# Probing topological spin liquids in Rydberg atom arrays

Theoretical Condensed Matter Physics Principal Investigators' Meeting
Office of Basic Energy Sciences, U.S. Department of Energy
October 28, 2021

Subir Sachdev

Talk online: sachdev.physics.harvard.edu

INSTITUTE FOR ADVANCED STUDY

PHYSICS HARVARD

# Probing topological spin liquids in Rydberg atom arrays

(Distinct from the ten-fold "*band topology*" classification of "*topological insulators*" and "*topological superconductors*")

Theoretical Condensed Matter Physics Principal Investigators' Meeting
Office of Basic Energy Sciences, U.S. Department of Energy
October 28, 2021

Subir Sachdev

PHYSICS
VE RI TAS
HARVARD

Talk online: sachdev.physics.harvard.edu

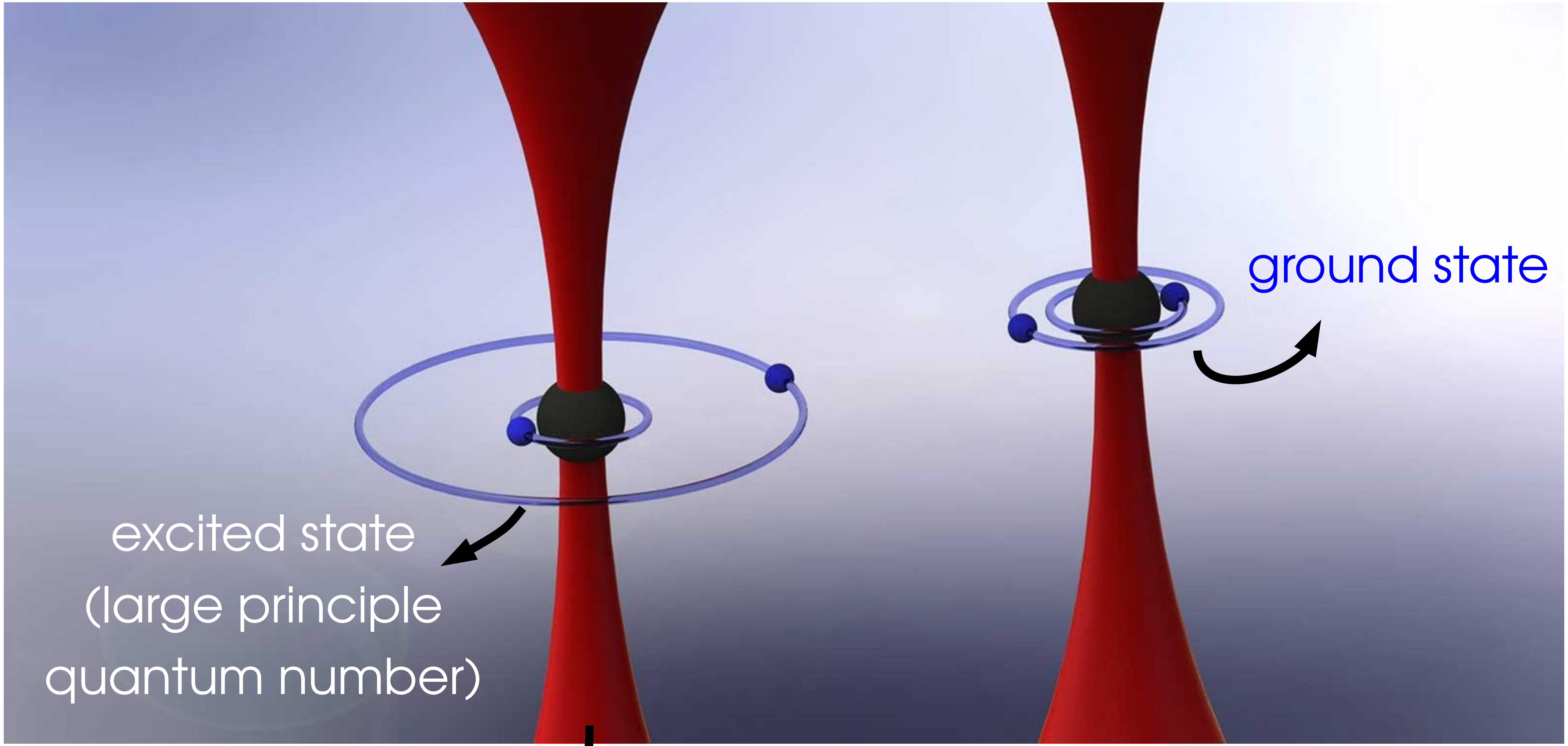
Rhine Samajdar

Seth Whitsitt


Wen Wei Ho

Hannes Pichler

Mikhail Lukin



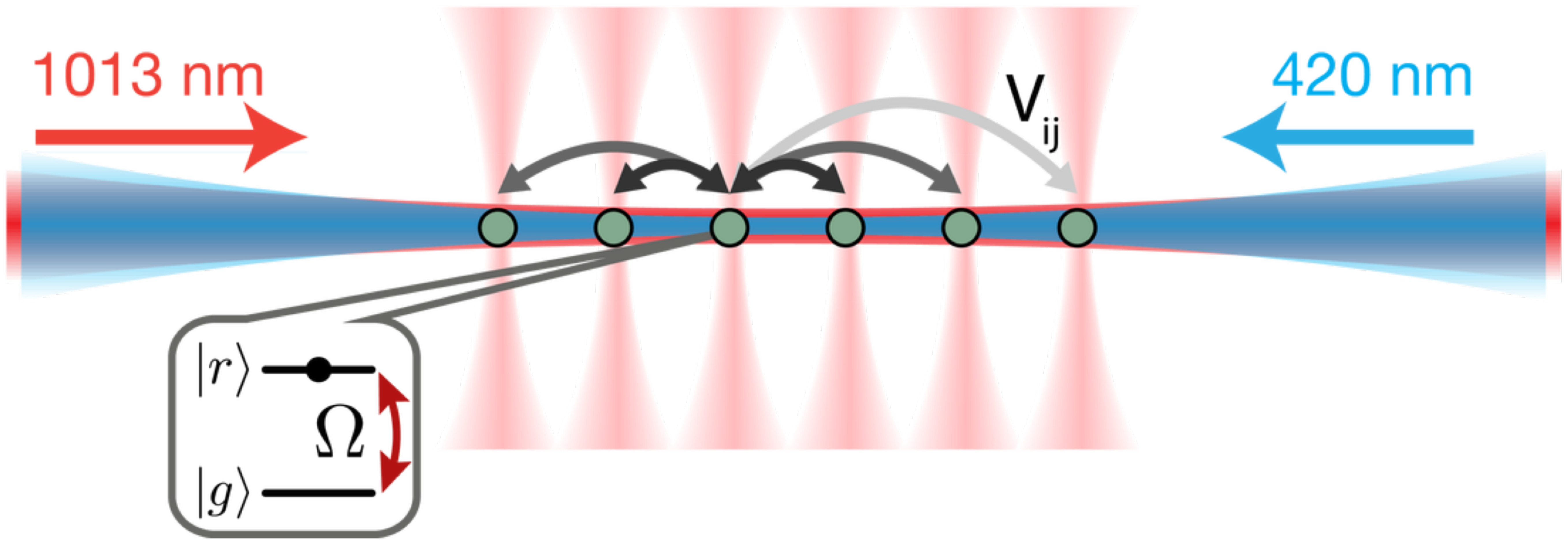

$$V_{|\ell-\ell'|} \sim \frac{1}{|\ell-\ell'|^6}$$

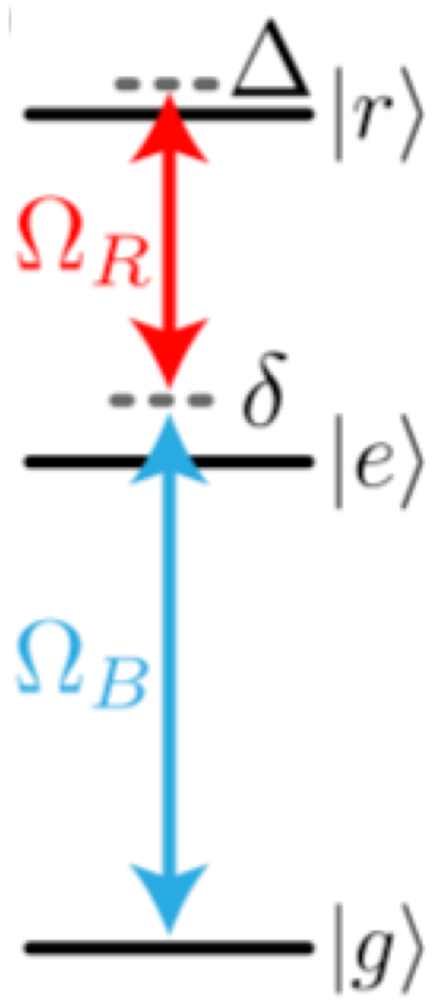
optical tweezer (traps atom)

Fig: https://www.caltech.edu/about/news/quantum-innovations-achieved-using-alkaline-earth-atoms

$$H_{\mathrm{Ryd}} = \sum_{\ell}\left[\frac{\Omega}{2}\left(|g\rangle\langle r| + |r\rangle\langle g|\right)_{\ell} - \Delta |r\rangle\langle r|\right] + \sum_{(\ell,\ell')} V_{|\ell-\ell'|}\Big(|r\rangle\langle r|_{\ell} \otimes |r\rangle\langle r|_{\ell'}\Big)$$

# QPTs in a Rydberg quantum simulator




$$|g\rangle \equiv |0\rangle$$

$$|r\rangle \equiv b^\dagger |0\rangle$$

$$\mathcal{H} = \sum_\ell \left[ \frac{\Omega}{2} \left( b_\ell + b_\ell^\dagger \right) - \Delta n_\ell \right] + \sum_{\ell < \ell'} V_{|\ell - \ell'|} n_\ell n_{\ell'}$$

$$V_{|\ell - \ell'|} \sim \frac{1}{|\ell - \ell'|^6}$$

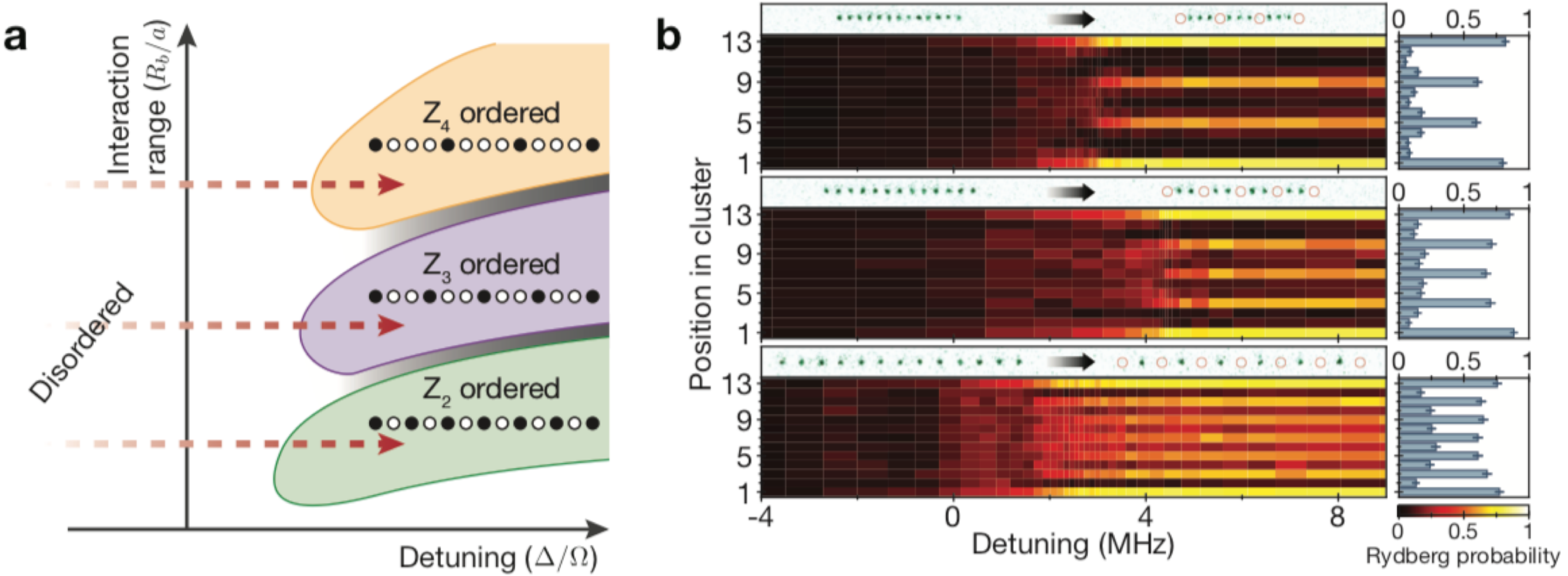
$$n_\ell \equiv b_\ell^\dagger b_\ell$$

$n_\ell = 0, 1$ 'hard core' bosons

FSS model

S. Sachdev, K. Sengupta, and S.M. Girvin, PRB **66**, 075128 (2002)
P. Fendley, K. Sengupta, S. Sachdev, PRB **69**, 075106 (2004)

# Density wave order and quantum phase transitions in one dimension




$$\mathcal{H} = \sum_{\ell} \left[ \frac{\Omega}{2} \left( b_\ell + b_\ell^\dagger \right) - \Delta n_\ell \right] + \sum_{\ell < \ell'} V_{|\ell - \ell'|} n_\ell n_{\ell'}$$

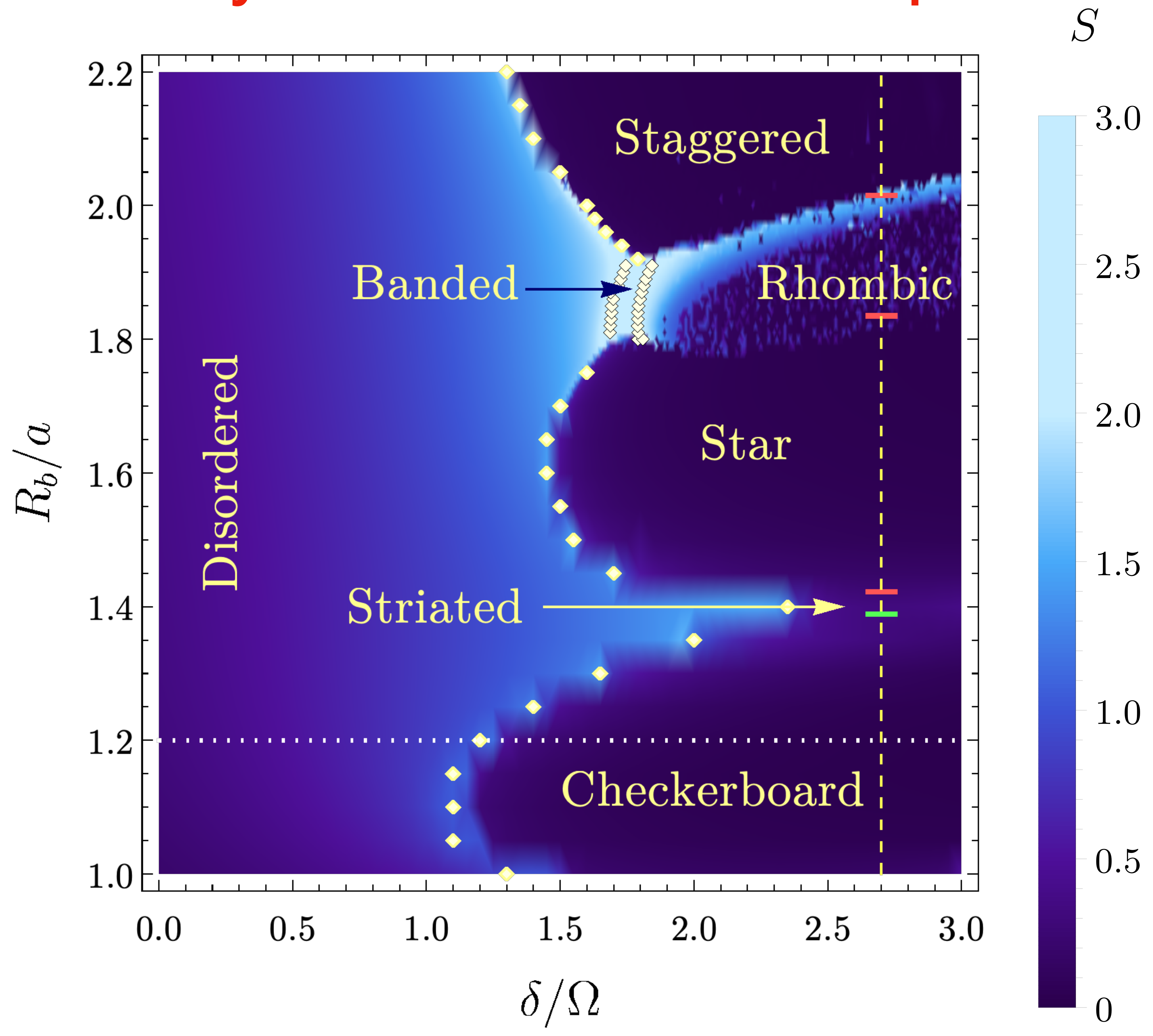
$$n_\ell \equiv b_\ell^\dagger b_\ell$$

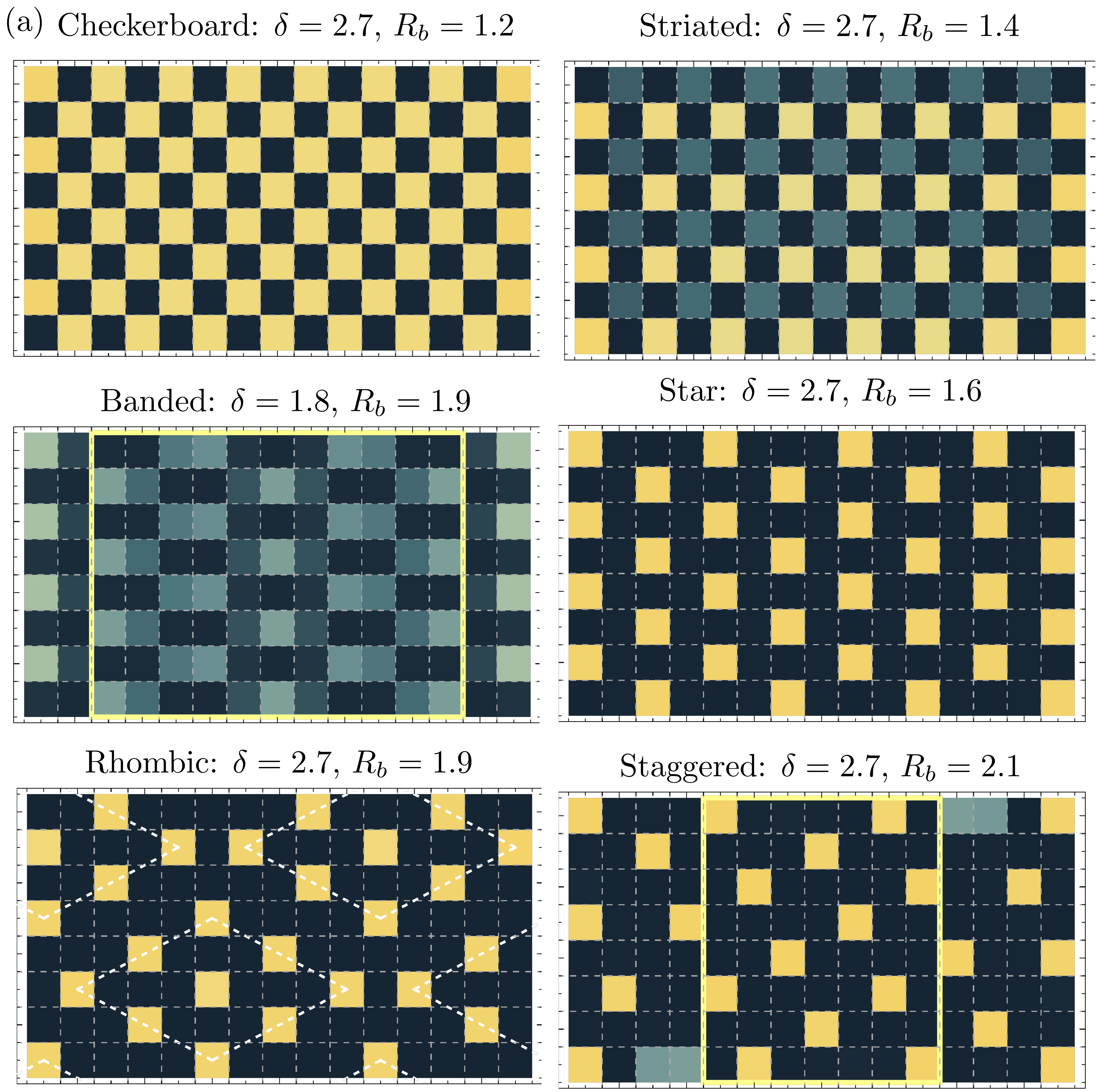
$n_\ell = 0, 1$ ‘hard core’ bosons

FSS model

Bernien et. al., Nature **551**, 579 (2017)
Keesling et. al. Nature **568**, 207 (2019)

# Density wave order and quantum phase transitions on the square lattice




$$\mathcal{H} = \sum_{\ell} \left[ \frac{\Omega}{2} \left( b_\ell + b_\ell^\dagger \right) - \Delta n_\ell \right] + \sum_{\ell < \ell'} V_{|\ell - \ell'|} n_\ell n_{\ell'}$$

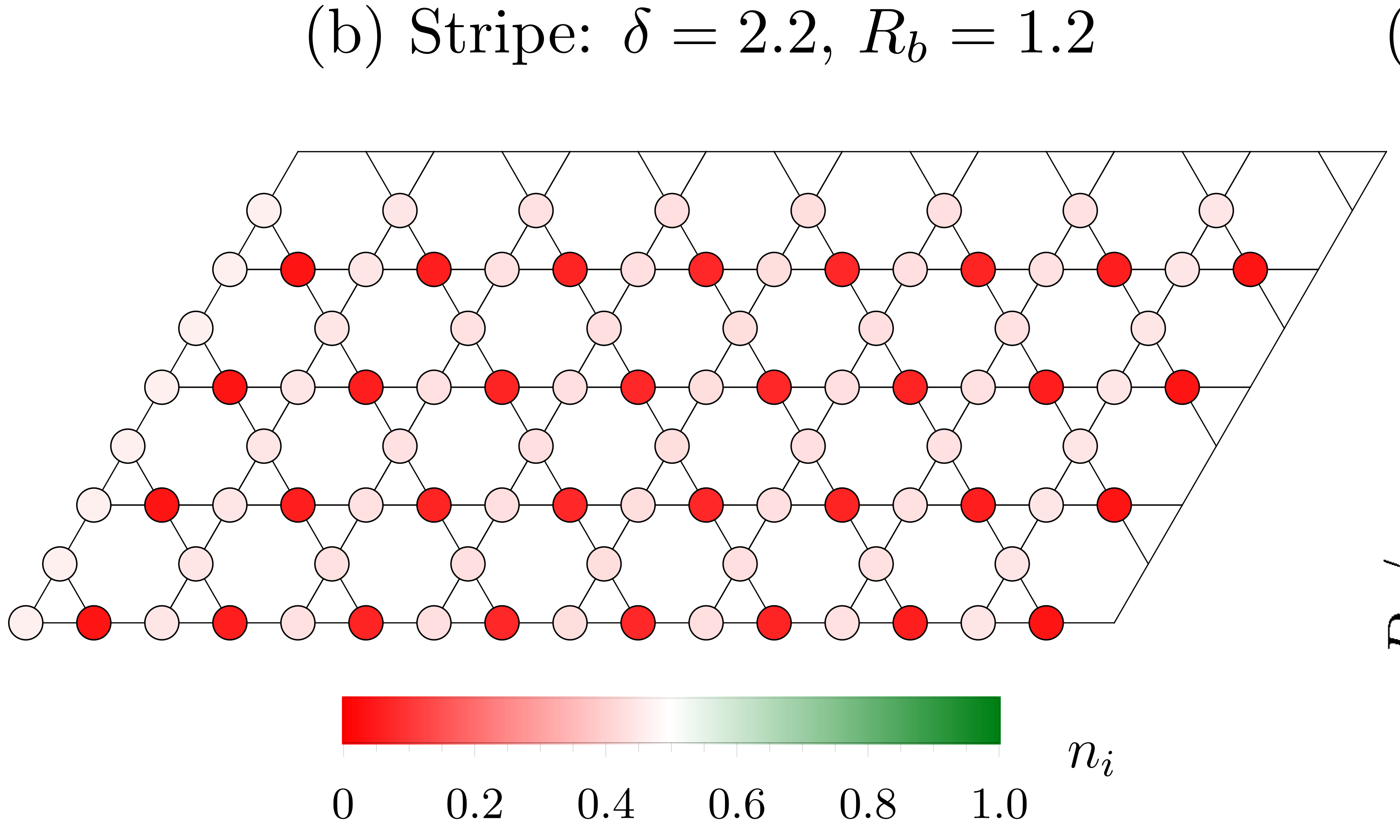
$$n_\ell \equiv b_\ell^\dagger b_\ell$$

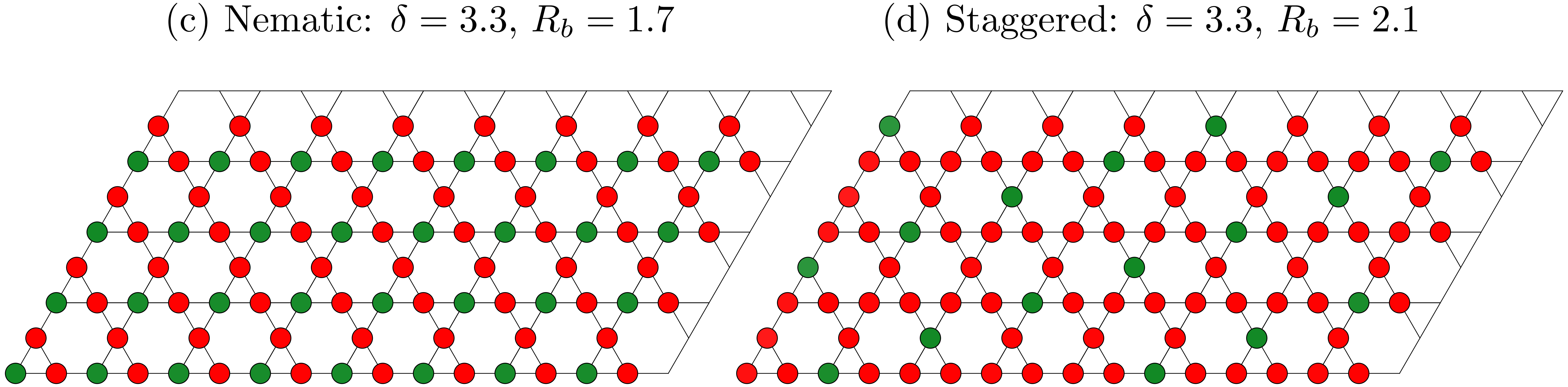
$n_\ell = 0, 1$ 'hard core' bosons

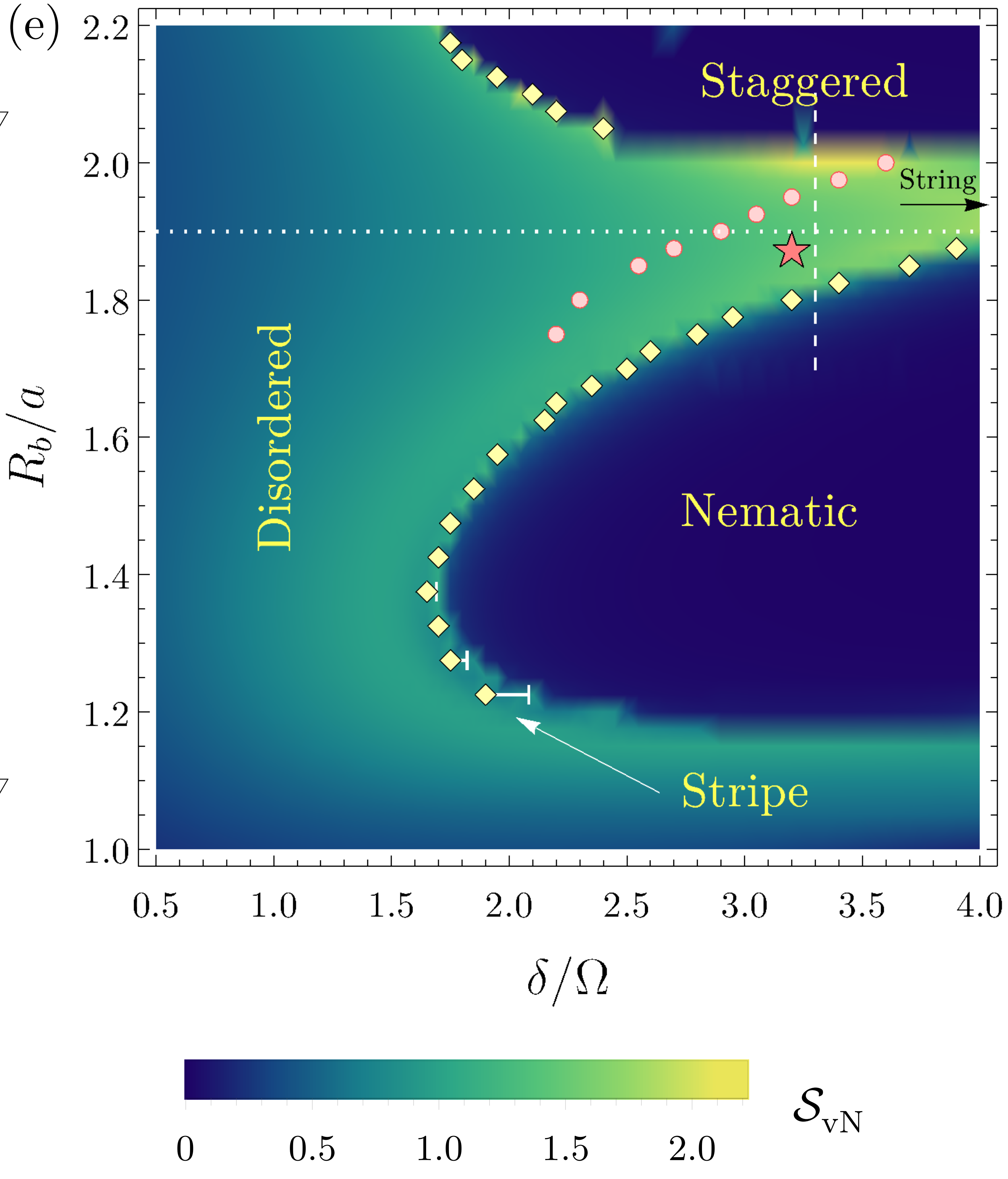
FSS model

R. Samajdar *et al.*, Physical Review Letters **124**, 103601 (2020).
S. Ebadi *et al.*, Nature **595**, 227 (2021).

# Rydberg atoms on site-kagome lattice: theory

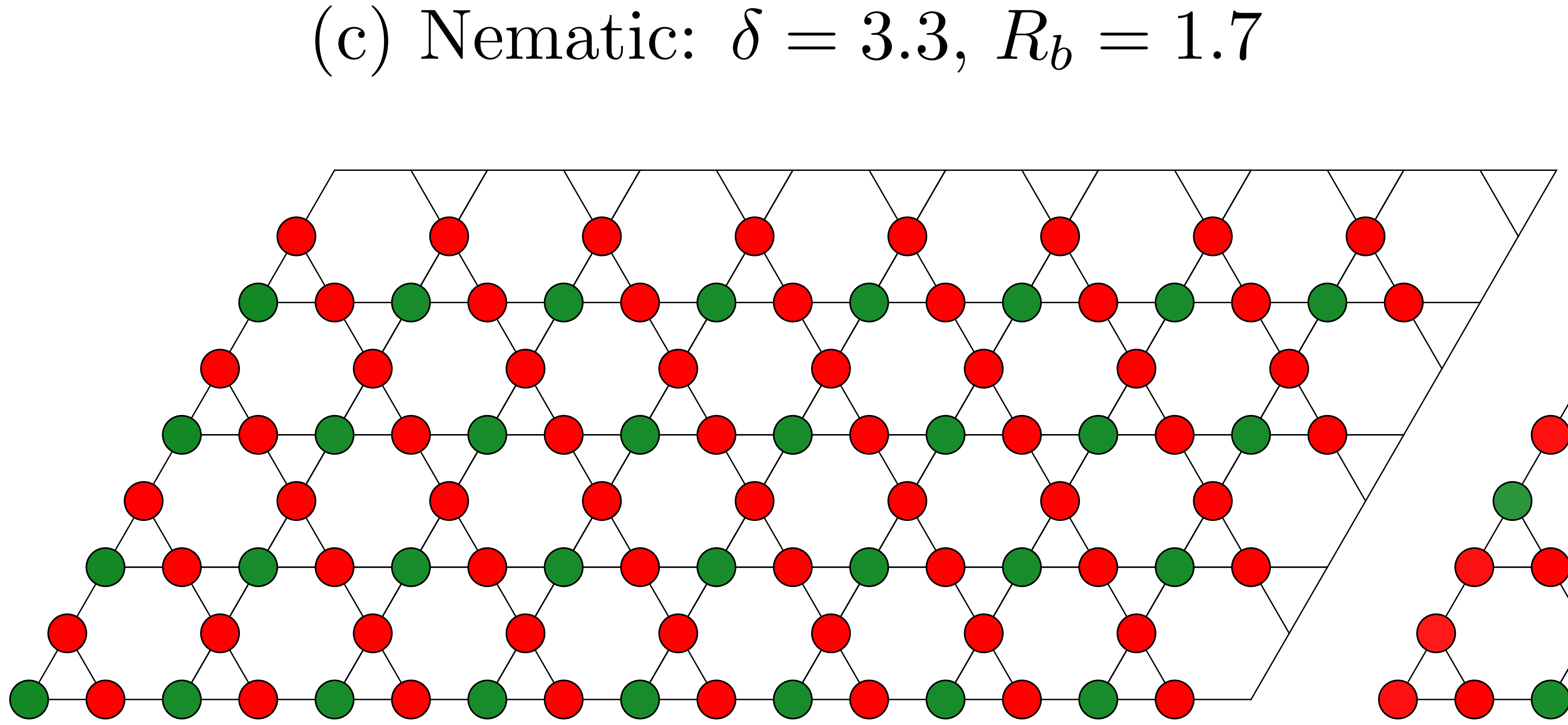


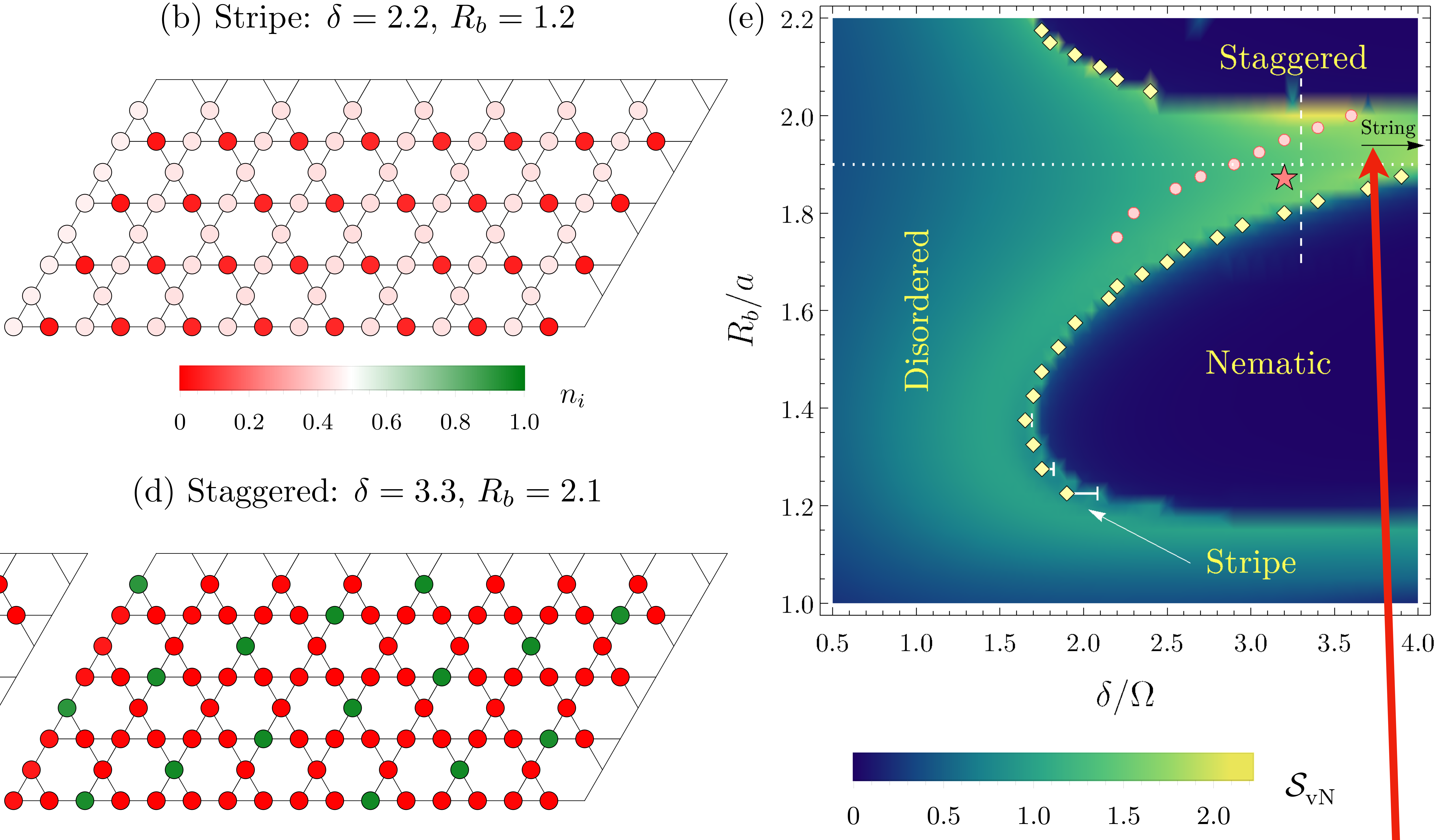




R. Samajdar, Wen Wei Ho, H. Pichler, M. D. Lukin, and S. Sachdev, PNAS **118**, e2015785118 (2021)

# Rydberg atoms on site-kagome lattice: theory




Topological spin liquid described by emergent $\mathbb{Z}_2$ gauge theory ?

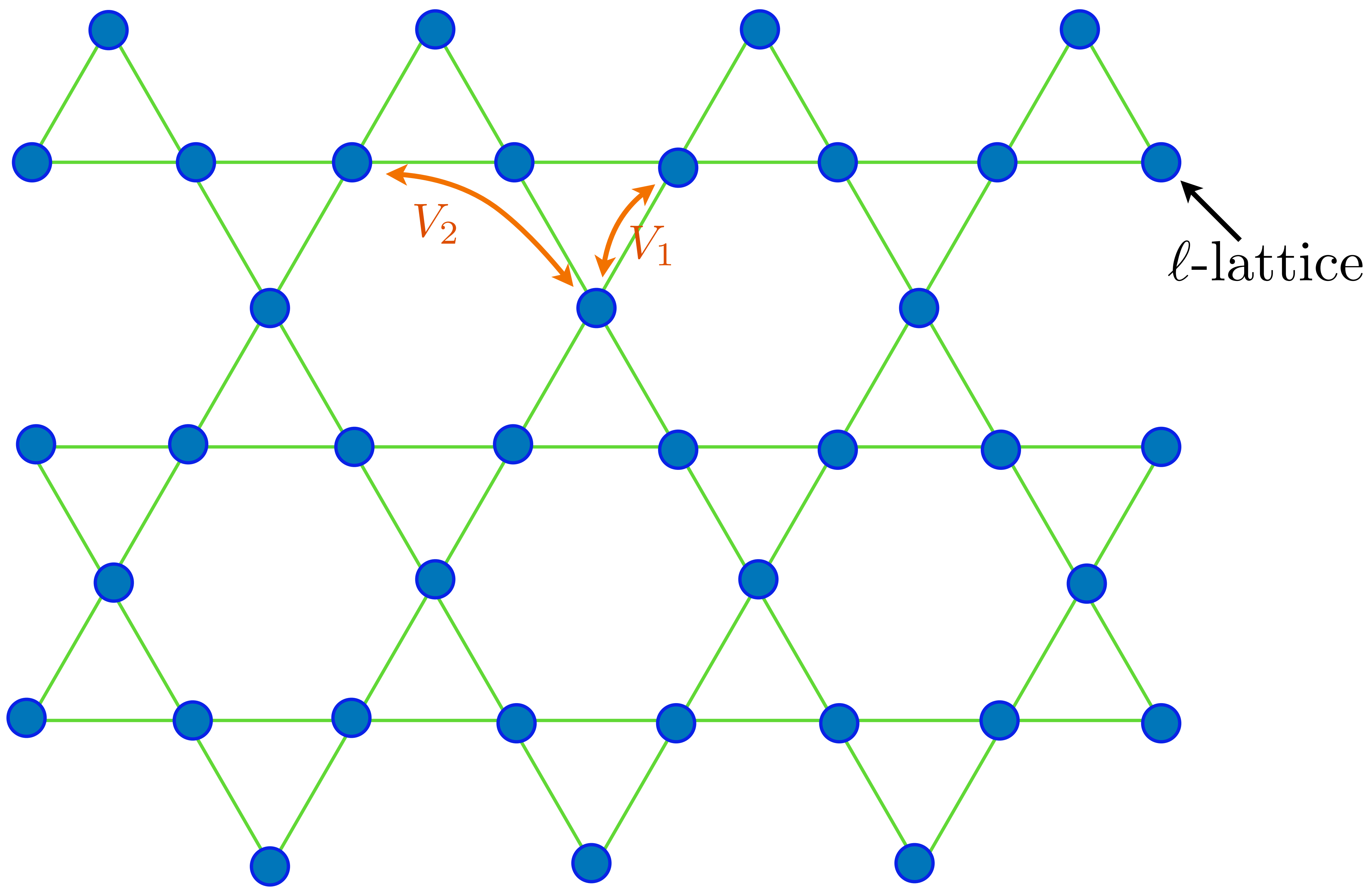
R. Samajdar, Wen Wei Ho, H. Pichler, M. D. Lukin, and S. Sachdev, PNAS **118**, e2015785118 (2021)

# From the FSS model to an emergent $\mathbb{Z}_2$ gauge theory

$$\mathcal{H} = \sum_\ell \left[ \frac{\Omega}{2} \left( b_\ell + b_\ell^\dagger \right) - \Delta n_\ell \right] + \sum_{\ell < \ell'} V_{|\ell - \ell'|} n_\ell n_{\ell'}$$

$$n_\ell \equiv b_\ell^\dagger b_\ell$$

$n_\ell = 0, 1$ 'hard core' bosons




Identify hard core bosons with a qubit $\sigma^{x,y,z}$

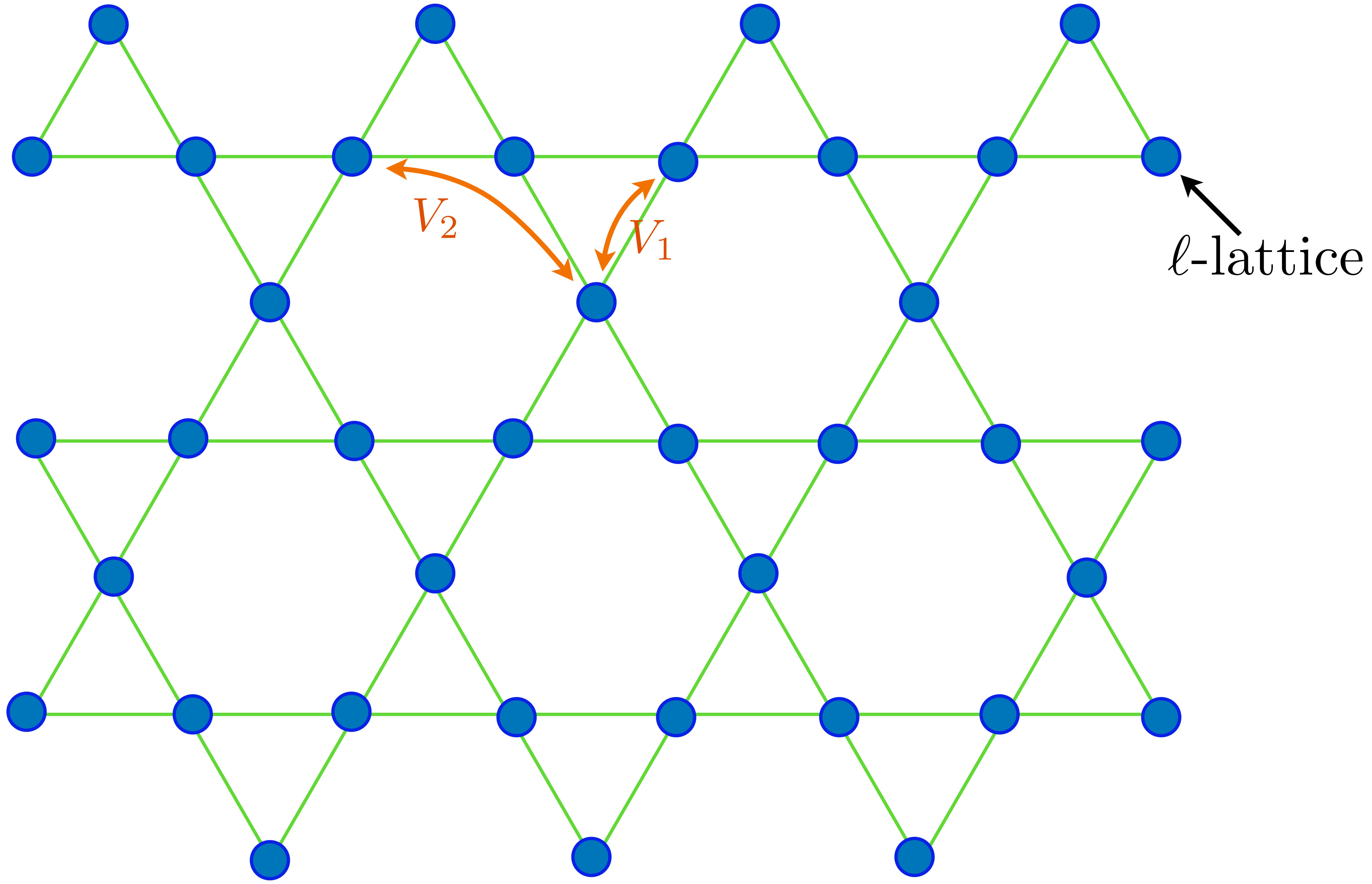
$$b_\ell + b_\ell^\dagger \quad \Leftrightarrow \quad \sigma_\ell^z$$

$$n_\ell \quad \Leftrightarrow \quad (1 - \sigma_\ell^x)/2$$

$\sigma^z$ will become the $\mathbb{Z}_2$ gauge field

# From the FSS model to an emergent $\mathbb{Z}_2$ gauge theory

$$\mathcal{H} = \sum_{\ell} \left[ \frac{\Omega}{2}\sigma^z_\ell + \frac{\Delta}{2}\sigma^x_\ell \right] + \sum_{\ell<\ell'} \frac{V_{|\ell-\ell'|}}{4}(1-\sigma^x_\ell)(1-\sigma^x_{\ell'})$$




Identify hard core bosons with a qubit $\sigma^{x,y,z}$

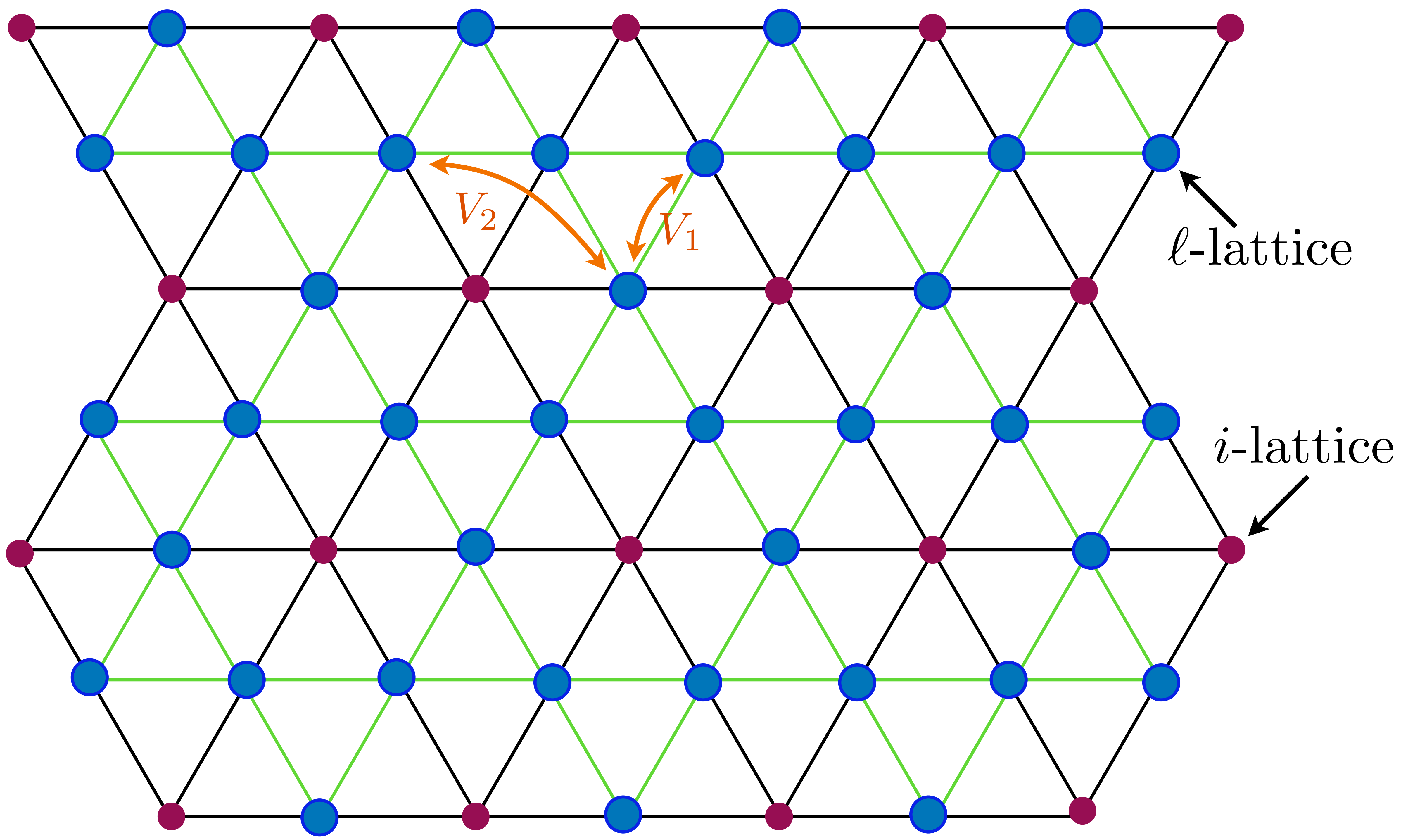
$$b_\ell + b^\dagger_\ell \quad \Leftrightarrow \quad \sigma^z_\ell$$
$$n_\ell \quad \Leftrightarrow \quad (1-\sigma^x_\ell)/2$$

$\sigma^z$ will become the $\mathbb{Z}_2$ gauge field

# From the FSS model to an emergent $\mathbb{Z}_2$ gauge theory

$$\mathcal{H} = \sum_{\ell \in (i,j)} \left[ \frac{\Omega}{2} \tau_i^z \sigma_\ell^z \tau_j^z + \frac{\Delta}{2} \sigma_\ell^x \right] + \sum_{\ell < \ell'} \frac{V_{|\ell - \ell'|}}{4} (1 - \sigma_\ell^x)(1 - \sigma_{\ell'}^x)$$

Introduce $\mathbb{Z}_2$ matter fields on '$i$ sites'. Gauge invariance: $\tau_i^z \to \varrho_i \tau_i^z$, $\sigma_{ij}^z \to \varrho_i \sigma_{ij}^z \varrho_j$, $\tau_i^x \to \tau_i^x$, $\sigma_i^x \to \sigma_i^x$, $\varrho_i = \pm 1$.

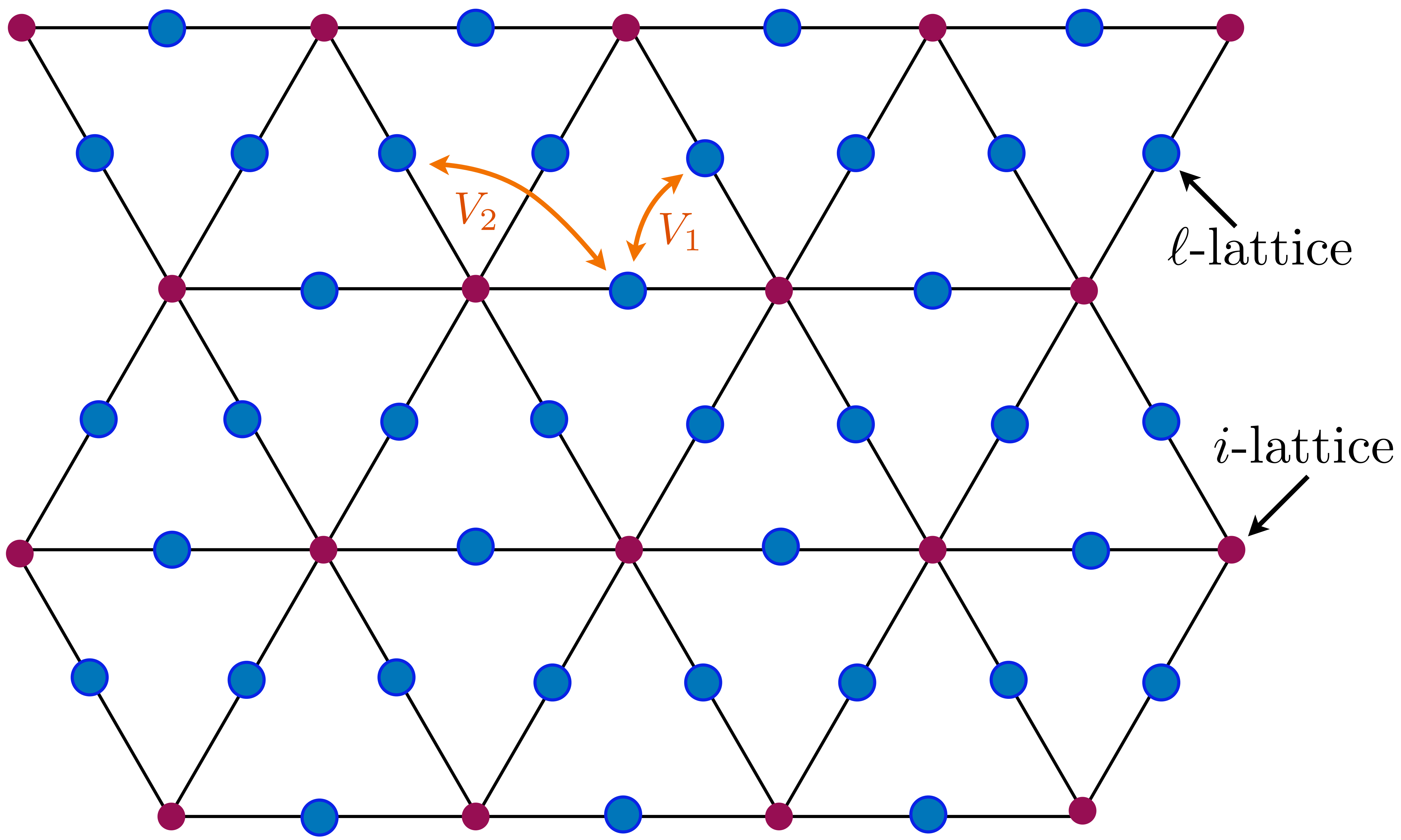



R. Samajdar, Wen Wei Ho, H. Pichler, M. D. Lukin, S. Sachdev, PNAS **118**, e2015785118 (2021)

# From the FSS model to an emergent $\mathbb{Z}_2$ gauge theory

$$\mathcal{H} = \sum_{\ell \in (i,j)} \left[ \frac{\Omega}{2} \tau_i^z \sigma_\ell^z \tau_j^z + \frac{\Delta}{2} \sigma_\ell^x \right] + \sum_{\ell < \ell'} \frac{V_{|\ell - \ell'|}}{4} (1 - \sigma_\ell^x)(1 - \sigma_{\ell'}^x) - \sum_{\text{loops}} K_{\text{loop}} \prod_{\ell_1, \ell_2, \ell_3 \ldots \in \text{loop}} \sigma_{\ell_1}^z \sigma_{\ell_2}^z \sigma_{\ell_3}^z \ldots$$

The $K_{\text{loop}}$ terms are generated in a large $V$ expansion: 'resonance' between Rydberg states stabilizes a phase with deconfined $\mathbb{Z}_2$ gauge charges *i.e.* a $\mathbb{Z}_2$ spin liquid

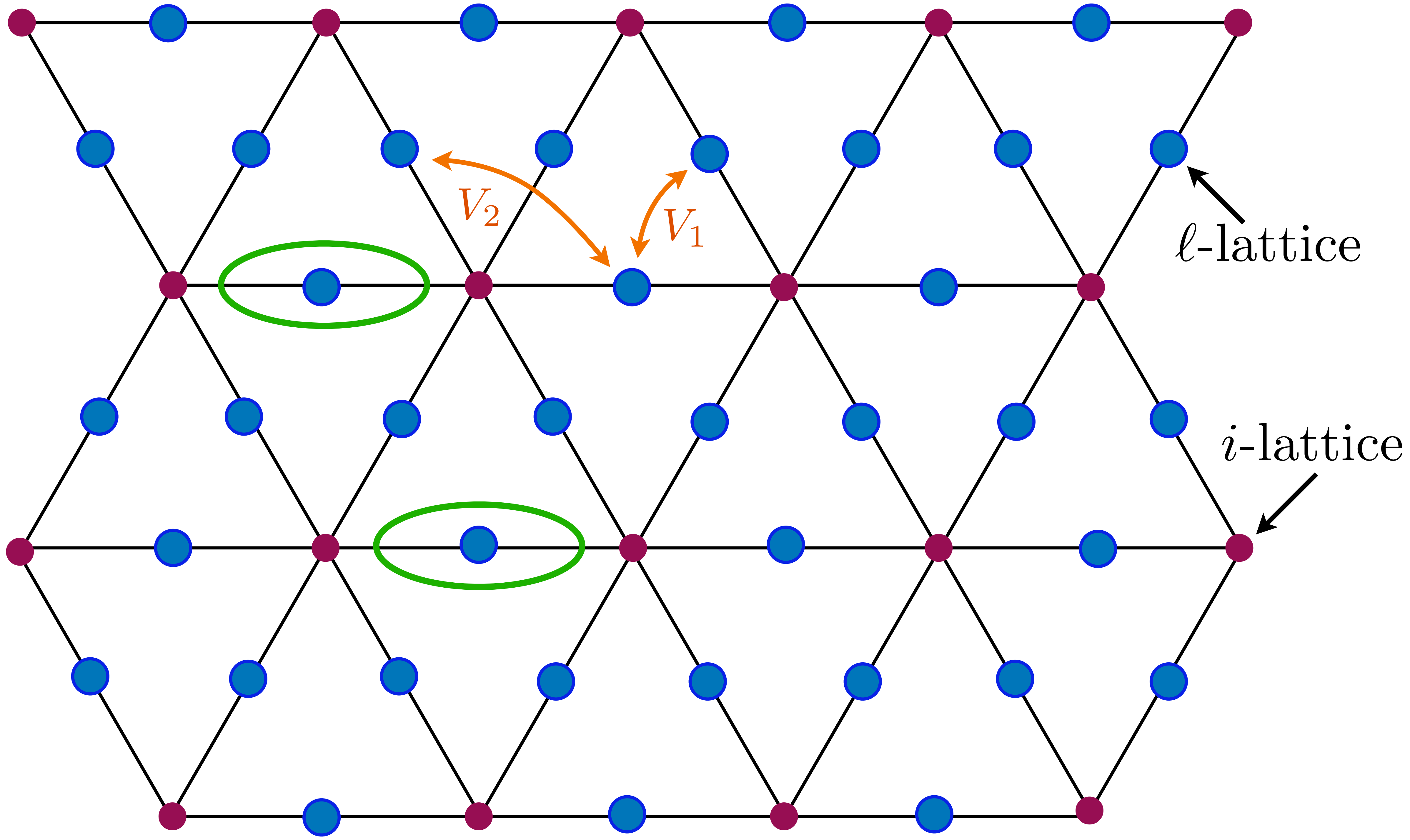



R. Samajdar, Wen Wei Ho, H. Pichler, M. D. Lukin, S. Sachdev, PNAS **118**, e2015785118 (2021)

# From the FSS model to an emergent $\mathbb{Z}_2$ gauge theory

$$\mathcal{H} = \sum_{\ell \in (i,j)} \left[ \frac{\Omega}{2} \tau_i^z \sigma_\ell^z \tau_j^z + \frac{\Delta}{2} \sigma_\ell^x \right] + \sum_{\ell < \ell'} \frac{V_{|\ell - \ell'|}}{4} (1 - \sigma_\ell^x)(1 - \sigma_{\ell'}^x) - \sum_{\text{loops}} K_{\text{loop}} \prod_{\ell_1, \ell_2, \ell_3 \ldots \in \text{loop}} \sigma_{\ell_1}^z \sigma_{\ell_2}^z \sigma_{\ell_3}^z \ldots$$

The $K_{\text{loop}}$ terms are generated in a large $V$ expansion: 'resonance' between Rydberg states stabilizes a phase with deconfined $\mathbb{Z}_2$ gauge charges *i.e.* a $\mathbb{Z}_2$ spin liquid

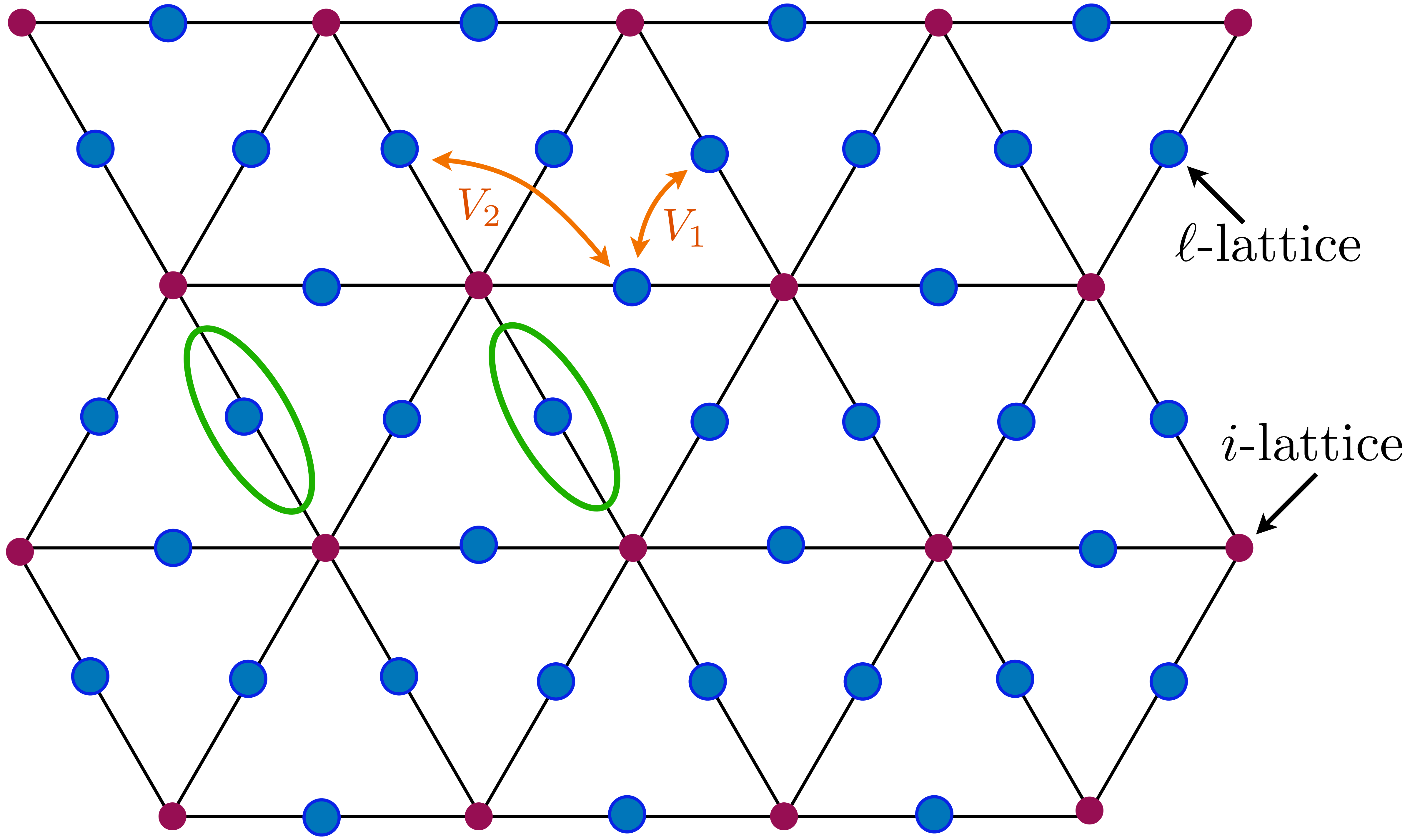



R. Samajdar, Wen Wei Ho, H. Pichler, M. D. Lukin, S. Sachdev, PNAS **118**, e2015785118 (2021)

# From the FSS model to an emergent $\mathbb{Z}_2$ gauge theory

$$\mathcal{H} = \sum_{\ell \in (i,j)} \left[ \frac{\Omega}{2} \tau_i^z \sigma_\ell^z \tau_j^z + \frac{\Delta}{2} \sigma_\ell^x \right] + \sum_{\ell < \ell'} \frac{V_{|\ell - \ell'|}}{4} (1 - \sigma_\ell^x)(1 - \sigma_{\ell'}^x) - \sum_{\text{loops}} K_{\text{loop}} \prod_{\ell_1, \ell_2, \ell_3 \ldots \in \text{loop}} \sigma_{\ell_1}^z \sigma_{\ell_2}^z \sigma_{\ell_3}^z \ldots$$

The $K_{\text{loop}}$ terms are generated in a large $V$ expansion: 'resonance' between Rydberg states stabilizes a phase with deconfined $\mathbb{Z}_2$ gauge charges *i.e.* a $\mathbb{Z}_2$ spin liquid

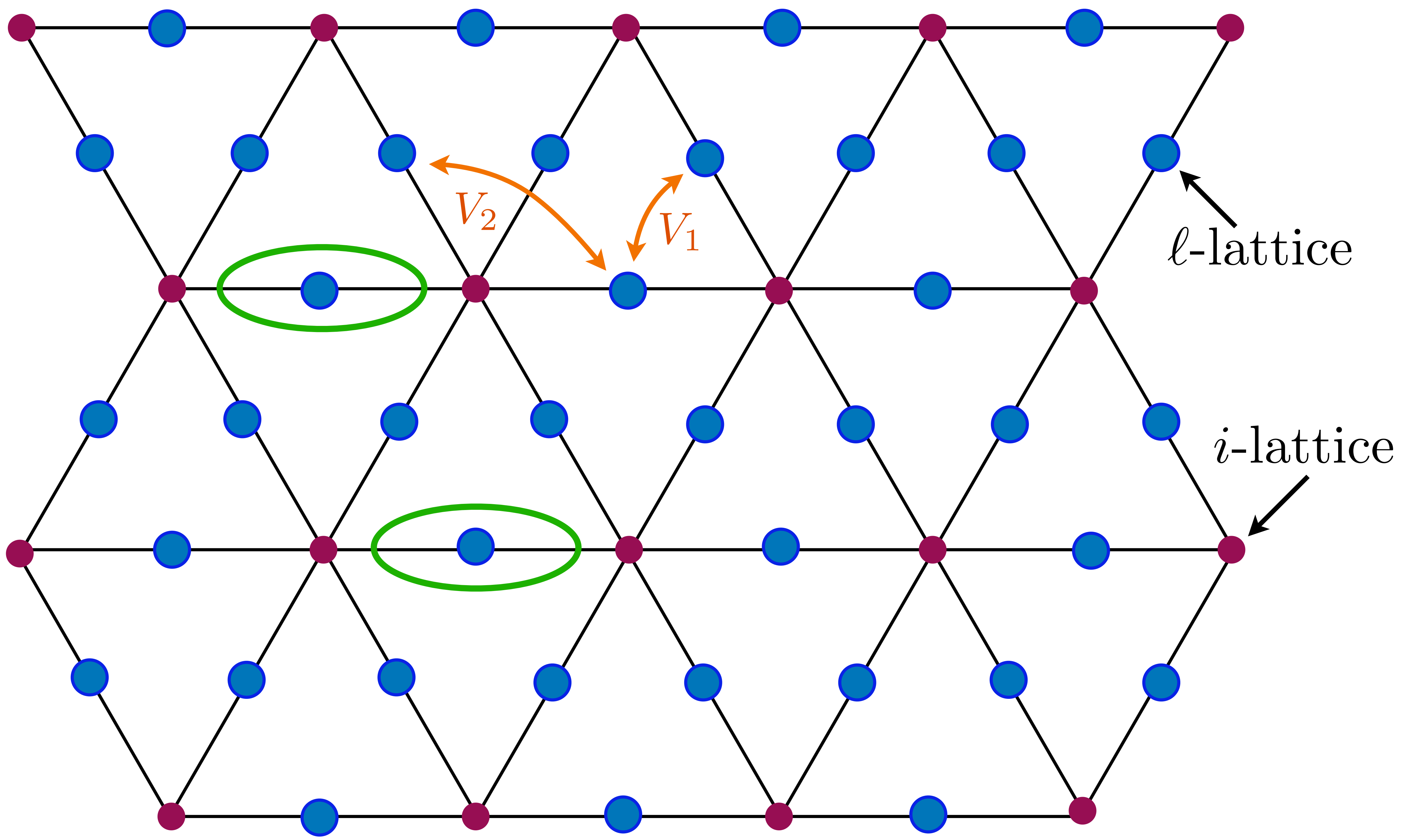



R. Samajdar, Wen Wei Ho, H. Pichler, M. D. Lukin, S. Sachdev, PNAS **118**, e2015785118 (2021)

# From the FSS model to an emergent $\mathbb{Z}_2$ gauge theory

$$\mathcal{H} = \sum_{\ell \in (i,j)} \left[ \frac{\Omega}{2} \tau_i^z \sigma_\ell^z \tau_j^z + \frac{\Delta}{2} \sigma_\ell^x \right] + \sum_{\ell < \ell'} \frac{V_{|\ell - \ell'|}}{4} (1 - \sigma_\ell^x)(1 - \sigma_{\ell'}^x) - \sum_{\text{loops}} K_{\text{loop}} \prod_{\ell_1, \ell_2, \ell_3 \ldots \in \text{loop}} \sigma_{\ell_1}^z \sigma_{\ell_2}^z \sigma_{\ell_3}^z \ldots$$

The $K_{\text{loop}}$ terms are generated in a large $V$ expansion: 'resonance' between Rydberg states stabilizes a phase with deconfined $\mathbb{Z}_2$ gauge charges *i.e.* a $\mathbb{Z}_2$ spin liquid

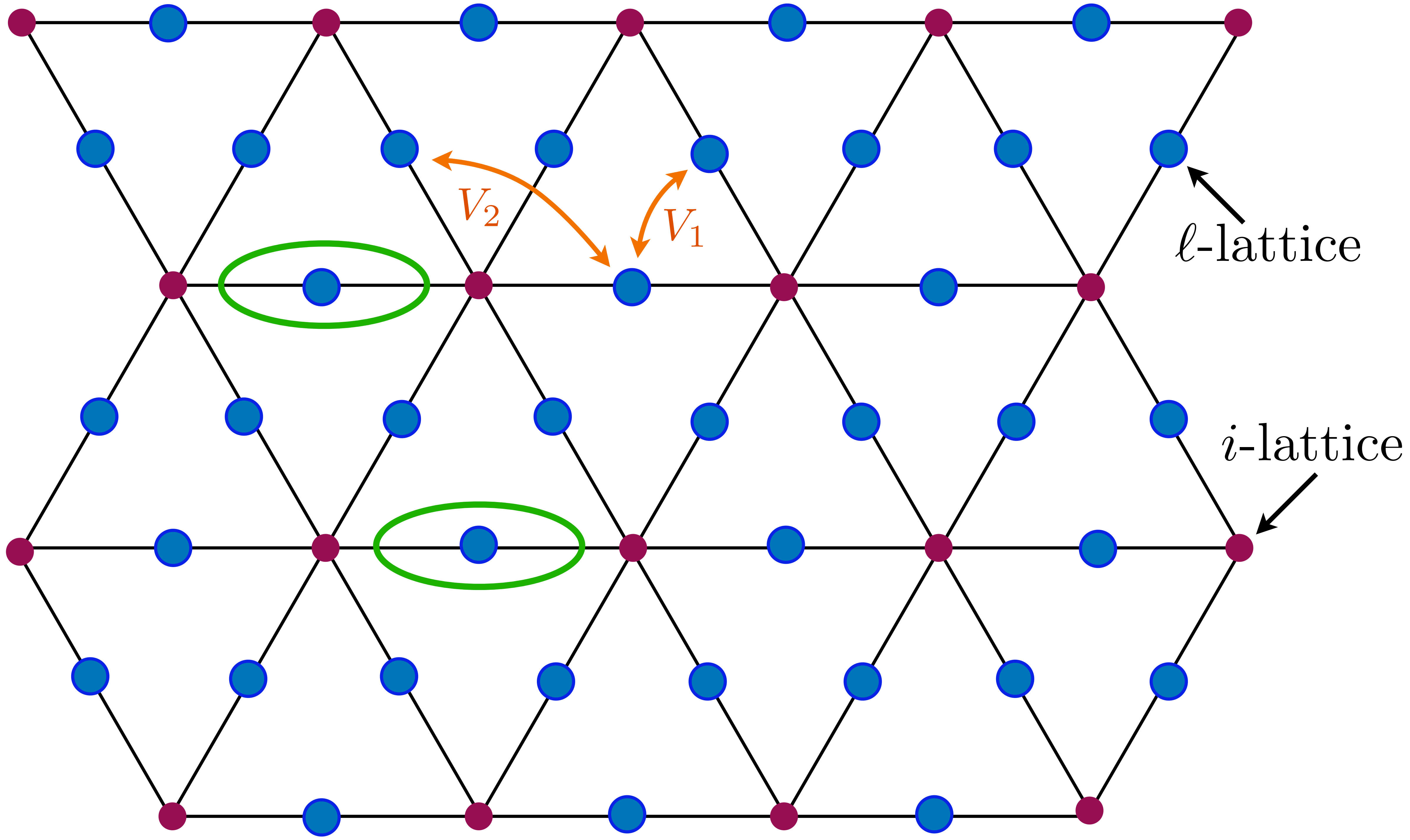


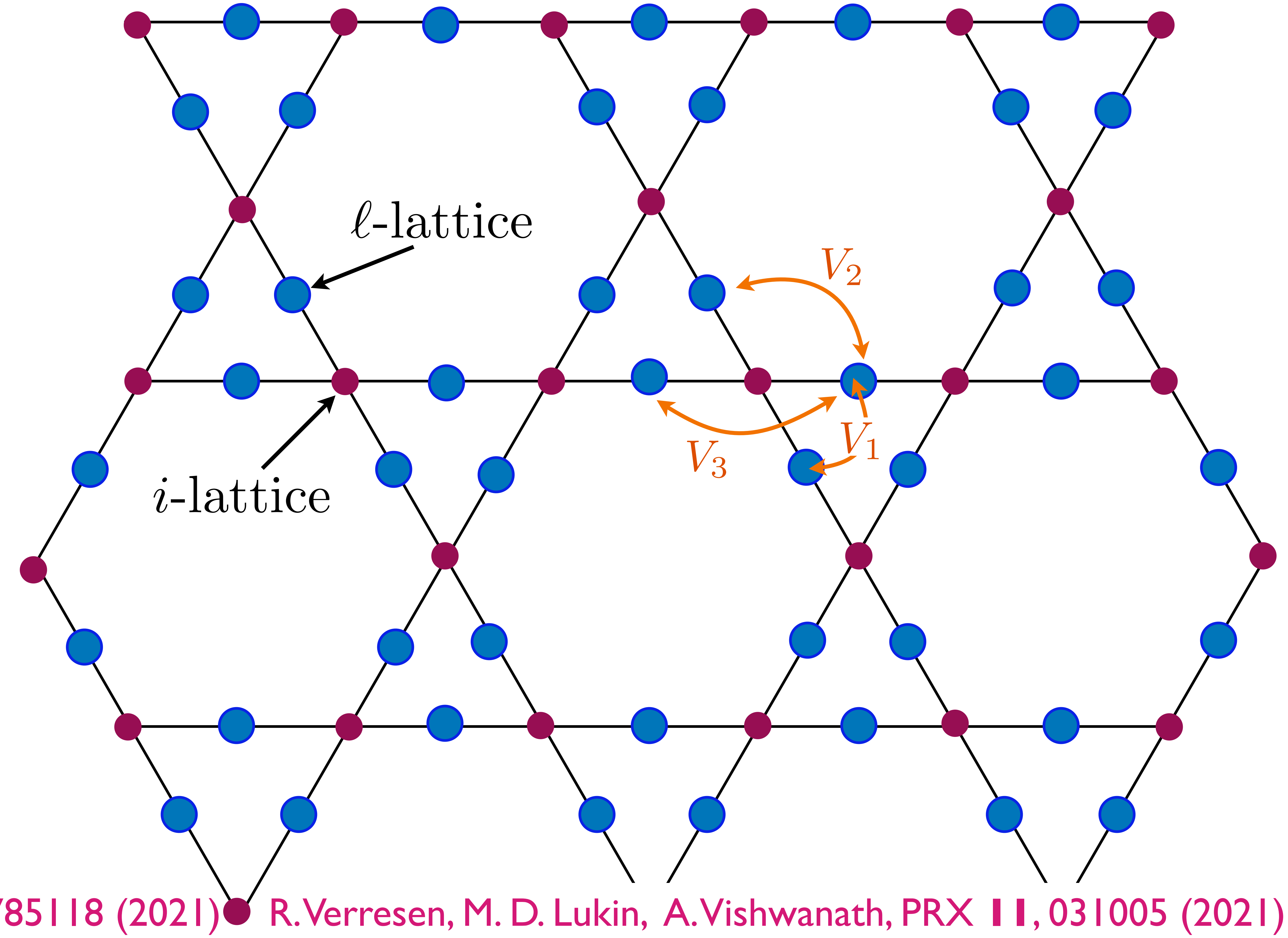

R. Samajdar, Wen Wei Ho, H. Pichler, M. D. Lukin, S. Sachdev, PNAS **118**, e2015785118 (2021)

# From the FSS model to an emergent $\mathbb{Z}_2$ gauge theory

$$\mathcal{H} = \sum_{\ell \in (i,j)} \left[ \frac{\Omega}{2} \tau_i^z \sigma_\ell^z \tau_j^z + \frac{\Delta}{2} \sigma_\ell^x \right] + \sum_{\ell < \ell'} \frac{V_{|\ell - \ell'|}}{4} (1 - \sigma_\ell^x)(1 - \sigma_{\ell'}^x) - \sum_{\text{loops}} K_{\text{loop}} \prod_{\ell_1, \ell_2, \ell_3 \ldots \in \text{loop}} \sigma_{\ell_1}^z \sigma_{\ell_2}^z \sigma_{\ell_3}^z \ldots$$

The $K_{\text{loop}}$ terms are generated in a large $V$ expansion: 'resonance' between Rydberg states stabilizes a phase with deconfined $\mathbb{Z}_2$ gauge charges *i.e.* a $\mathbb{Z}_2$ spin liquid



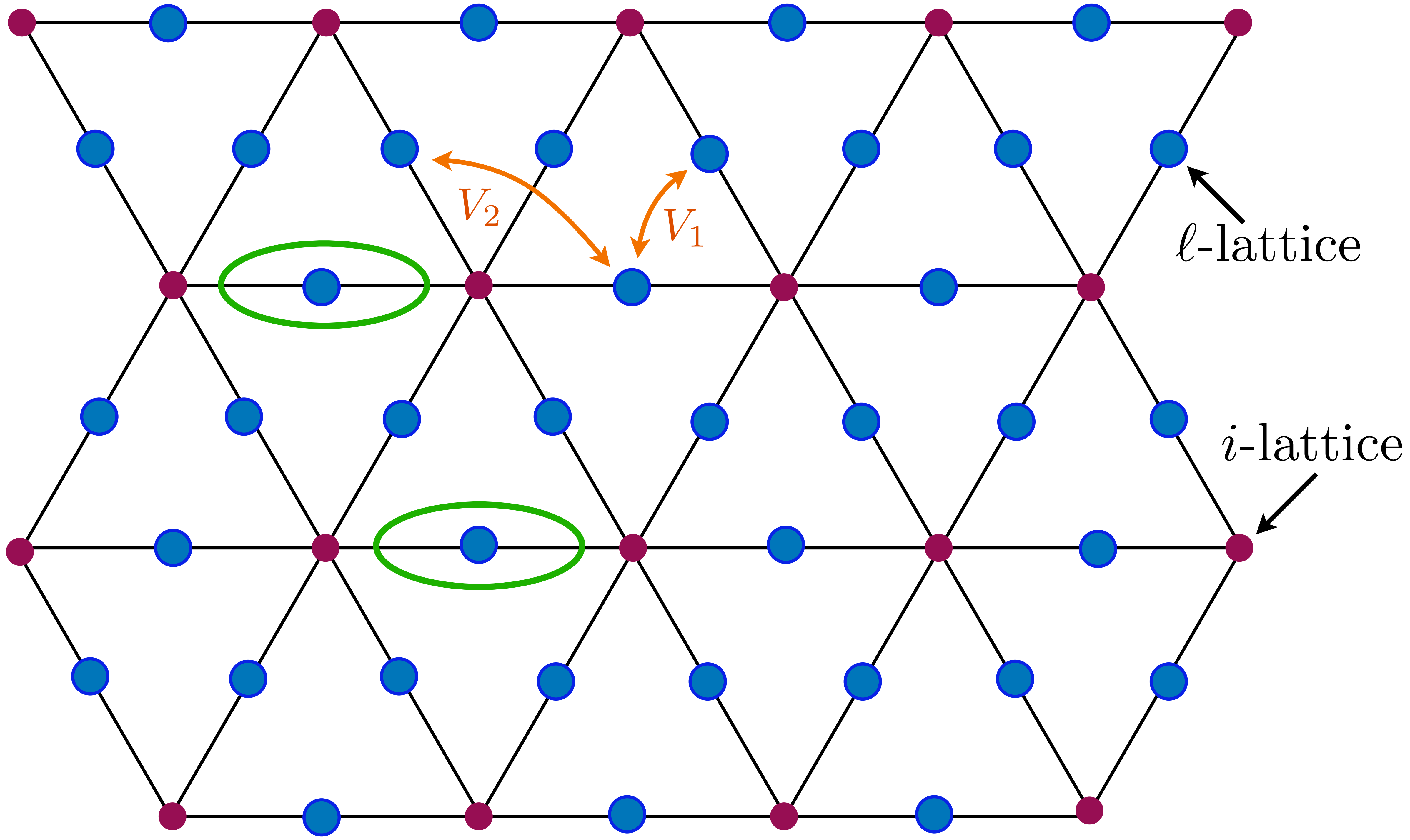



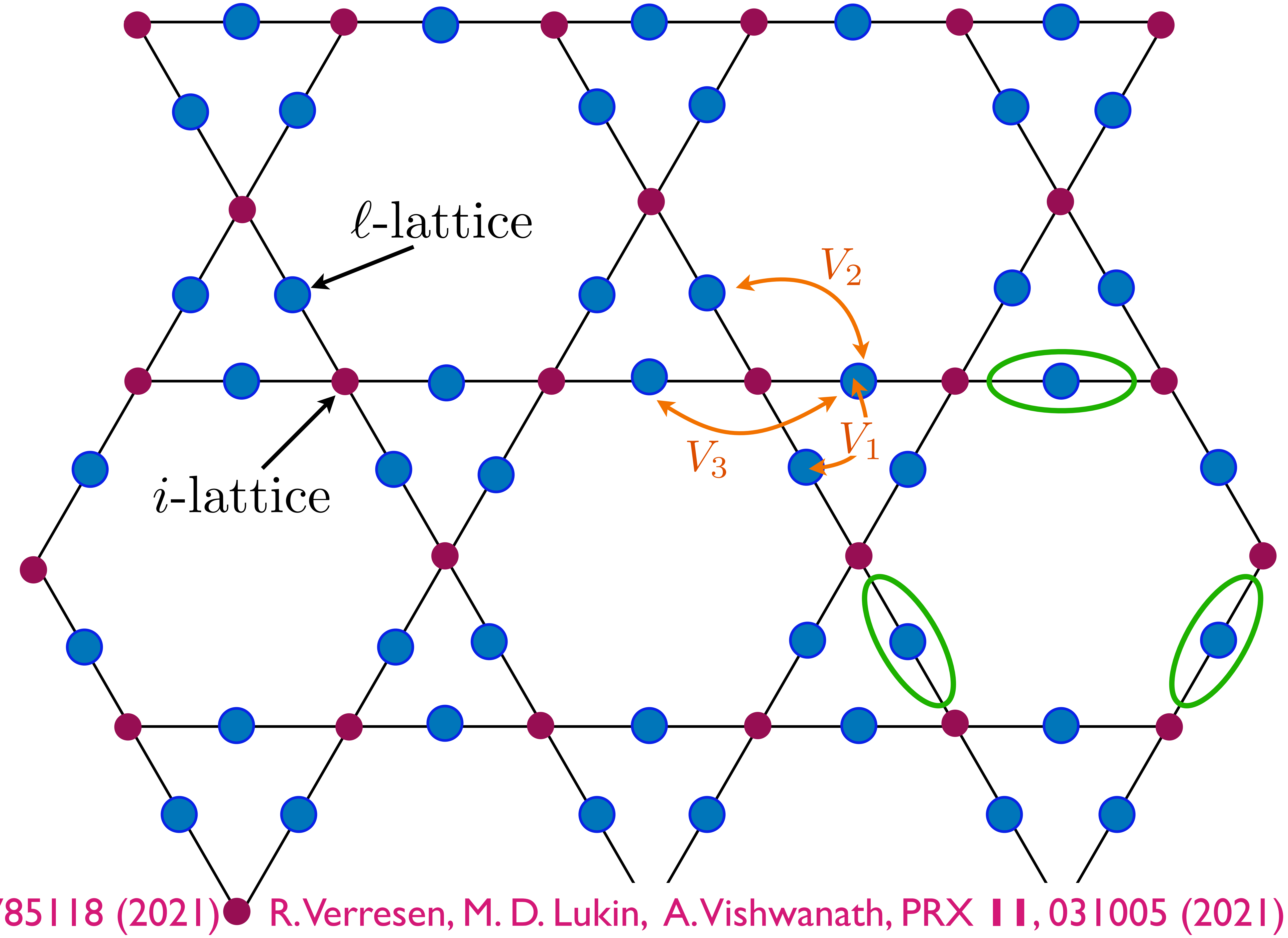

R. Samajdar, Wen Wei Ho, H. Pichler, M. D. Lukin, S. Sachdev, PNAS **118**, e2015785118 (2021) R. Verresen, M. D. Lukin, A. Vishwanath, PRX **11**, 031005 (2021)

# From the FSS model to an emergent $\mathbb{Z}_2$ gauge theory

$$\mathcal{H} = \sum_{\ell \in (i,j)} \left[ \frac{\Omega}{2} \tau_i^z \sigma_\ell^z \tau_j^z + \frac{\Delta}{2} \sigma_\ell^x \right] + \sum_{\ell < \ell'} \frac{V_{|\ell - \ell'|}}{4} (1 - \sigma_\ell^x)(1 - \sigma_{\ell'}^x) - \sum_{\text{loops}} K_{\text{loop}} \prod_{\ell_1, \ell_2, \ell_3 \ldots \in \text{loop}} \sigma_{\ell_1}^z \sigma_{\ell_2}^z \sigma_{\ell_3}^z \ldots$$

The $K_{\text{loop}}$ terms are generated in a large $V$ expansion: 'resonance' between Rydberg states stabilizes a phase with deconfined $\mathbb{Z}_2$ gauge charges *i.e.* a $\mathbb{Z}_2$ spin liquid



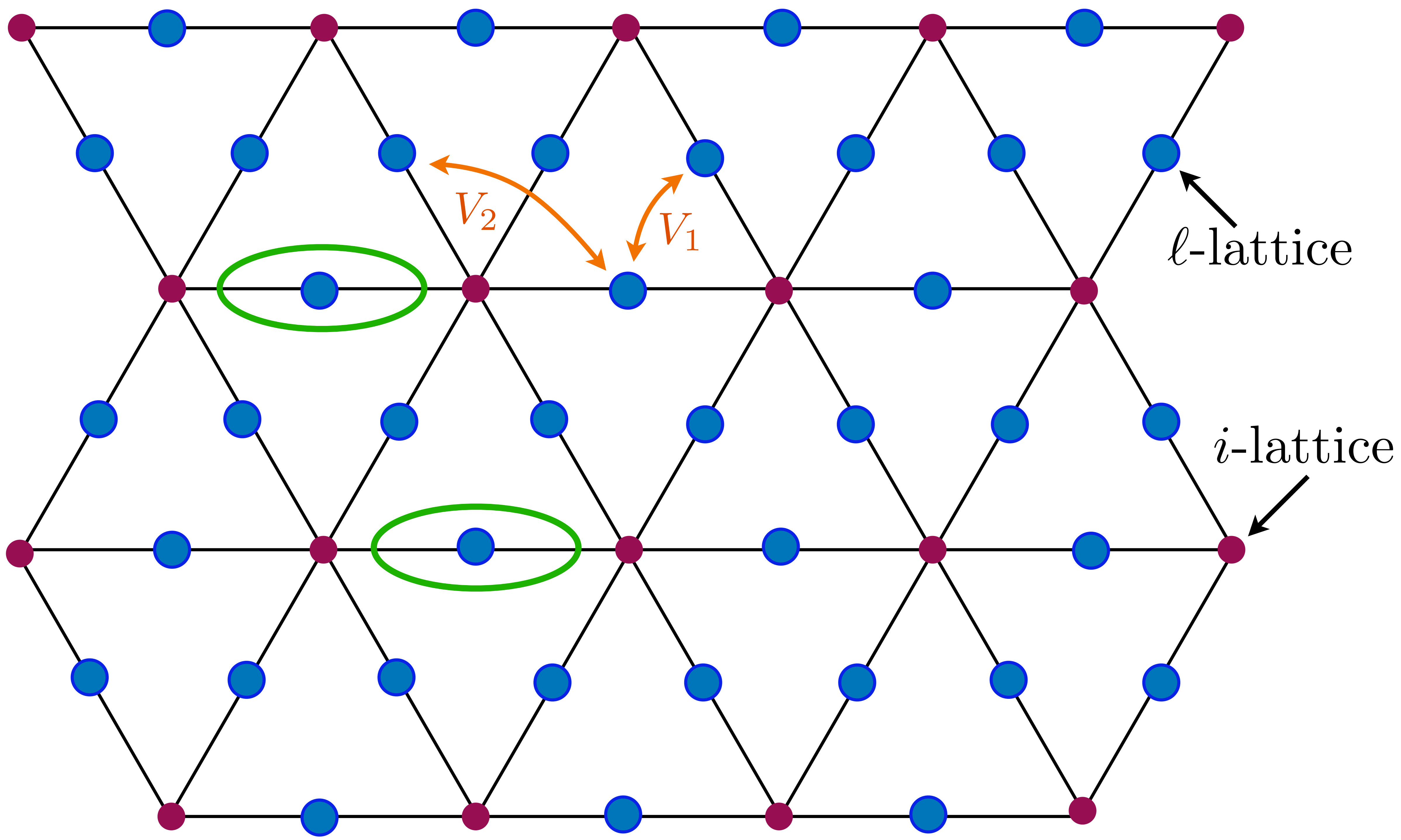



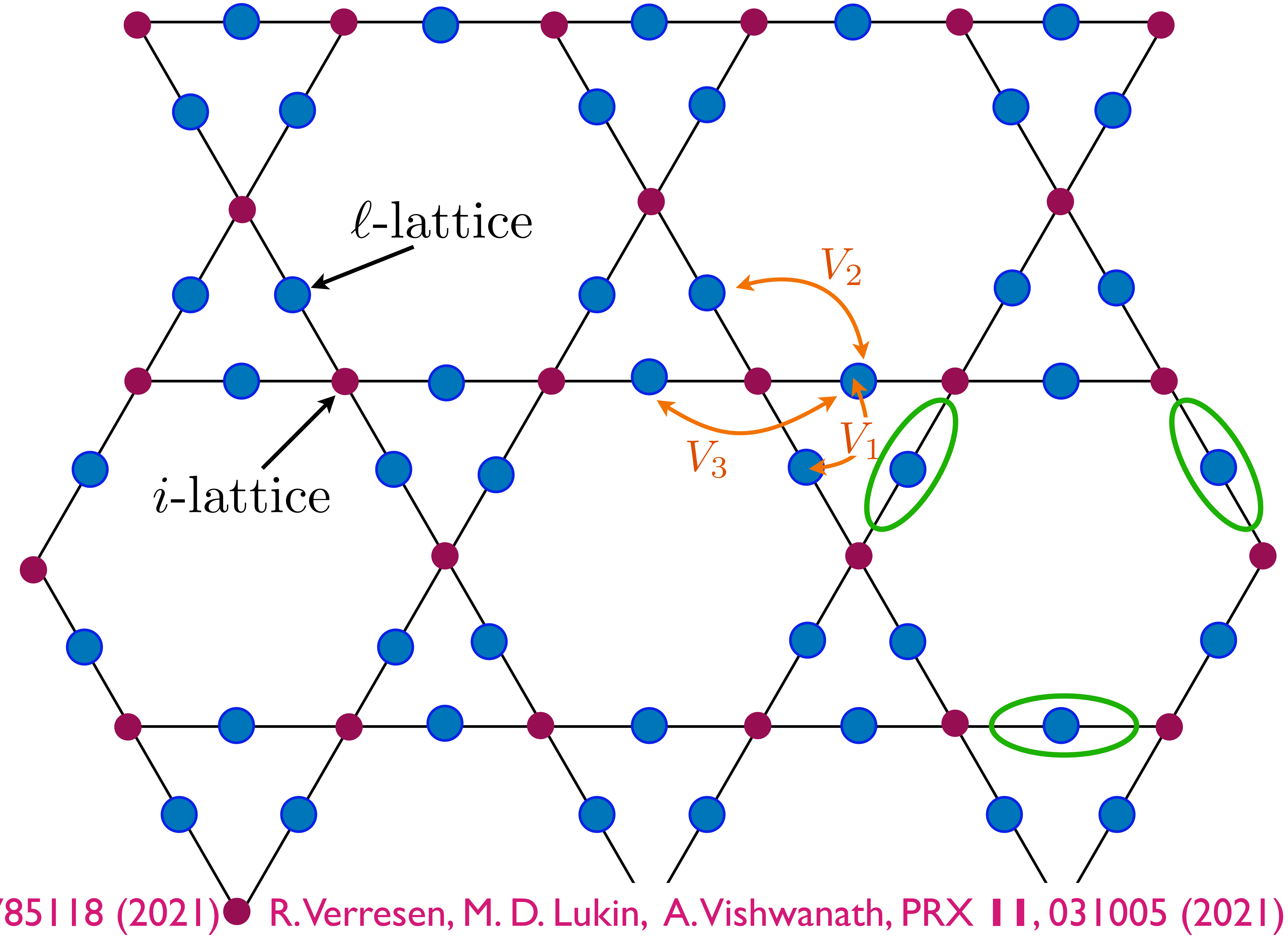

R. Samajdar, Wen Wei Ho, H. Pichler, M. D. Lukin, S. Sachdev, PNAS **118**, e2015785118 (2021) R. Verresen, M. D. Lukin, A. Vishwanath, PRX **11**, 031005 (2021)

# From the FSS model to an emergent $\mathbb{Z}_2$ gauge theory

$$\mathcal{H} = \sum_{\ell\in(i,j)} \left[\frac{\Omega}{2}\tau_i^z\sigma_\ell^z\tau_j^z + \frac{\Delta}{2}\sigma_\ell^x\right] + \sum_{\ell<\ell'} \frac{V_{|\ell-\ell'|}}{4}(1-\sigma_\ell^x)(1-\sigma_{\ell'}^x) - \sum_{\text{loops}} K_{\text{loop}} \prod_{\ell_1,\ell_2,\ell_3\ldots\in\,\text{loop}} \sigma_{\ell_1}^z\sigma_{\ell_2}^z\sigma_{\ell_3}^z\ldots$$

The $K_{\text{loop}}$ terms are generated in a large $V$ expansion: 'resonance' between Rydberg states stabilizes a phase with deconfined $\mathbb{Z}_2$ gauge charges *i.e.* a $\mathbb{Z}_2$ spin liquid



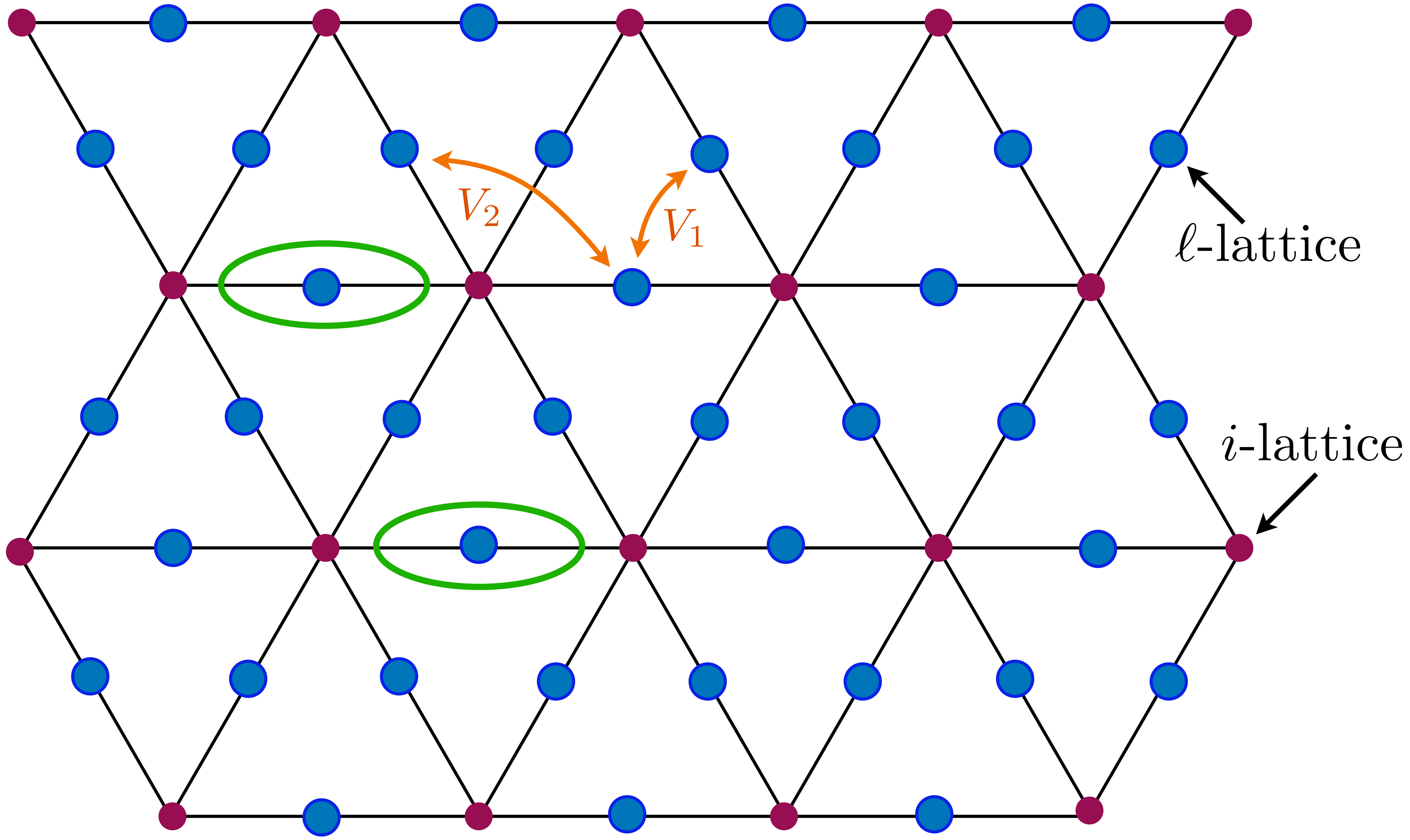



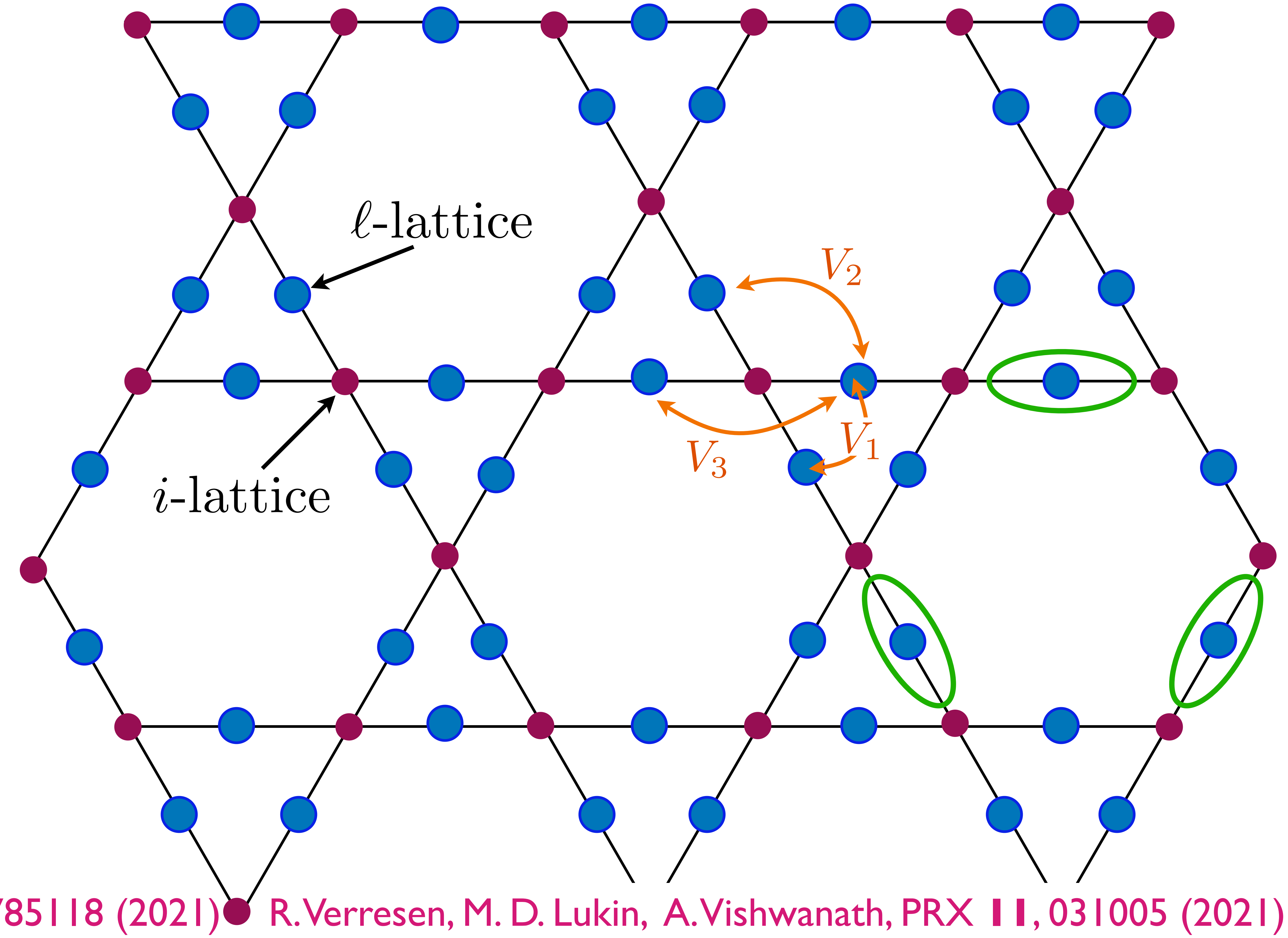

R. Samajdar, Wen Wei Ho, H. Pichler, M. D. Lukin, S. Sachdev, PNAS **118**, e2015785118 (2021) R. Verresen, M. D. Lukin, A. Vishwanath, PRX **11**, 031005 (2021)

# From the FSS model to an emergent $\mathbb{Z}_2$ gauge theory

$$\mathcal{H} = \sum_{\ell \in (i,j)} \left[ \frac{\Omega}{2} \tau_i^z \sigma_\ell^z \tau_j^z + \frac{\Delta}{2} \sigma_\ell^x \right] + \sum_{\ell < \ell'} \frac{V_{|\ell - \ell'|}}{4} (1 - \sigma_\ell^x)(1 - \sigma_{\ell'}^x) - \sum_{\text{loops}} K_{\text{loop}} \prod_{\ell_1, \ell_2, \ell_3 \ldots \in \text{loop}} \sigma_{\ell_1}^z \sigma_{\ell_2}^z \sigma_{\ell_3}^z \ldots$$

The $K_{\text{loop}}$ terms are generated in a large $V$ expansion: 'resonance' between Rydberg states stabilizes a phase with deconfined $\mathbb{Z}_2$ gauge charges *i.e.* a $\mathbb{Z}_2$ spin liquid



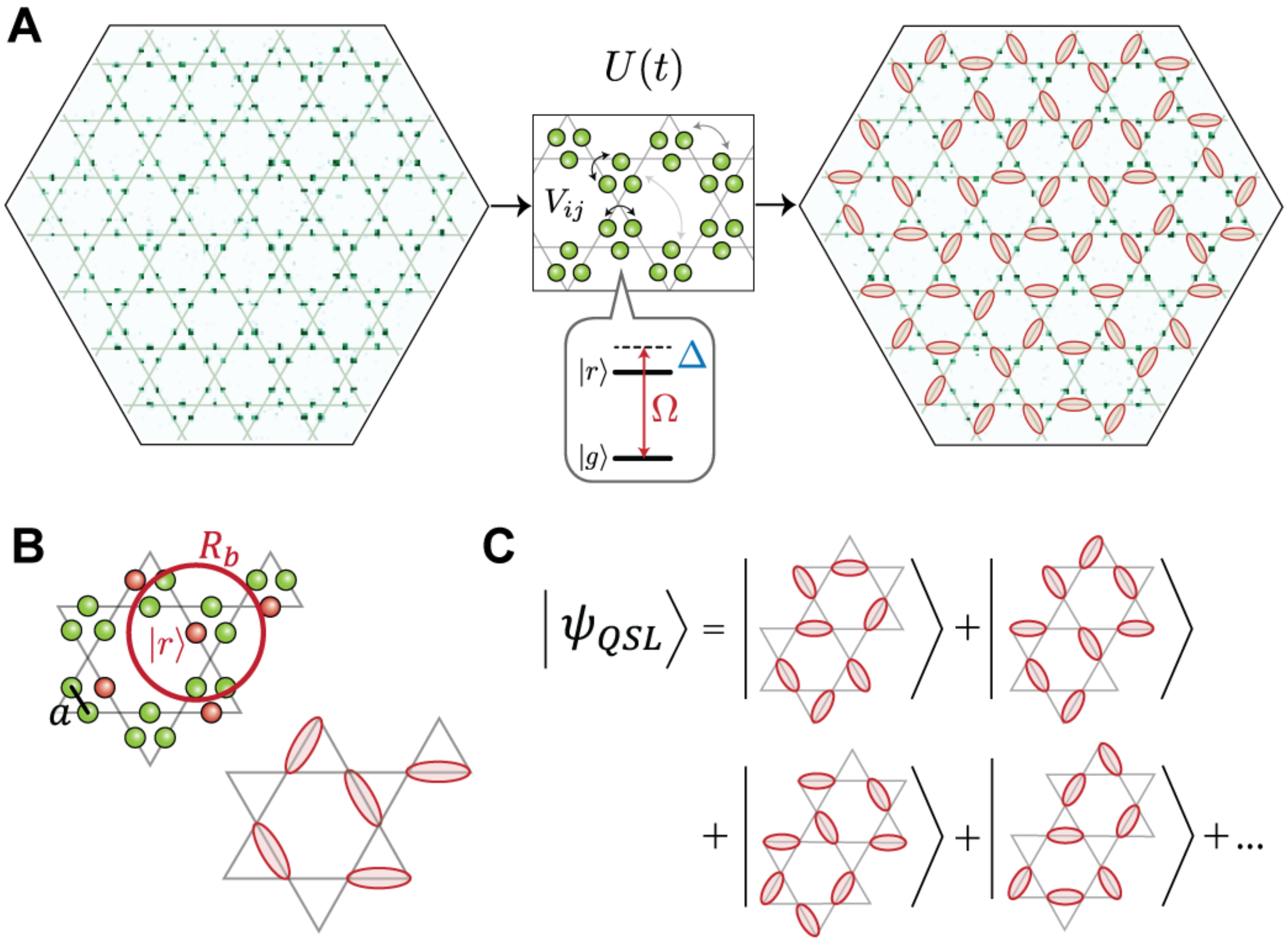




R. Samajdar, Wen Wei Ho, H. Pichler, M. D. Lukin, S. Sachdev, PNAS **118**, e2015785118 (2021) R. Verresen, M. D. Lukin, A. Vishwanath, PRX **11**, 031005 (2021)

# Probing Topological Spin Liquids on a Programmable Quantum Simulator

G. Semeghini, H. Levine, A. Keesling, S. Ebadi, T. T. Wang, D. Bluvstein, R. Verresen, H. Pichler, M. Kalinowski, R. Samajdar, A. Omran, S. Sachdev, A. Vishwanath, M. Greiner, V. Vuletic, M. D. Lukin, arXiv:2104.04119; Science, to appear.

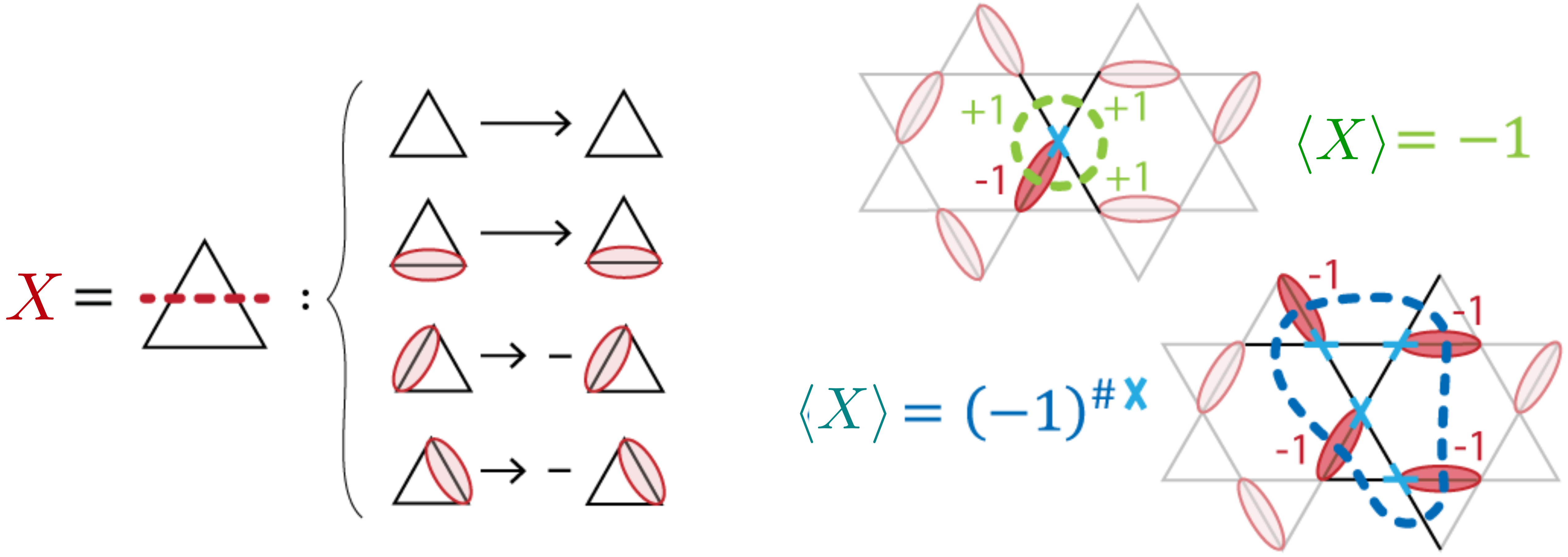
Rydberg atoms
on the
link-kagome lattice:
experiment



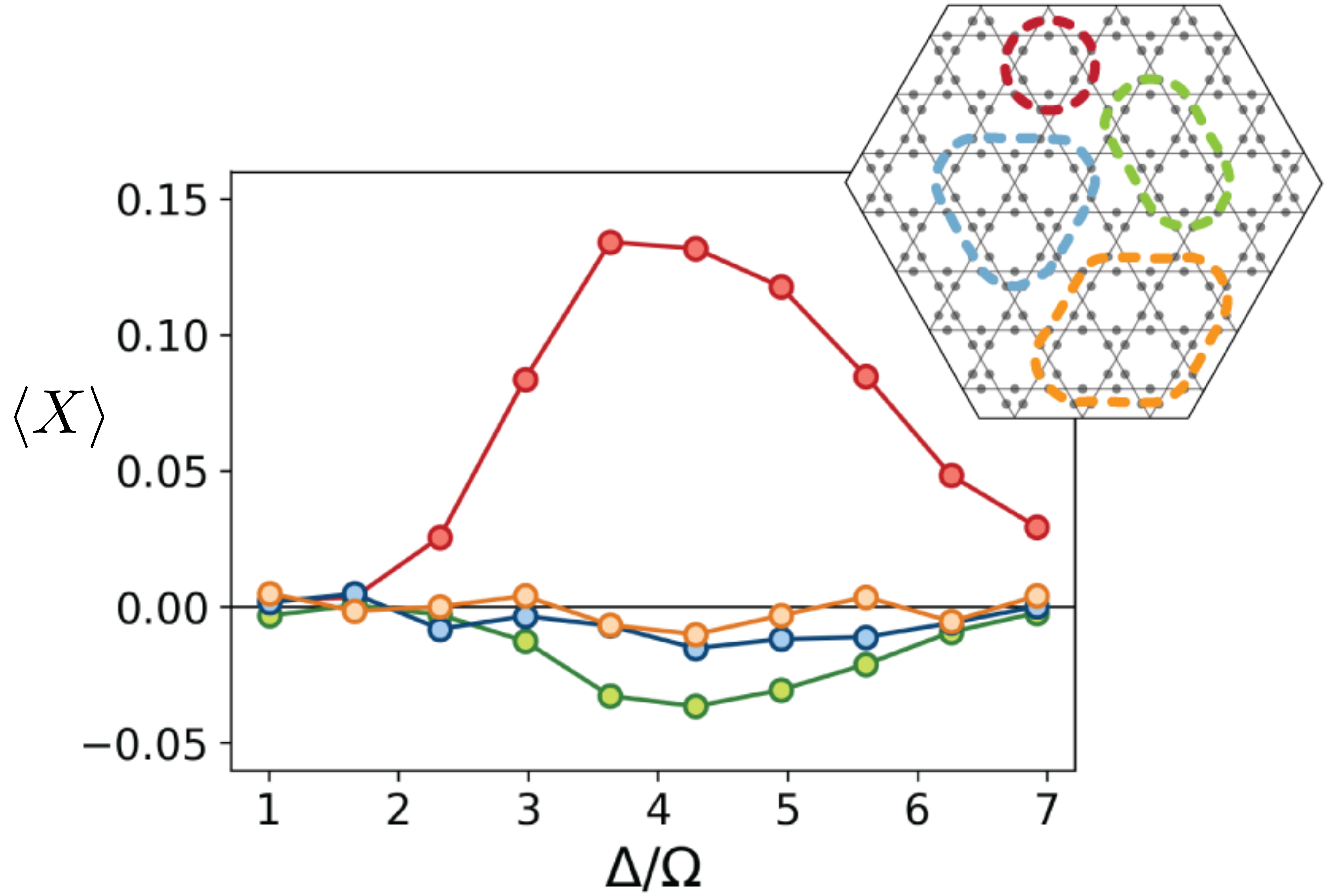
## Probing Topological Spin Liquids on a Programmable Quantum Simulator

G. Semeghini, H. Levine, A. Keesling, S. Ebadi, T.T. Wang, D. Bluvstein, R. Verresen, H. Pichler, M. Kalinowski, R. Samajdar, A. Omran, S. Sachdev, A. Vishwanath, M. Greiner, V. Vuletic, M. D. Lukin, arXiv:2104.04119; Science, to appear.

Rydberg atoms
on the
link-kagome lattice:
experiment

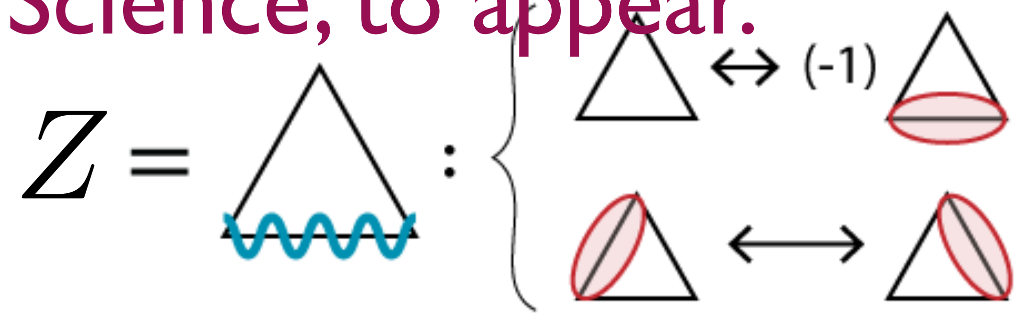



Measurement of
the topological
$X$ operator
$= \prod_{\text{loop}} \sigma^x_\ell$.
Detects close-packed dimers.

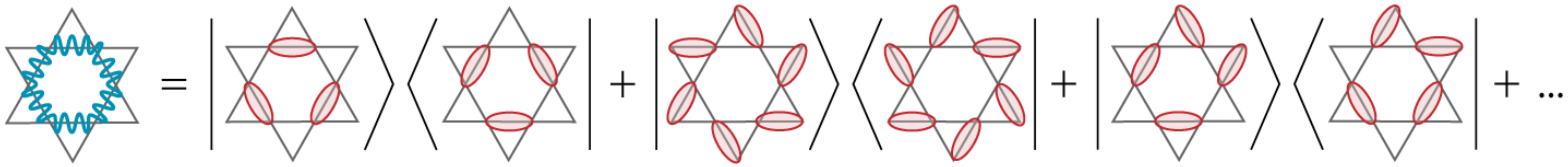


# Probing Topological Spin Liquids on a Programmable Quantum Simulator

G. Semeghini, H. Levine, A. Keesling, S. Ebadi, T. T. Wang, D. Bluvstein, R. Verresen, H. Pichler, M. Kalinowski, R. Samajdar, A. Omran, S. Sachdev, A. Vishwanath, M. Greiner, V. Vuletic, M. D. Lukin, arXiv:2104.04119; Science, to appear.




Rydberg atoms on the link-kagome lattice: experiment




Measurement of the topological $Z$ operator. Detects resonance between dimer loops.