

Locality and Quantum Spin Liquids from Global Cavity Interactions

Mark Oehlgrien

ICFO - The Institute of Photonic Sciences



Co-funded by
the European Union



UNIVERSITAT POLITÈCNICA
DE CATALUNYA
BARCELONATECH

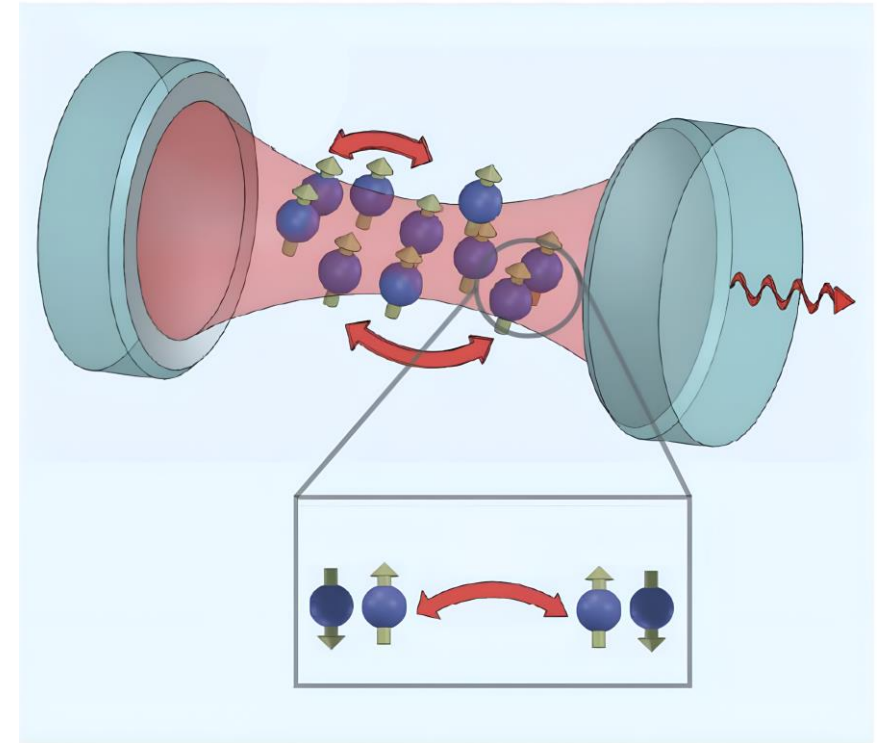
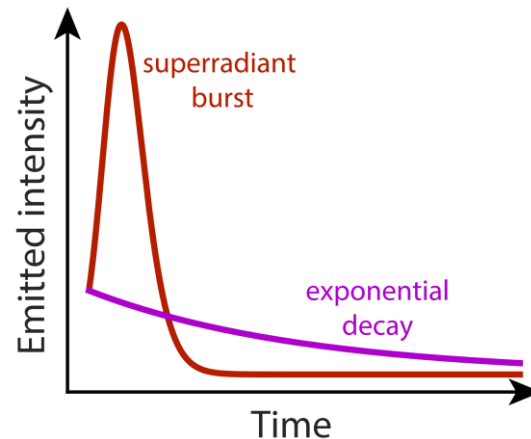
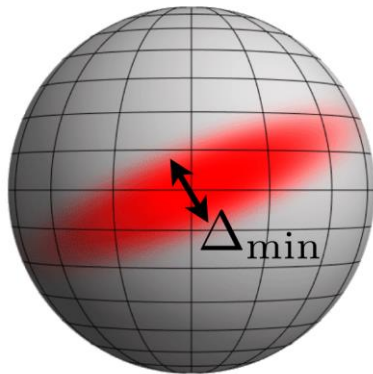
Quantum optics struggles to realize many-body physics

- cavity mediates all-to-all

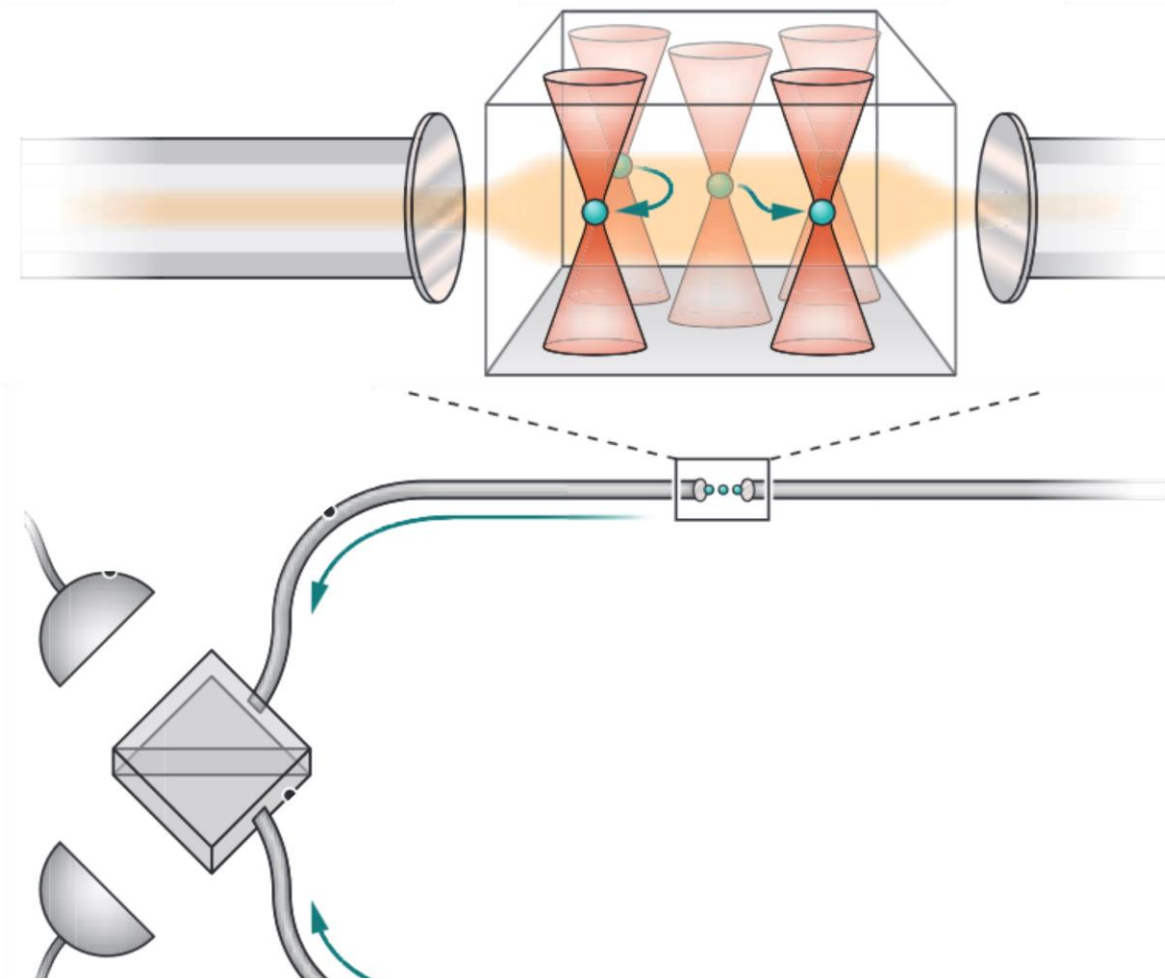
$$\sum_{i,j} S_i^+ S_j^- \rightarrow \mathbf{S}^2 - (S_z)^2$$

$$\rightarrow (S_x)^2$$

- large spin physics is semi-classical



New Rydberg tweezer-cavity platform combines long-range and short-range interactions



- $H = V_{\text{all-to-all}} + \sum_{i < j} J_{ij} S_i^z S_j^z$
(Cavity) (Rydberg)

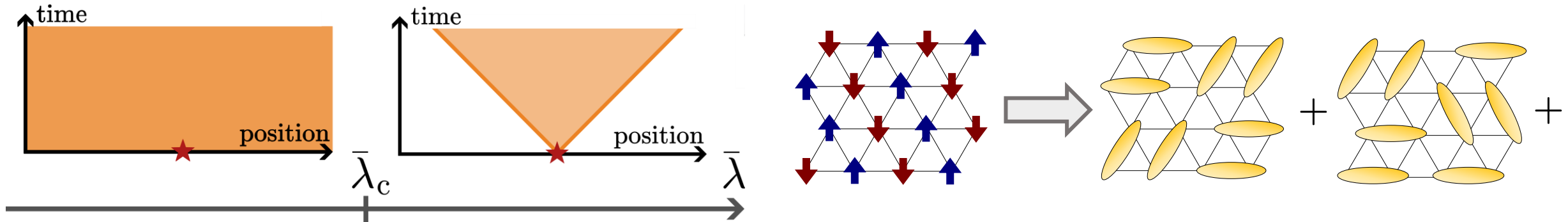
Choi (Q-Block), Stamper-Kurn (Berkeley), Vuletic/Lukin (MIT/Harvard), Zeiher (MPQ), Nägerl (Innsbruck), Leonard (TU Vienna), Schine (Maryland), Zhang (Shanxi), Rempe (MPQ), Köhl (Bonn), ...

- Experimental motivation: information processing

Many-body complexity in quantum optics

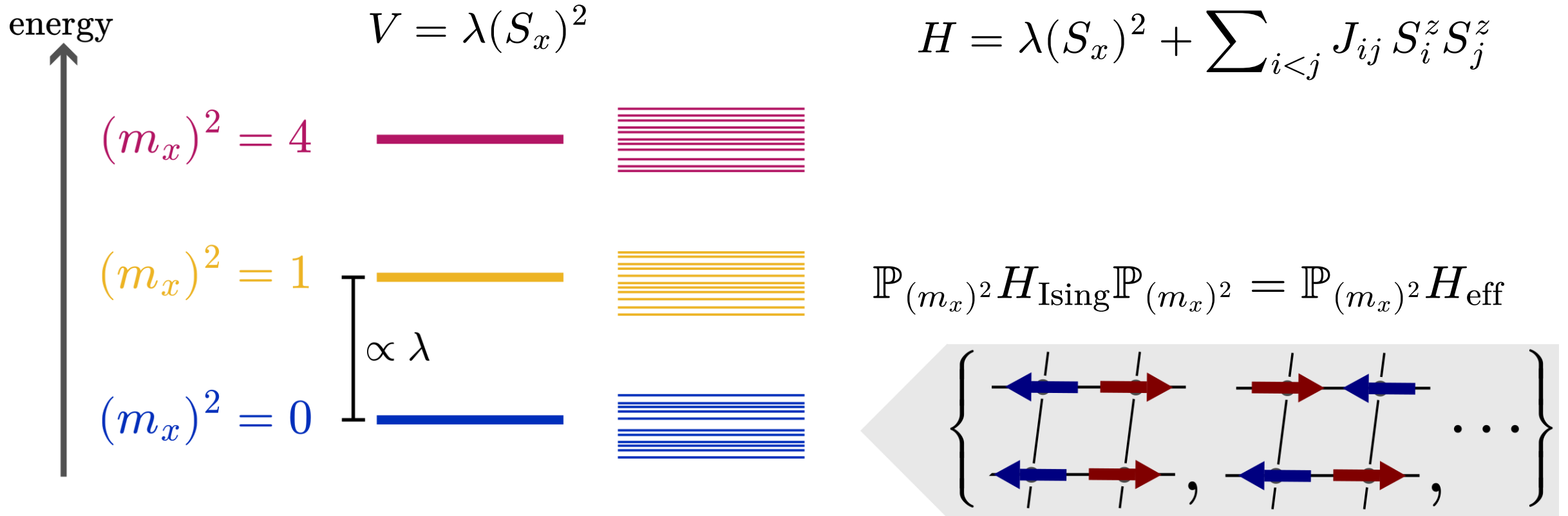
$$H = V_{\text{all-to-all}} + \sum_{i < j} J_{ij} S_i^z S_j^z$$

- the stronger $V_{\text{all-to-all}}$, the faster the dynamics the more mean-field ?



- $V_{\text{all-to-all}} \Rightarrow$ global constraint \Rightarrow complex phenomena

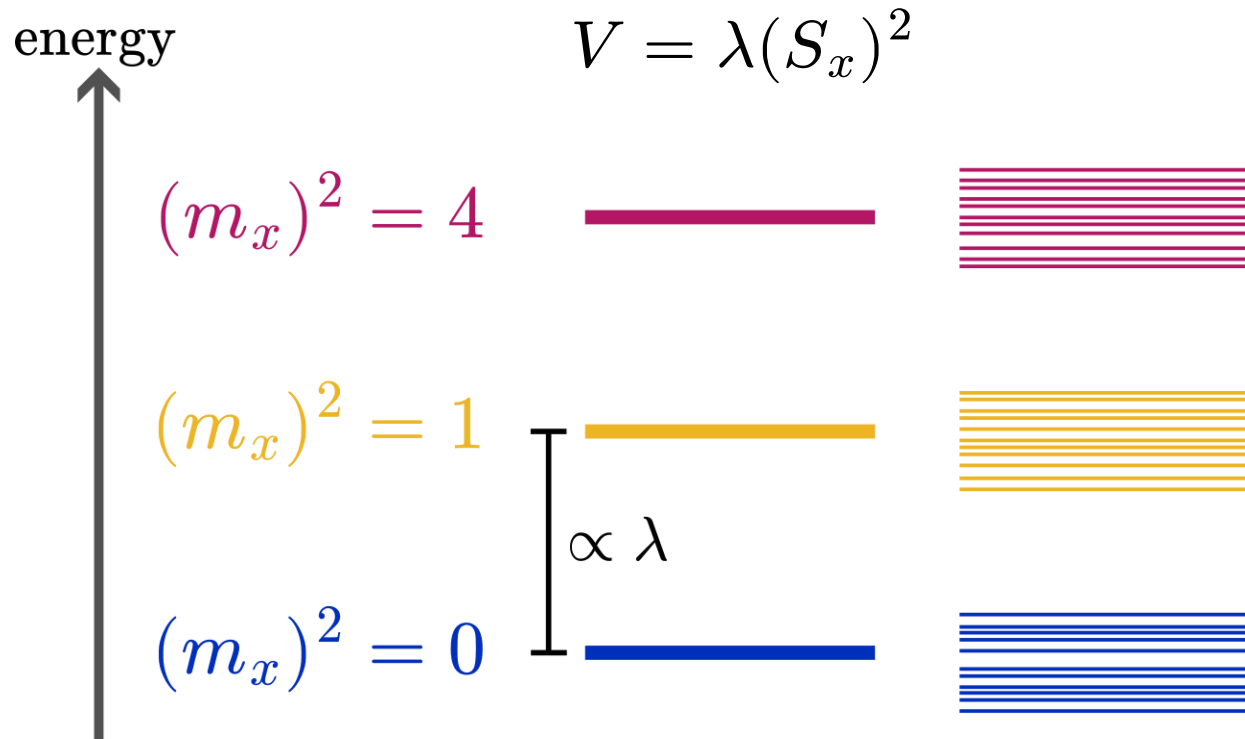
Projection into a product state subspaces is trivial



- local operator couples product states that differ locally

$$S_i^z S_j^z (\cdots \otimes |\leftarrow\rangle_i \otimes |\rightarrow\rangle_j \otimes \cdots) = (\cdots \otimes S_i^z |\leftarrow\rangle_i \otimes S_j^z |\rightarrow\rangle_j \otimes \cdots)$$

Projection into a product state subspaces is trivial



$$H = \lambda(S_x)^2 + \sum_{i < j} J_{ij} S_i^z S_j^z$$

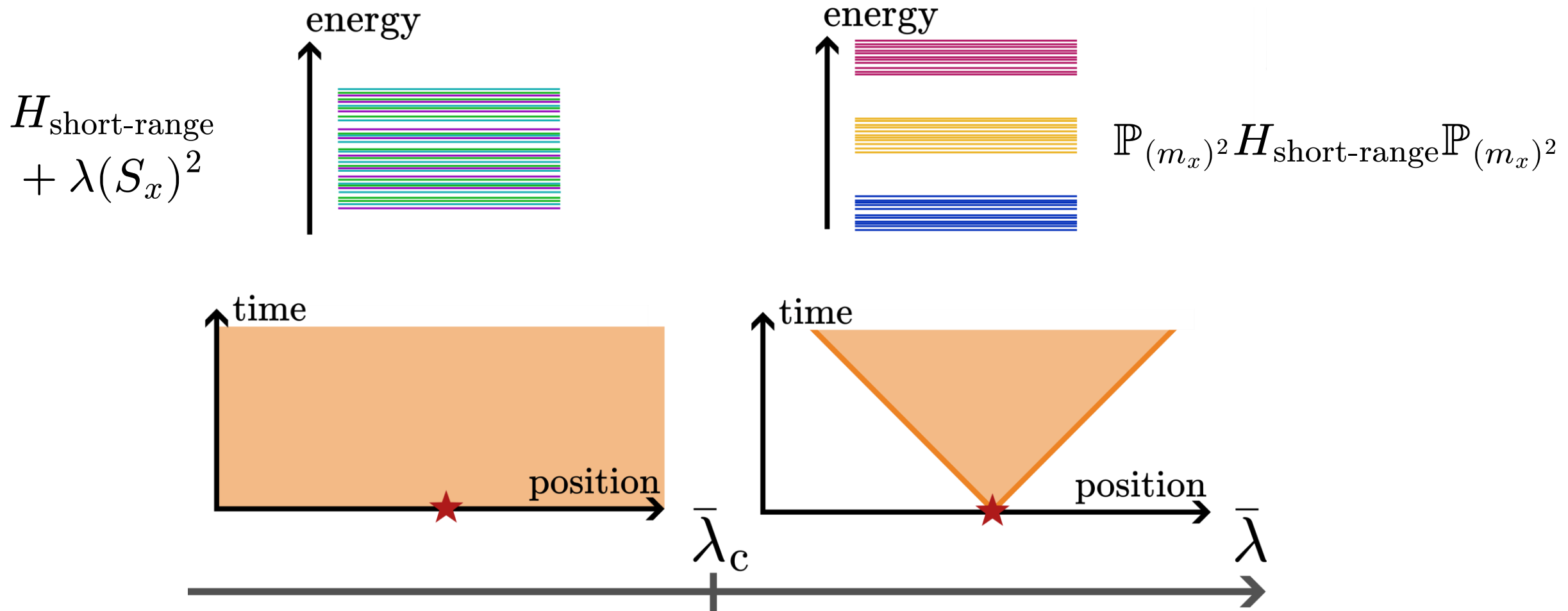
Intuition:

$$\mathbb{P}_{(m_x)^2} H_{\text{short-range}}^{(\text{eff})}$$

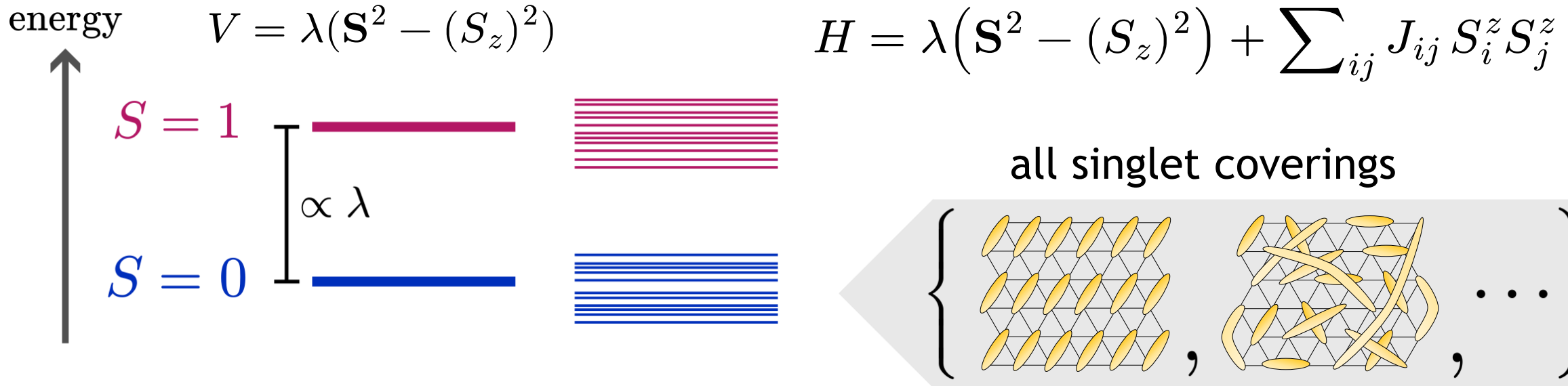
- local operator couples product states that differ locally

$$S_i^z S_j^z (\cdots \otimes |\leftarrow\rangle_i \otimes |\rightarrow\rangle_j \otimes \cdots) = (\cdots \otimes S_i^z |\leftarrow\rangle_i \otimes S_j^z |\rightarrow\rangle_j \otimes \cdots)$$

Strong all-to-all interaction introduces local quantum fluctuations



Projection into entangled subspace is hard



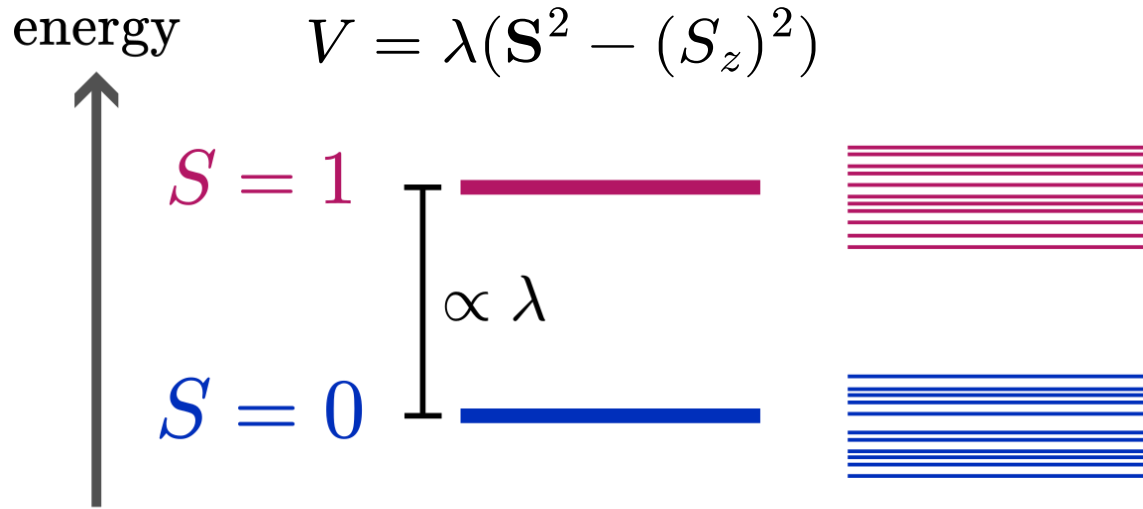
- total spin subspace is entangled

Highly Entangled Stationary States from Strong Symmetries; Li et al., PRX **15**, 011068 (2025)

- spin addition is not additive

$$S_i^z \quad S_j^z = \text{two pink ovals} = |S=0\rangle + |S=2\rangle$$

Projection into entangled subspace is hard



$$H = \lambda(\mathbf{S}^2 - (S_z)^2) + \sum_{ij} J_{ij} S_i^z S_j^z$$

Intuition:

$$\mathbb{P}_{(S, m_z)} H_{\text{long-range}}^{(\text{eff})}$$

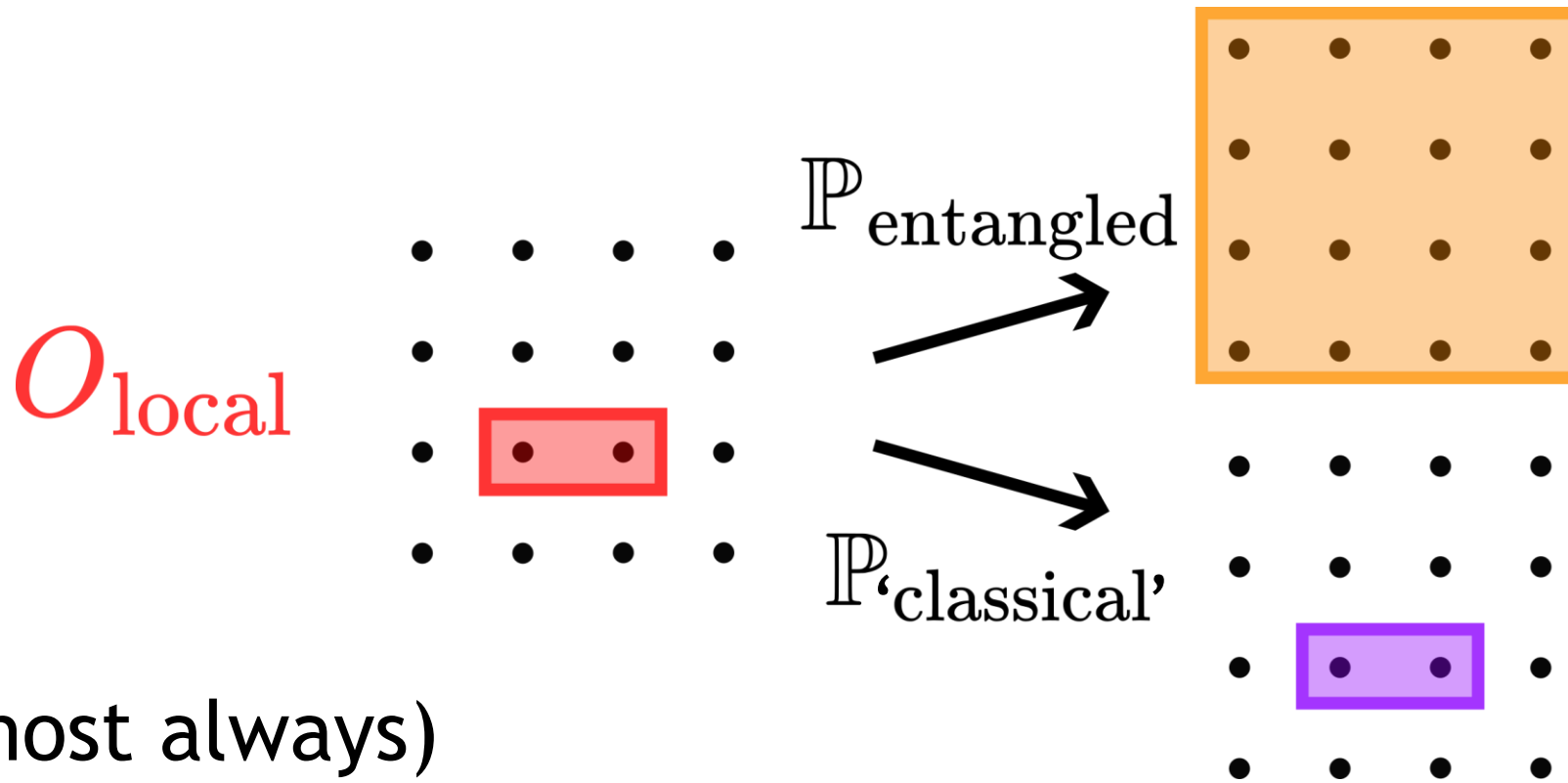
- total spin subspace is entangled

Highly Entangled Stationary States from Strong Symmetries; Li et al., PRX **15**, 011068 (2025)

- spin addition is not additive

$$S_i^z \quad S_j^z = |S = 0\rangle + |S = 2\rangle$$

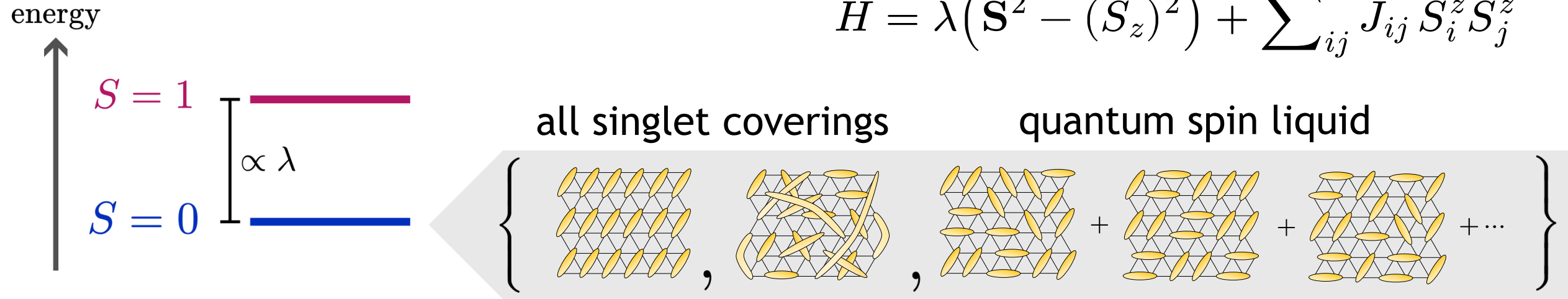
Locality of effective Hamiltonian depends on entanglement of the subspace



- (almost always)

The singlet subspace is exceptional

$$H = \lambda(\mathbf{S}^2 - (S_z)^2) + \sum_{ij} J_{ij} S_i^z S_j^z$$



- singlet states are invariant under rotation

$$R(\Omega)|S = 0\rangle = |S = 0\rangle, \quad R(\Omega) = e^{-i\alpha S_x} e^{-i\beta S_y} e^{-i\gamma S_z}$$

- Ising model becomes symmetrized: Heisenberg model

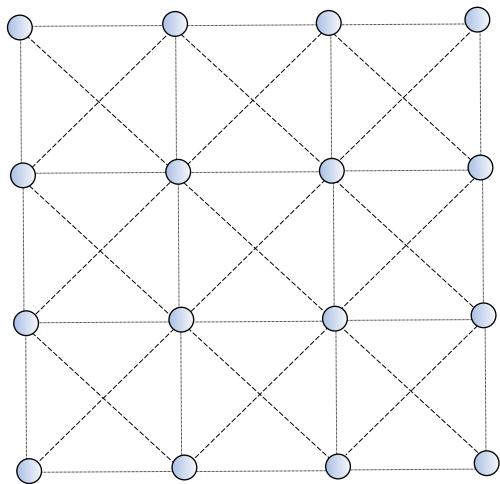
$$\mathbb{P}_{(S=0)} H_{\text{Ising}} \mathbb{P}_{(S=0)} = \frac{1}{3} \mathbb{P}_{(S=0)} H_{\text{Heisenberg}}$$

Cavity-Rydberg model should host QSL ground state if the Heisenberg model does

- Heisenberg J_1 - J_2 model:
$$H_{\text{Heis}} = J_1 \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j + J_2 \sum_{\langle\langle i,j \rangle\rangle} \mathbf{S}_i \cdot \mathbf{S}_j$$

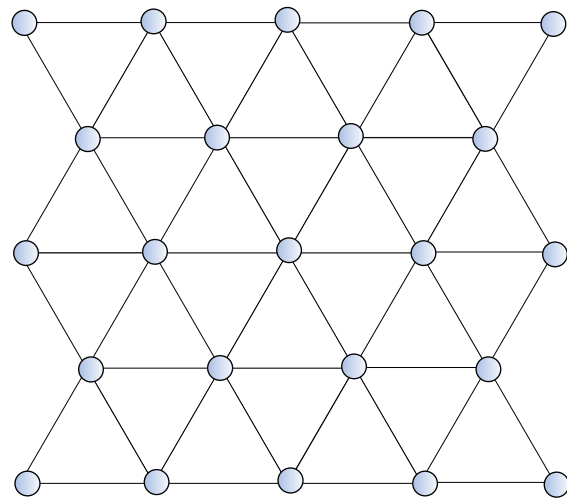
Square

$$J_2/J_1 \sim 0.45 - 0.55$$



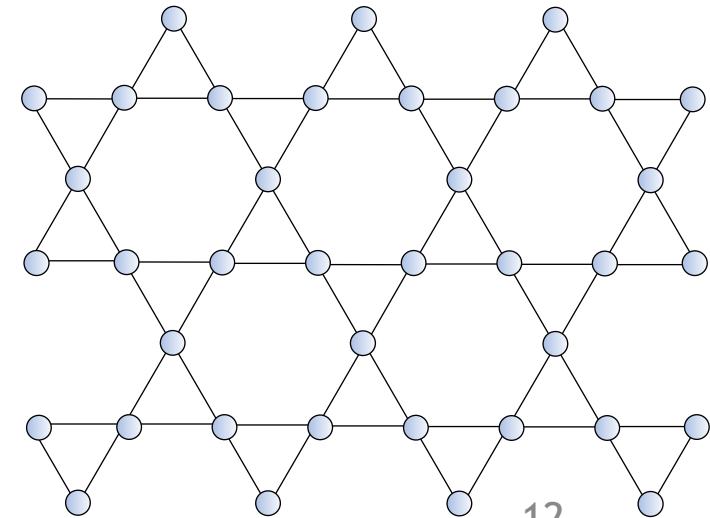
Triangular

$$J_2/J_1 \sim 0.05 - 0.15$$



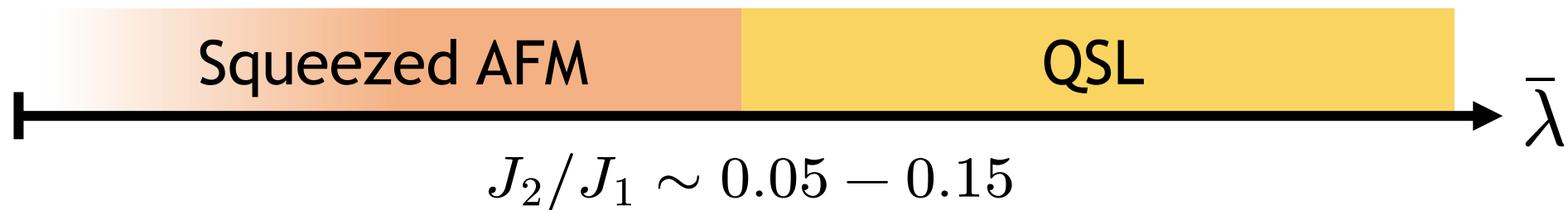
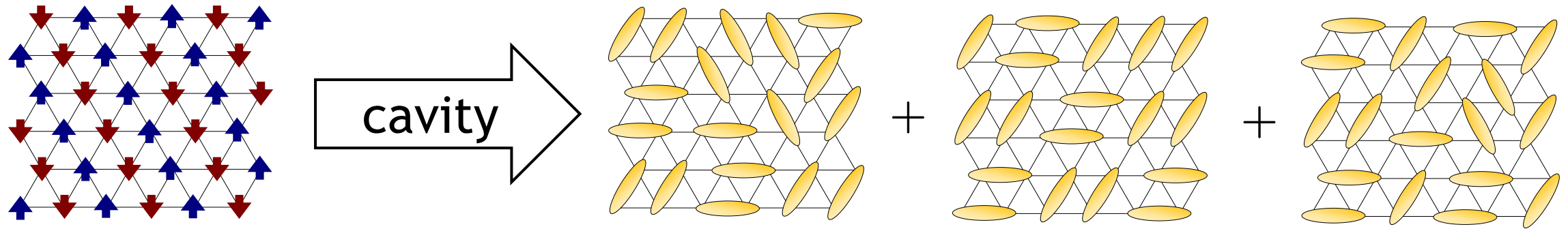
Kagome

$$J_2/J_1 \sim 0.0 - 0.2$$



Global cavity fluctuations can melt classical Ising magnets into Heisenberg QSL

$$H = \lambda \left(\mathbf{S}^2 - (S_z)^2 \right) + J_1 \sum_{\langle i,j \rangle} S_i^z S_j^z + J_2 \sum_{\langle\langle i,j \rangle\rangle} S_i^z S_j^z$$



Quantum optics can realize many-body physics

- strong all-to-all interactions
 - ⇒ subspace locality
 - ⇒ quantum spin liquids
- pathway to many-body regime beyond short-range models

arxiv: 2512.05630

Squeezing Classical Antiferromagnets into Quantum Spin Liquids via Global Cavity Fluctuations

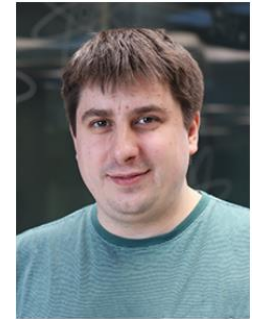
ICFO^R



Darrick
Chang



Charlie-Ray
Mann



Błażej
Jaworowski

INFN-
Padova



Giuseppe
Calajò

SUNY
Buffalo



Jamir
Marino

Q-Block
Computing



Kyung
Choi

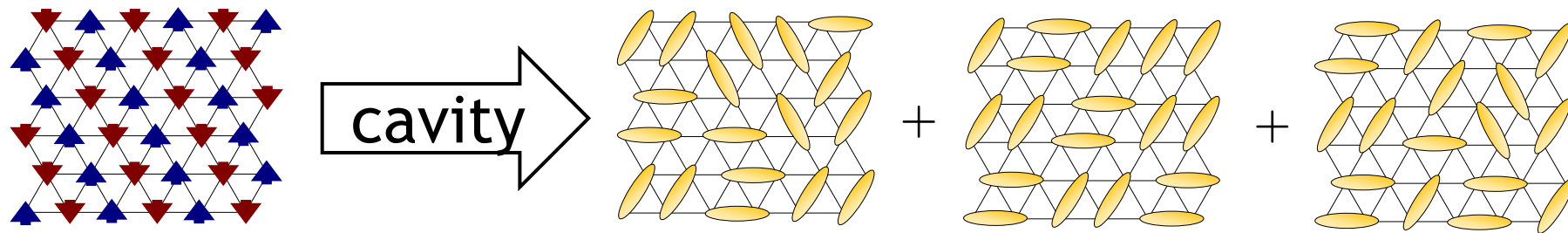
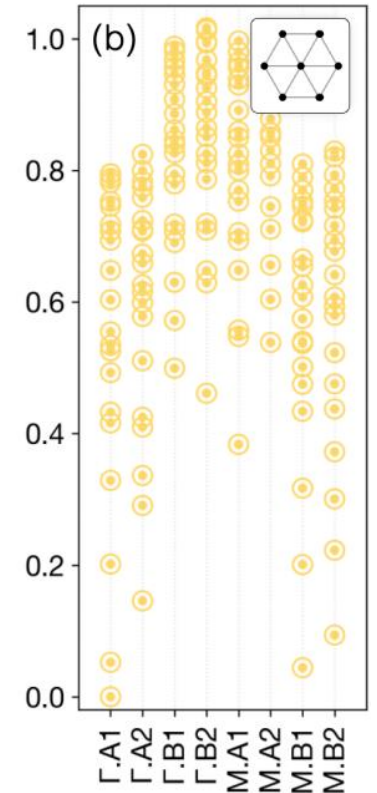
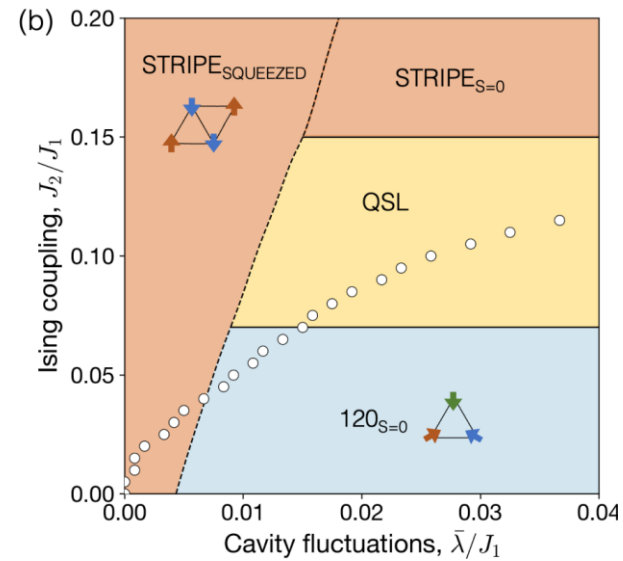
Appendix

Quantum Spin Liquids from all-to-all interactions

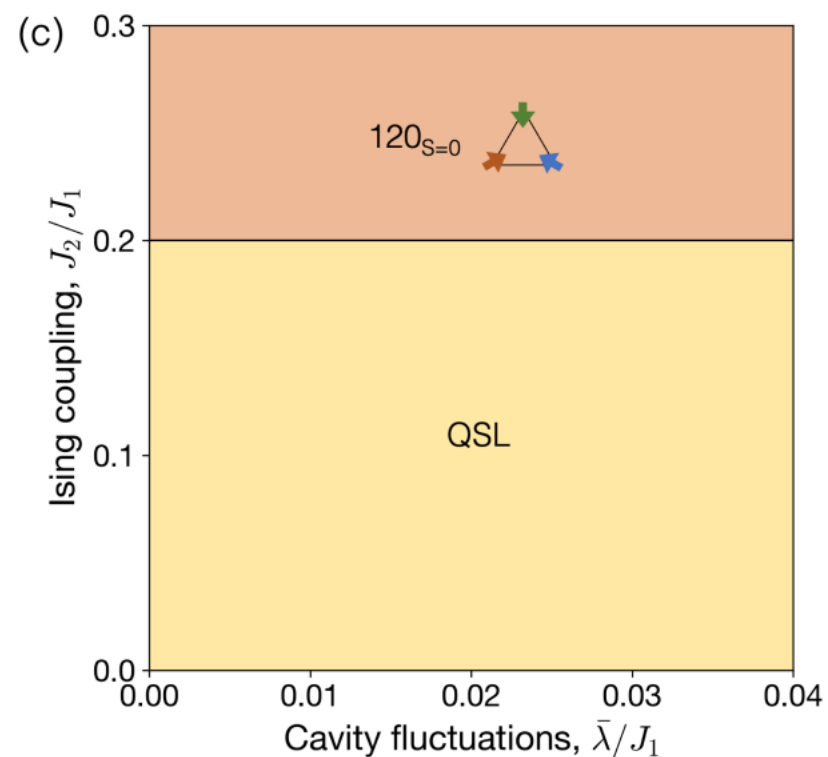
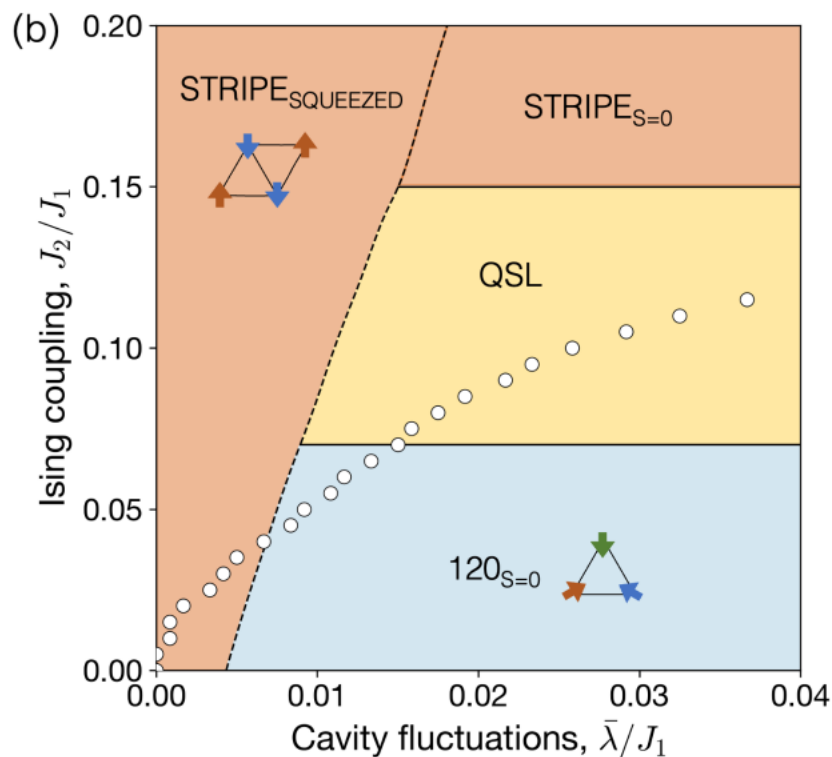
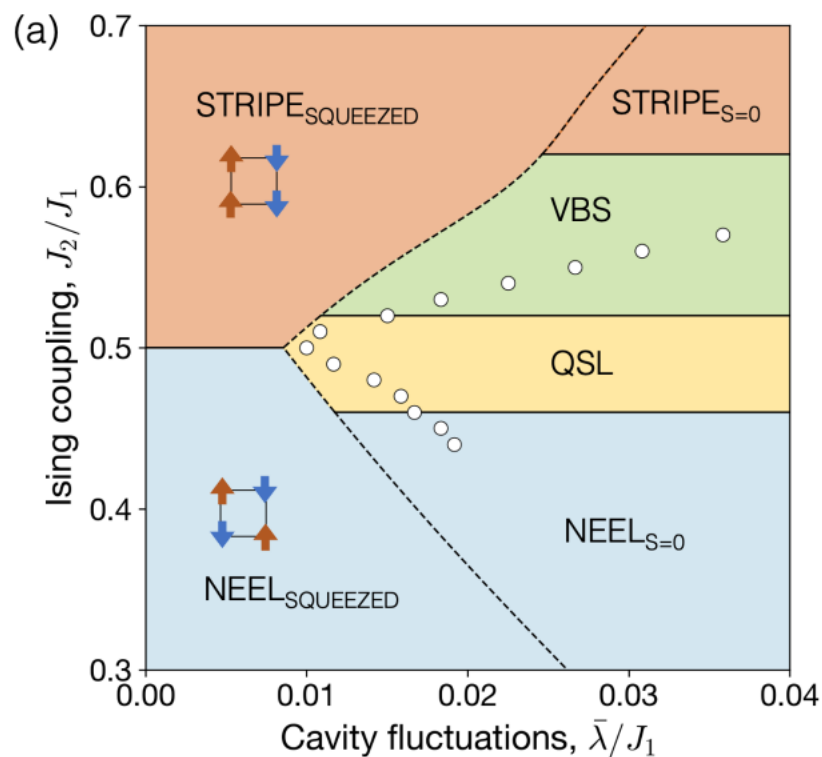
Squeezing Classical Antiferromagnets into Quantum Spin Liquids via Global Cavity Fluctuations; Mann, MO, et al., arXiv:2512.05630 (2025)

Heisenberg correspondence in singlet subspace

$$\mathbb{P}_{(0,0)} H_{\text{Ising}} \mathbb{P}_{(0,0)} = \frac{1}{3} \mathbb{P}_{(0,0)} H_{\text{Heis}}$$



Ground state (variational) phase diagram



$$H = \lambda \left(\mathbf{S}^2 - (S_z)^2 \right) + J_1 \sum_{\langle i,j \rangle} S_i^z S_j^z + J_2 \sum_{\langle\langle i,j \rangle\rangle} S_i^z S_j^z$$