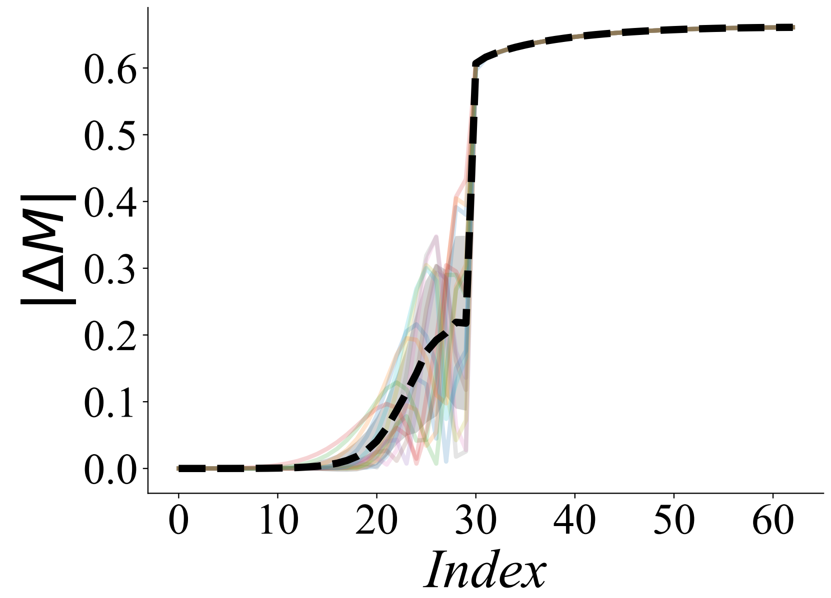

$$\min_{M} -\frac{1}{|I^{+}|}\sum_{i\in I^{+}}\langle M\rangle_i^2 + \frac{\gamma}{|I^{-}|}\sum_{j\in I^{-}}\langle M\rangle_j^2$$

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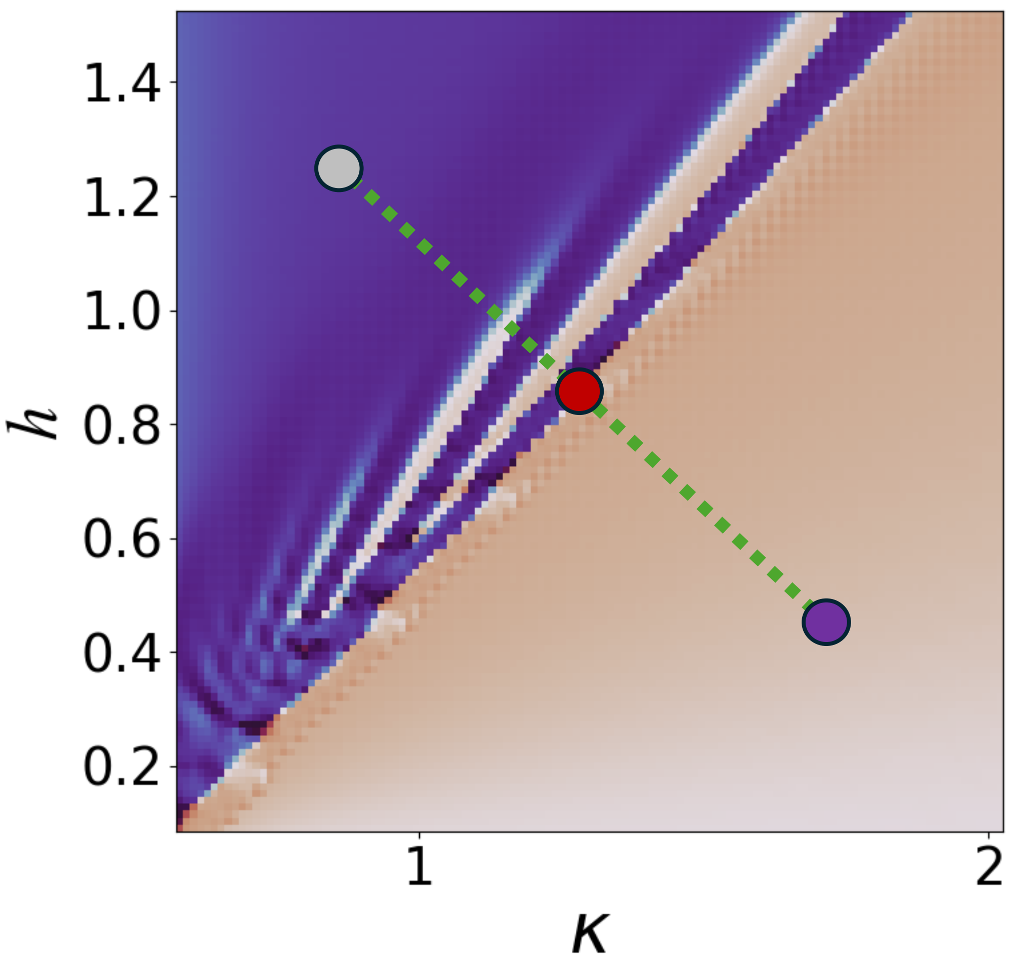
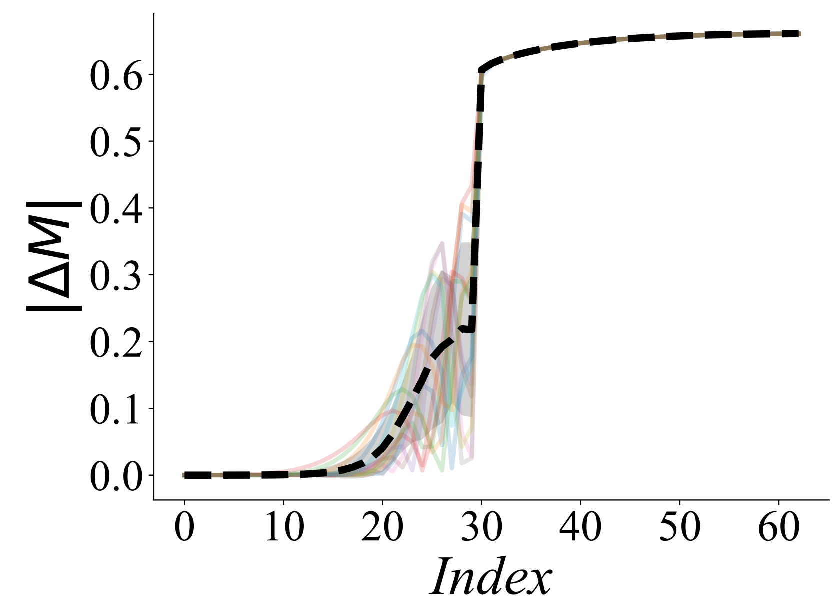




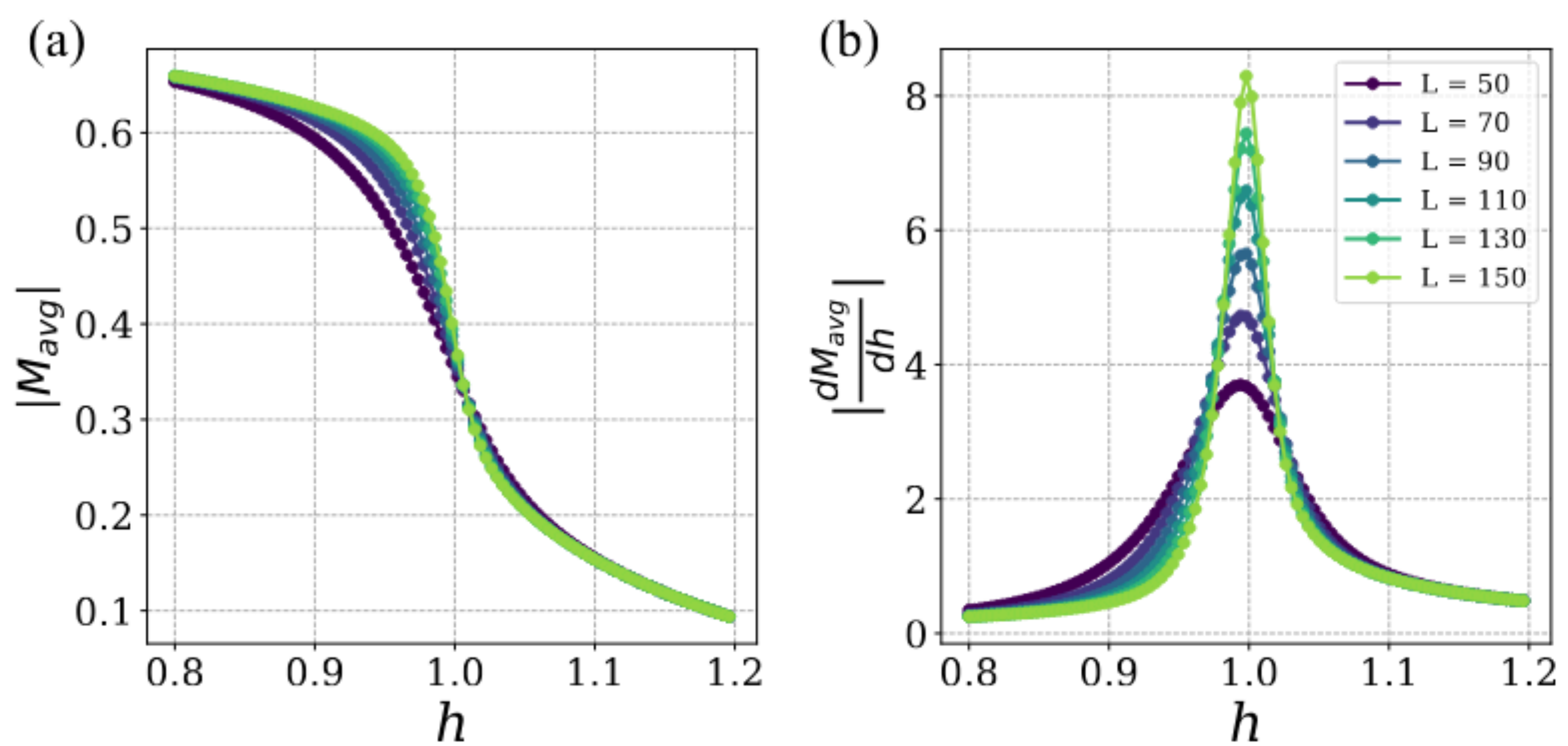
quadratically constrained quadratic program

$$\min_{M} -\frac{1}{|I^+|}\sum_{i\in I^+}\langle M\rangle_i^2 + \frac{\gamma}{|I^-|}\sum_{j\in I^-}\langle M\rangle_j^2$$

$$\Rightarrow \min_{\mathbf{x}\in\mathbb{C}^{m^2}} \mathbf{x}^\dagger A\mathbf{x} \quad |\mathbf{x}|_2^2 \leq 1$$

Order parameter discovery:

The two-site observable obtained using the order parameter discovery framework

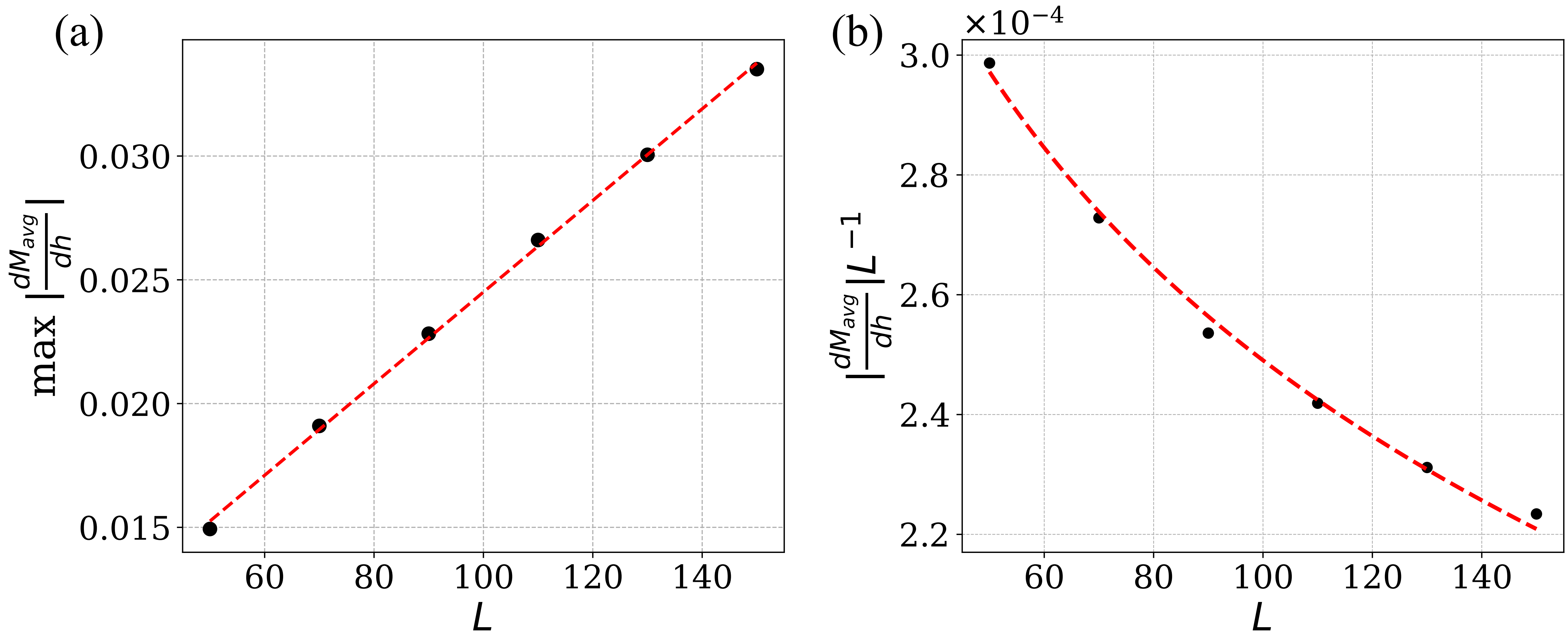


Calculations with O(150) sites

FSS for the ANNNI Model

QUANTUM TECHNOLOGY INITIATIVE
Universidad del País Vasco Euskal Herriko Unibertsitatea
EHU QC EHU Quantum Center
ikerbasque Basque Foundation for Science

Fit critical exponent…



$$\max_h \left\{ \frac{\partial}{\partial h} \langle M \rangle \right\} = aL^{1/\nu} \left(1 + bL^{-\theta/\nu}\right)$$

Summary and outlook

Results: design a mathematical tool

for classifying different phases of matter (classification)

We use the ***reduce density fidelity susceptibility*** for the qualitative classification of the different phases

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Results: design a mathematical tool

for classifying different phases of matter (classification)

We use the ***reduce density fidelity susceptibility*** for the <u>qualitative</u> classification of the different phases

for detecting the phase transitions (anomaly detection)

We define method for ***order parameter discovery*** which allows to have a <u>quantitative</u> description of the critical point

The team:

IBM Quantum

BasQ
Basque Quantum

CERN | QUANTUM TECHNOLOGY INITIATIVE

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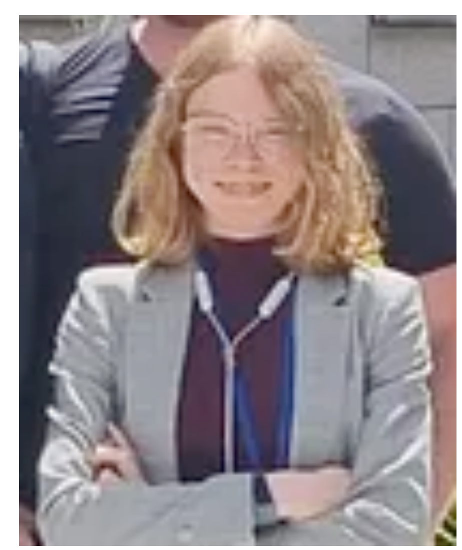
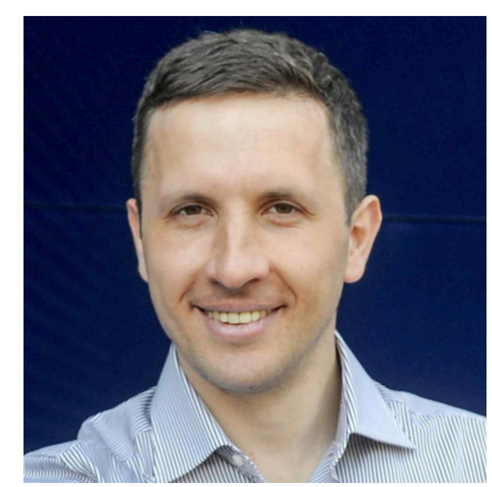
Sofia Vallecorsa.- Permanent researcher at CERN

Nicola Mariella, Tara Murphy, Sergiy Zhuk.- Researchers at IBM Dublin



Constructing the spin-1 Haldane phase on a qudit quantum processor

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arXiv > quant-ph > arXiv:2408.04702

Order Parameter Discovery for Quantum Many-Body Systems

Nicola Mariella+,[1,*] Tara Murphy+,[1,2,†] Francesco Di Marcantonio,[3,‡] Khadijeh Najafi,[4,§] Sofia Vallecorsa,[5,¶] Sergiy Zhuk,[1,**] and Enrique Rico[3,6,7,††]

arXiv > quant-ph > arXiv:2408.01400