THEORETICAL PHYSICS COLLOQUIUM
ARIZONA STATE UNIVERSITY
JAN 13, 2021

ATOMS AND IONS AS QUANTUM SIMULATORS OF QUARKS, GLUONS, AND NUCLEI?

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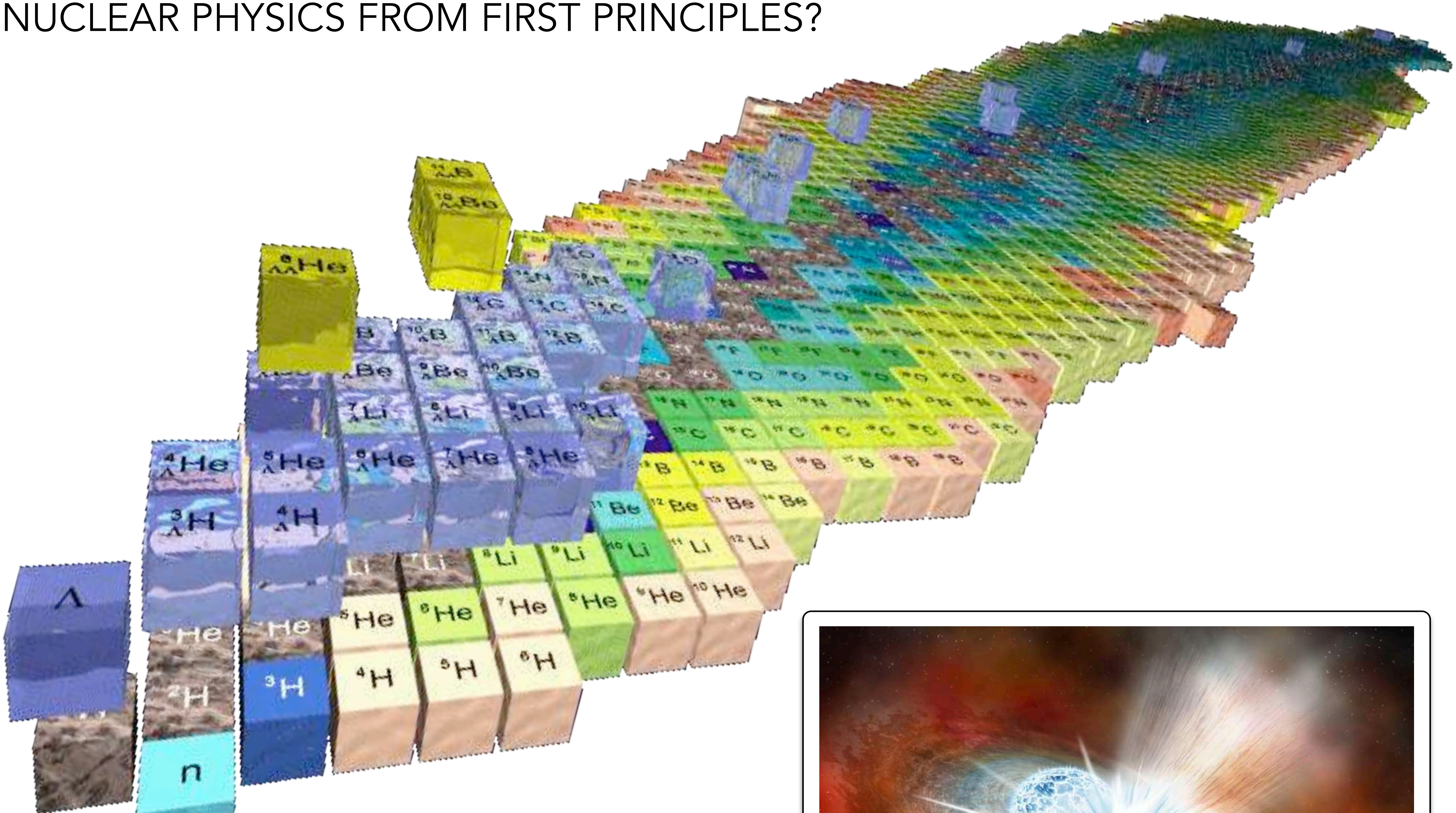
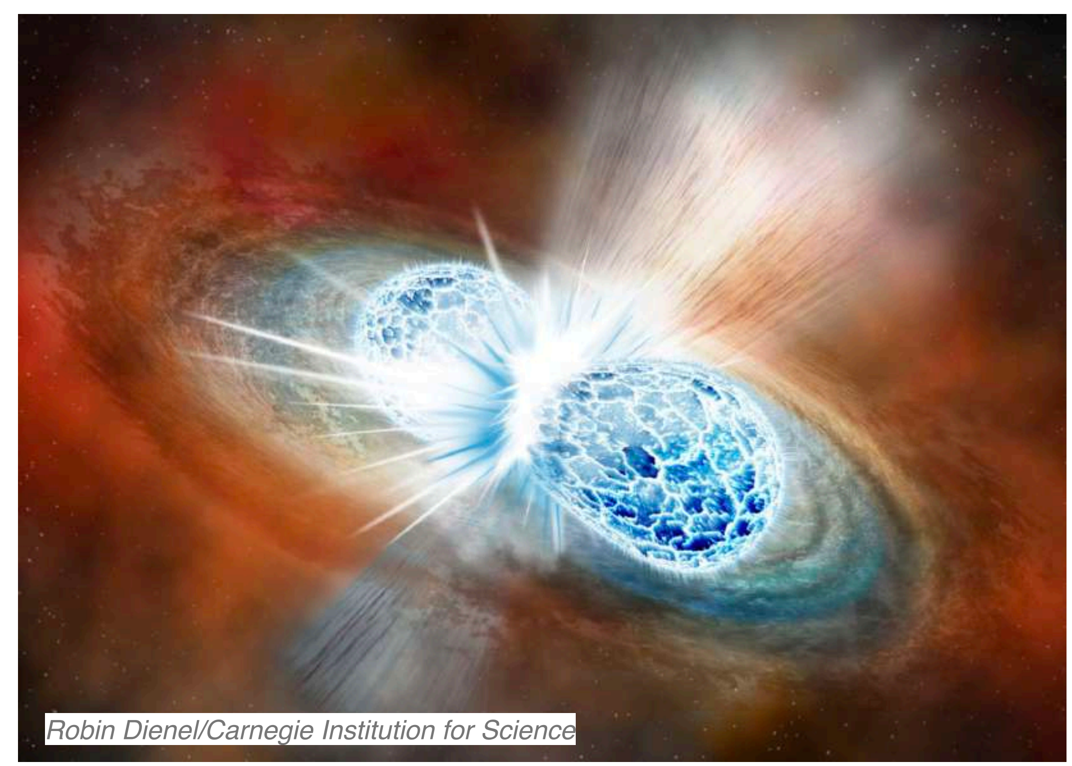
UNIVERSITY OF MARYLAND, COLLEGE PARK

NUCLEAR PHYSICS FROM FIRST PRINCIPLES?





QUANTUM CHROMODYNAMICS (QCD)

QCD is a SU(3) gauge theory augmented with several flavors of massive quarks:

$$\mathcal{L}_{QCD} = \sum_{f=1}^{N_f} [\bar{q}_f (i\gamma^\mu \partial_\mu - m_f) q_f - g A^i_\mu \bar{q}_f \gamma^\mu T^i q_f]$$
$$-\frac{1}{4} F^i_{\mu\nu} F^{i\mu\nu} + \frac{g}{2} f_{ijk} F^i_{\mu\nu} A^{i\mu} A^{j\nu} - \frac{g^2}{4} f_{ijk} f_{klm} A^j_\mu A^k_\nu A^{l\mu} A^{m\nu}$$

Features:

i) There are only $1 + N_f$ input parameters plus QED coupling. Fix them by few quantities and all nuclear physics is predicted (in principle)!

ii) QCD is asymptotically free and exhibits confinement.

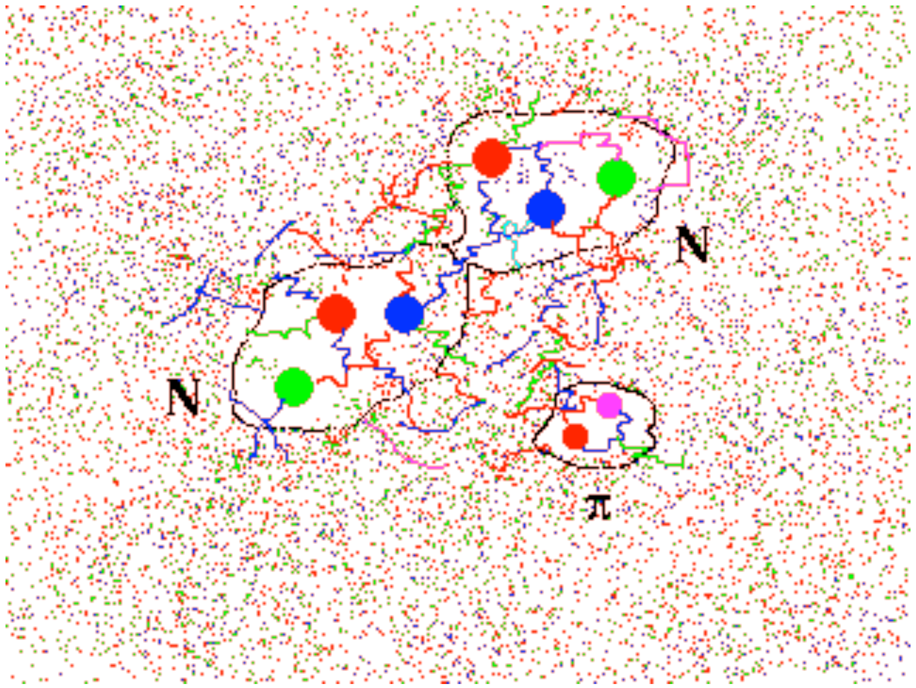
WHAT CAN WE DO AT LOW ENERGIES?

$$\mathcal{L}_{QCD}[q, \bar{q}, A; m_q, \alpha_s]$$

$$p, m << \Lambda$$

$$\mathcal{L}_{EFT}[\pi, N, ...; m_\pi, m_N, ..., C_i]$$

Low-energy constants



Write down effective interactions consistent with QCD: effective field theories

WHAT CAN WE DO AT LOW ENERGIES?

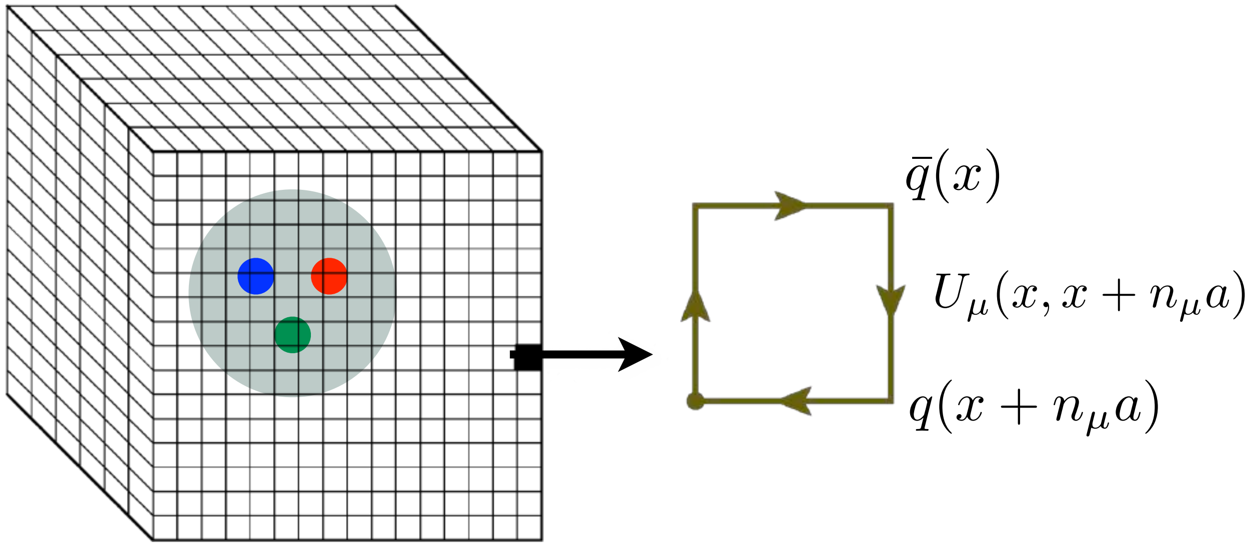
Solve it nonperturbatively: Lattice QCD

$$\mathcal{L}_{QCD}[q, \bar{q}, A; m_q, \alpha_s]$$

$$\int d^4x \to a^4 \sum_{\mathbf{n}}$$

$$\mathcal{L}_{LQCD}[q, \bar{q}, U[A]; m_q a, \beta]$$

Extrapolate to infinite volume and zero lattice spacing

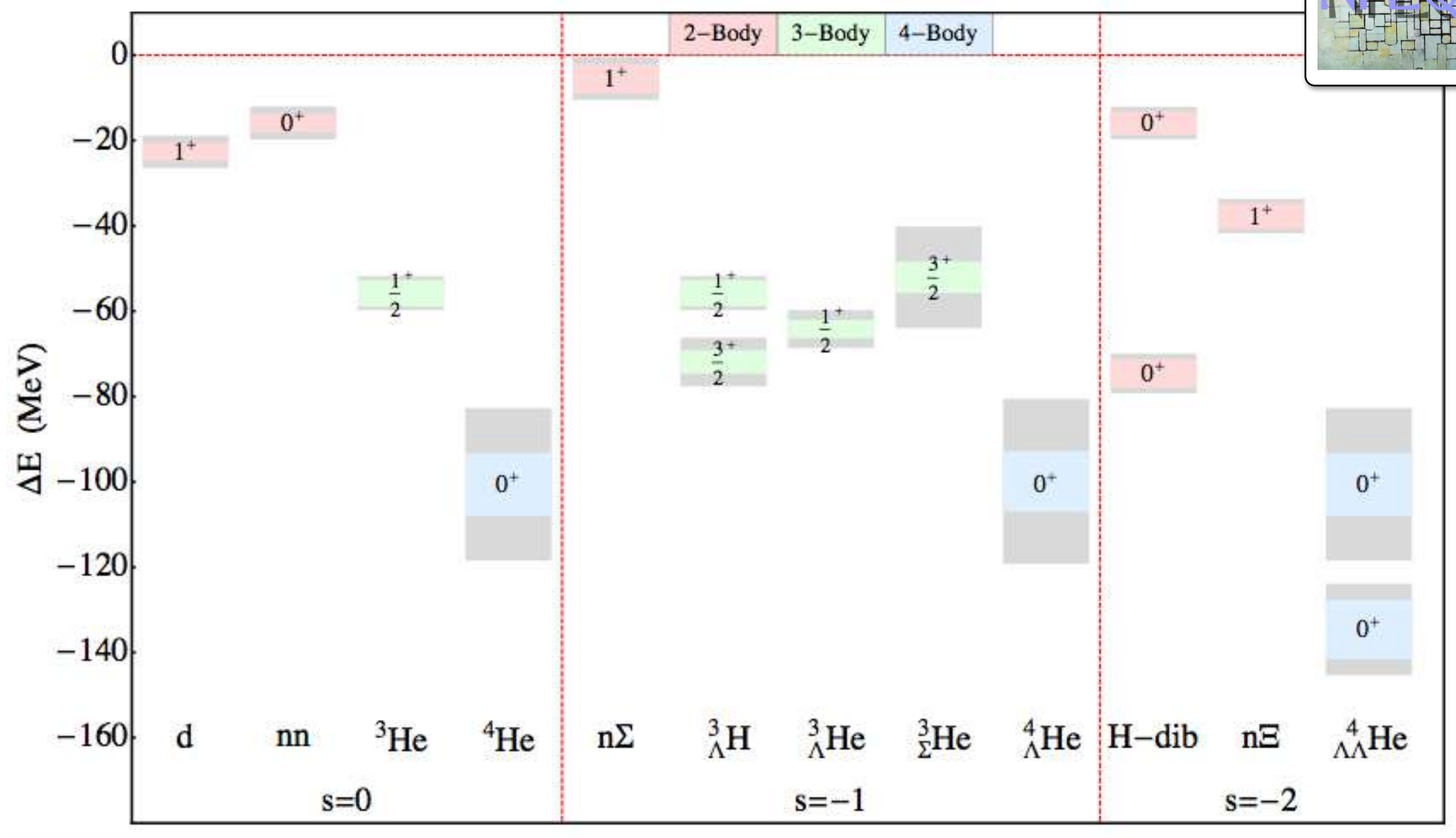


LATTICE QCD COMBINED WITH EFFECTIVE FIELD THEORIES IS ON TRACK TO DELIVER RESULTS ON IMPORTANT QUANTITIES IN NUCLEAR AND HIGH-ENERGY PHYSICS.

A recent review on low-energy nuclear physics from lattice QCD: ZD et al (NPLQCD), arXiv:2008.11160 [hep-lat], accepted to Physics Reports.

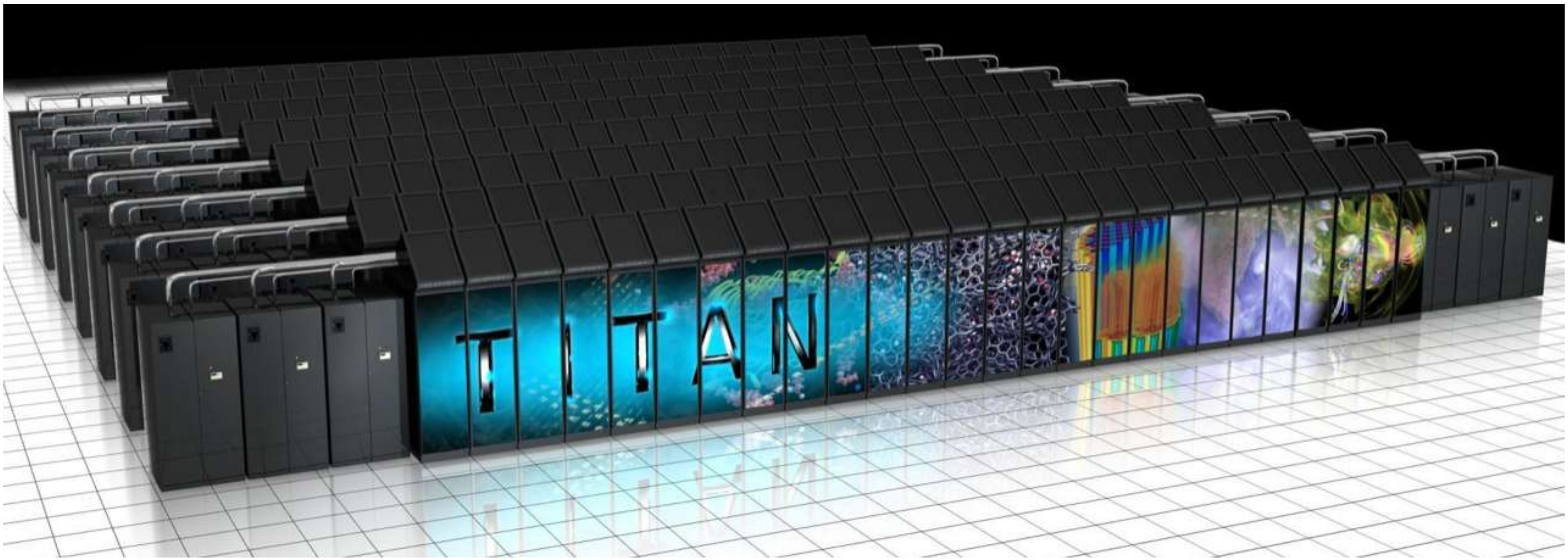
A MILESTONE: NUCLEI FROM QCD IN A WORLD WITH HEAVIER QUARKS THAN THOSE IN NATURE

$N_f = 3,\ m_\pi = 0.806\ \mathrm{GeV},\ a = 0.145(2)\ \mathrm{fm}$



Beane, et al. (NPLQCD), Phys.Rev. D87 (2013), Phys.Rev. C88 (2013)

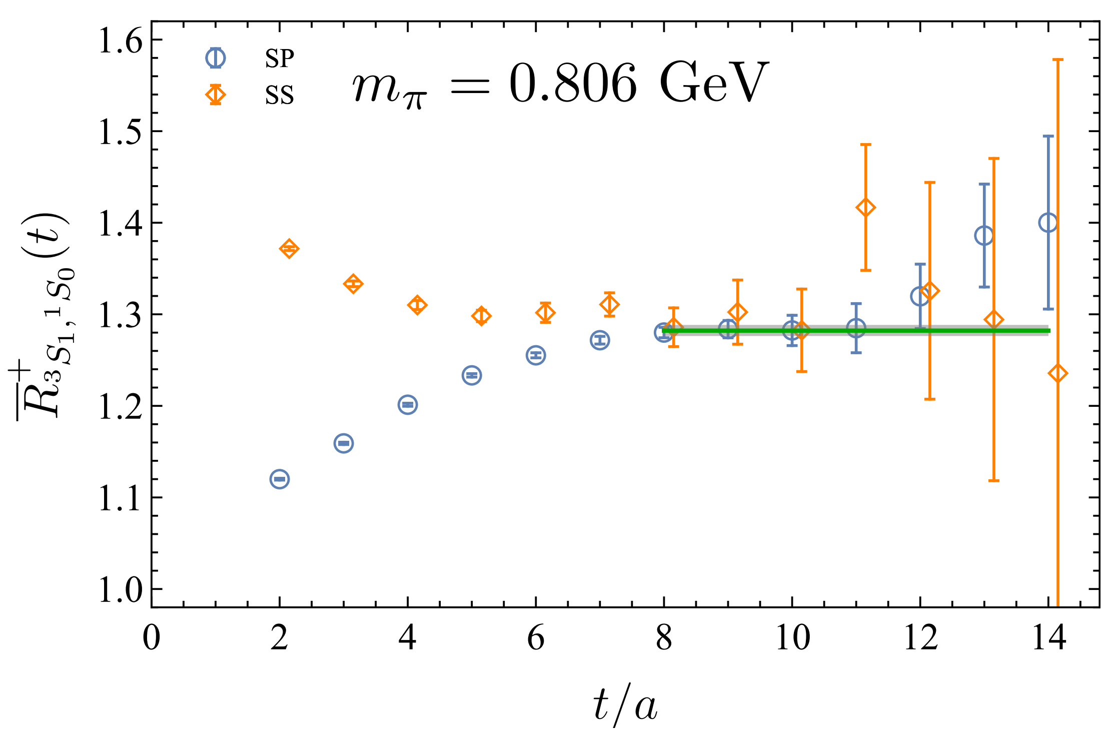
THIS STUDY TOOK ABOUT TWO YEARS AND A FEW HUNDRED MILLION CPU HOURS ON THE LARGEST SUPERCOMPUTERS IN THE U.S.!



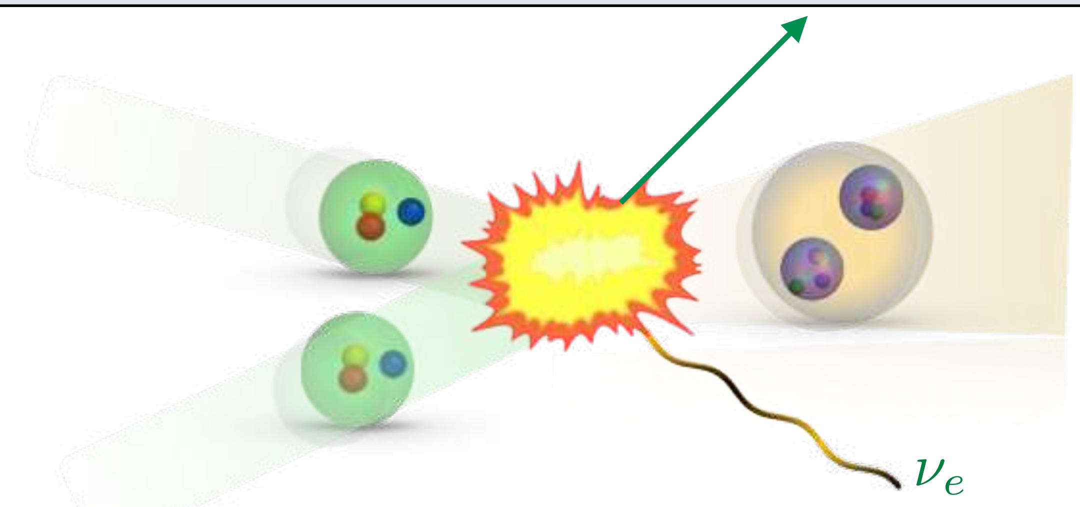
Titan supercomputer, Oak Ridge National Laboratory, USA

A SINGLE-WEAK PROCESS

$$pp \to de^+\nu_e$$



Savage, ZD et al, Phys.Rev.Lett.119,062002(2017).

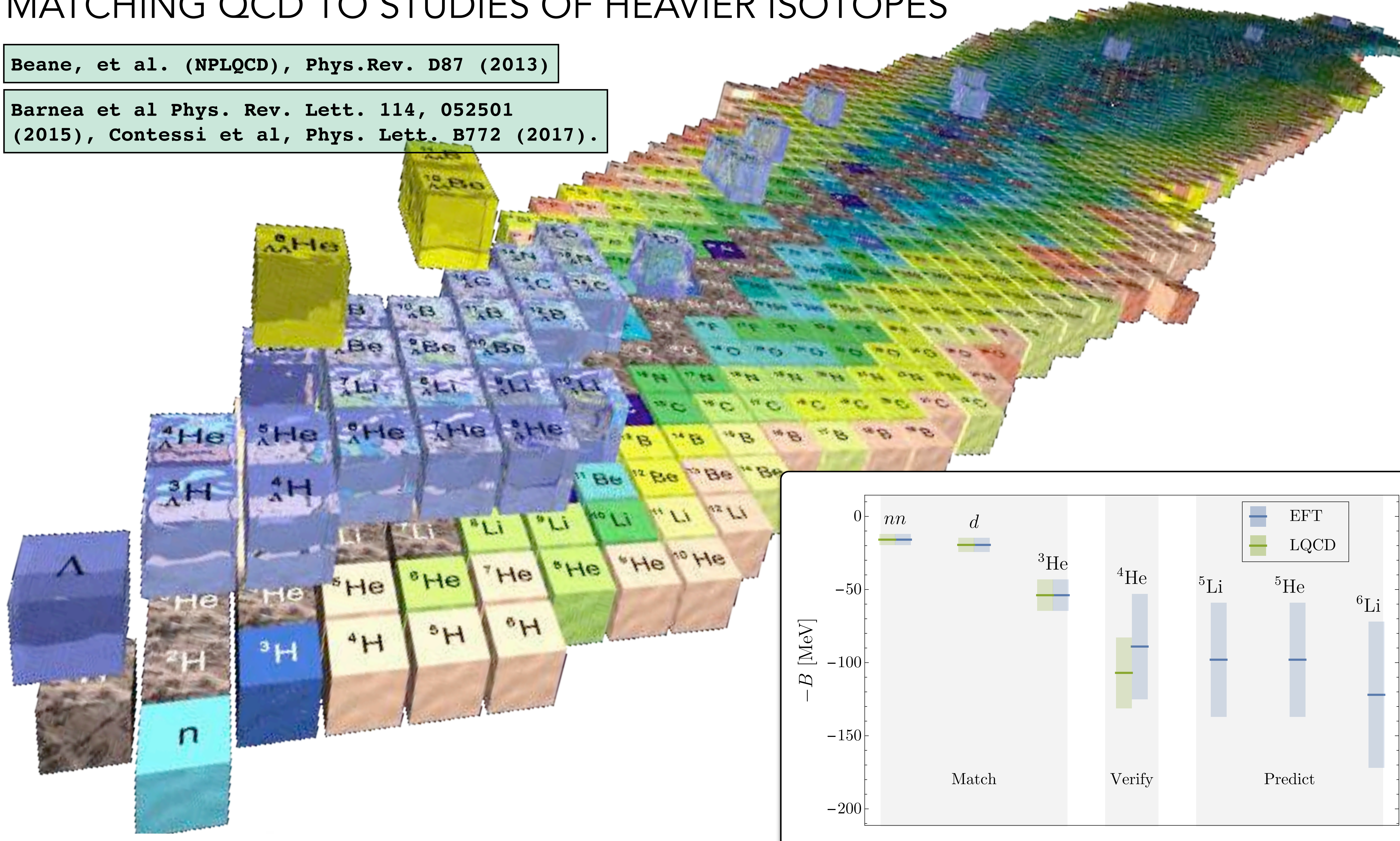


$L_{1,A} = 3.9(0.1)(1.0)(0.3)(0.9)\ \mathrm{fm}^3 \quad @\mu = m_\pi^{\mathrm{phys.}} = 140\ \mathrm{MeV}$

MATCHING QCD TO STUDIES OF HEAVIER ISOTOPES

Beane, et al. (NPLQCD), Phys.Rev. D87 (2013)

Barnea et al Phys. Rev. Lett. 114, 052501 (2015), Contessi et al, Phys. Lett. B772 (2017).



QCD input → Few-body EFT interactions → Many-body calculations of nuclei and hypernuclei

LATTICE GAUGE THEORY IS SUPPORTING A MULTI-BILLION DOLLAR EXPERIMENTAL PROGRAM!

Slide content courtesy of Martin Savage.

THREE FEATURES MAKE LATTICE QCD CALCULATIONS OF NUCLEI HARD:

i) The complexity of systems grows factorially with the number of quarks.

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Detmold and Orginos (2013)
Detmold and Savage (2010)
Doi and Endres (2013)
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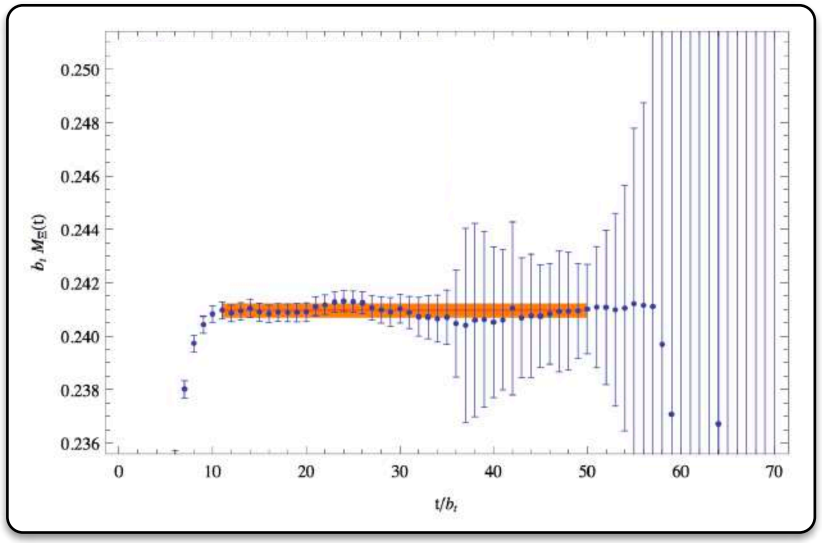

ii) There is a severe signal-to-noise degradation.

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Paris (1984) and Lepage (1989)
Wagman and Savage (2017, 2018)
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iii) Excitation energies of nuclei are much smaller than the QCD scale.

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Beane at al (NPLQCD) (2009)
Beane, Detmold, Orginos, Savage (2011)
ZD (2018)
Briceno, Dudek and Young (2018)
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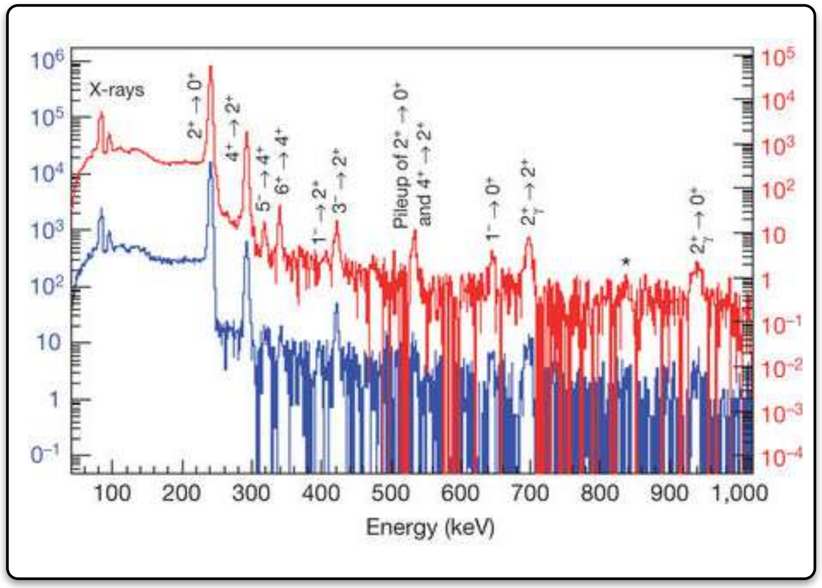
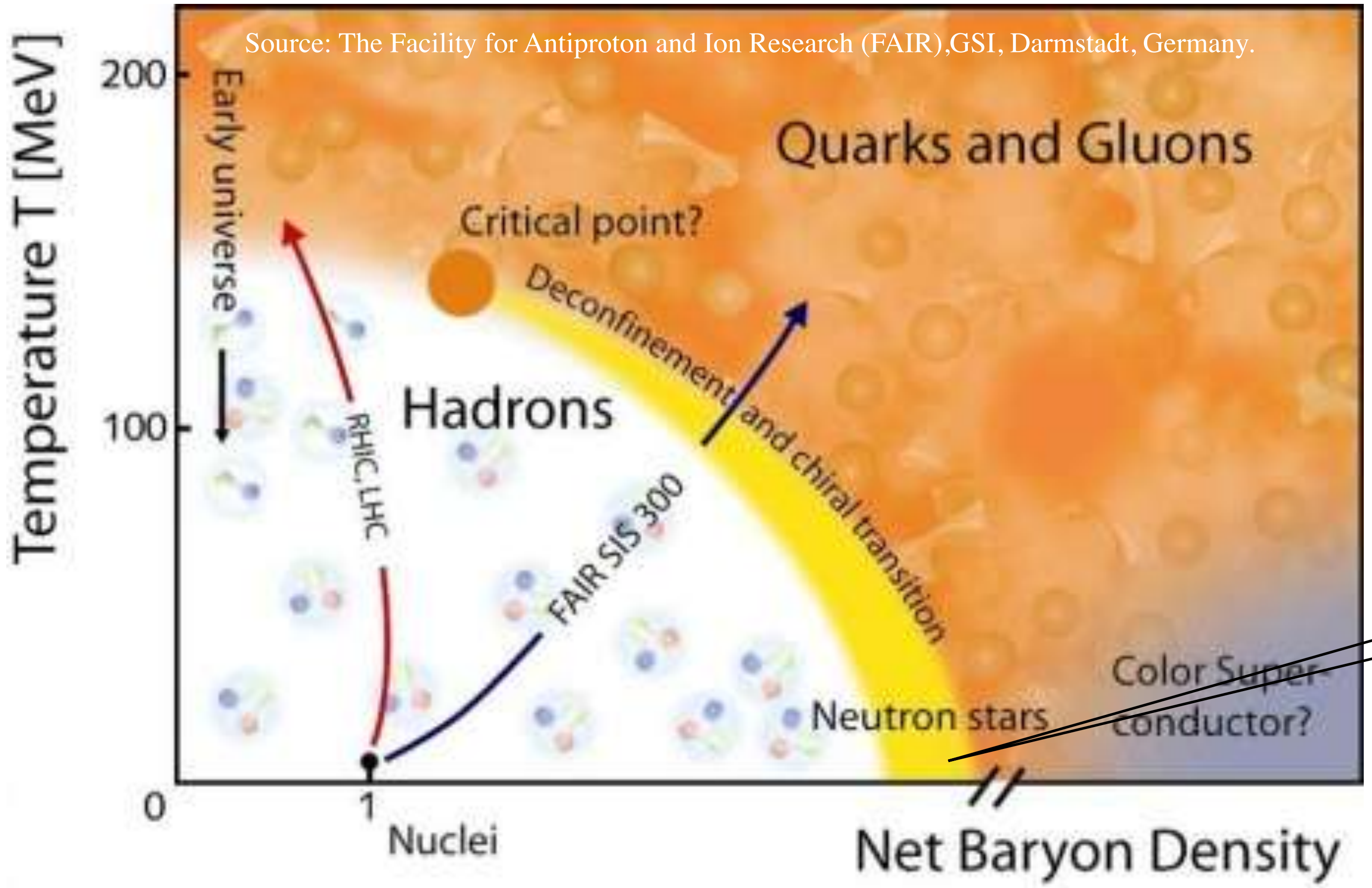
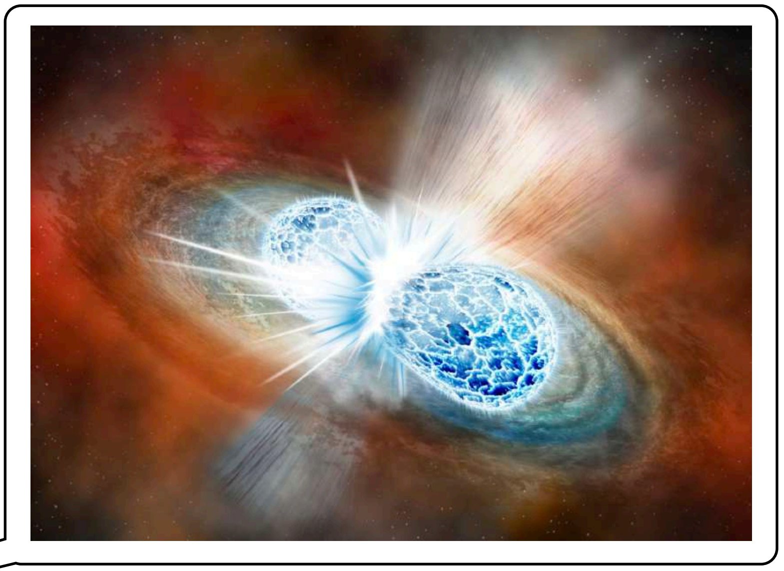


ADDITIONALLY THE SIGN PROBLEM FORBIDS:

i) Studies of nuclear isotopes, dense matter, and phase diagram of QCD… both with lattice QCD and with ab initio nuclear many-body methods.





Path integral formulation:

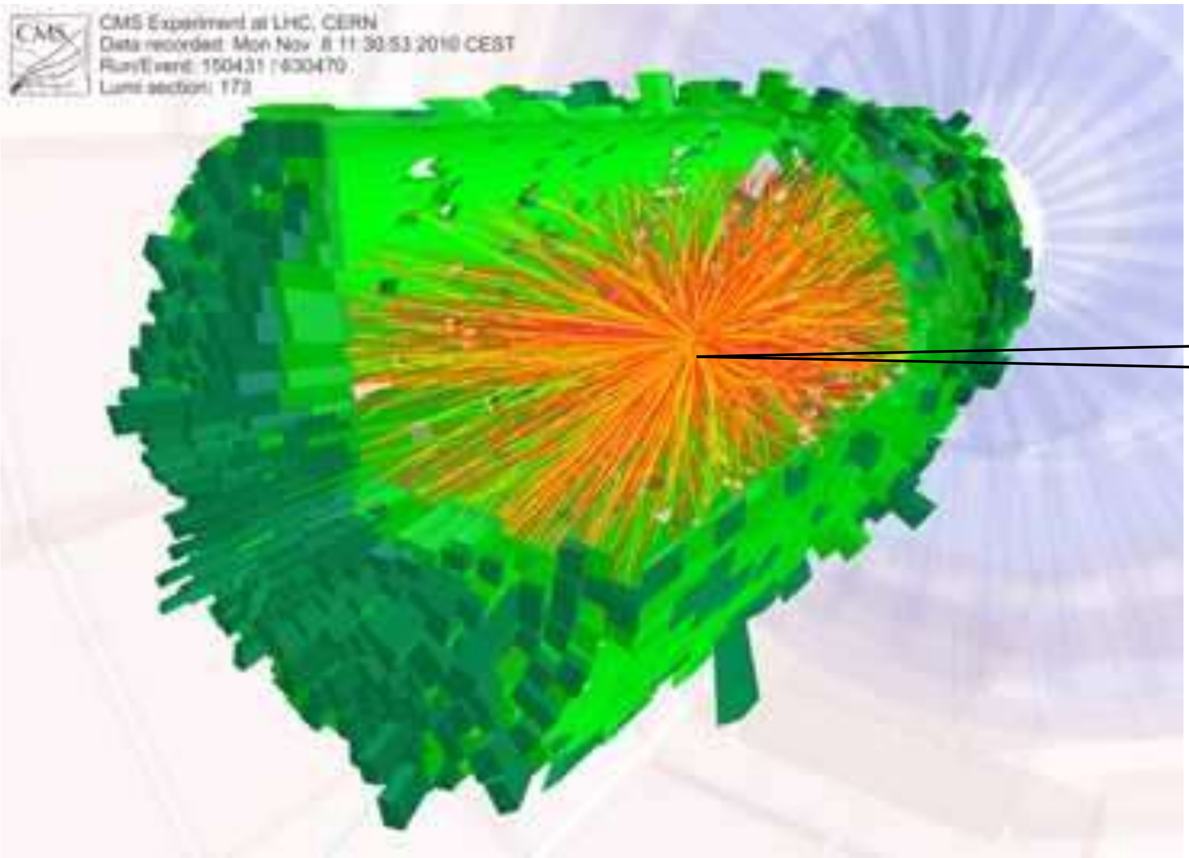
$$e^{-S[U,q,\bar{q}]}$$

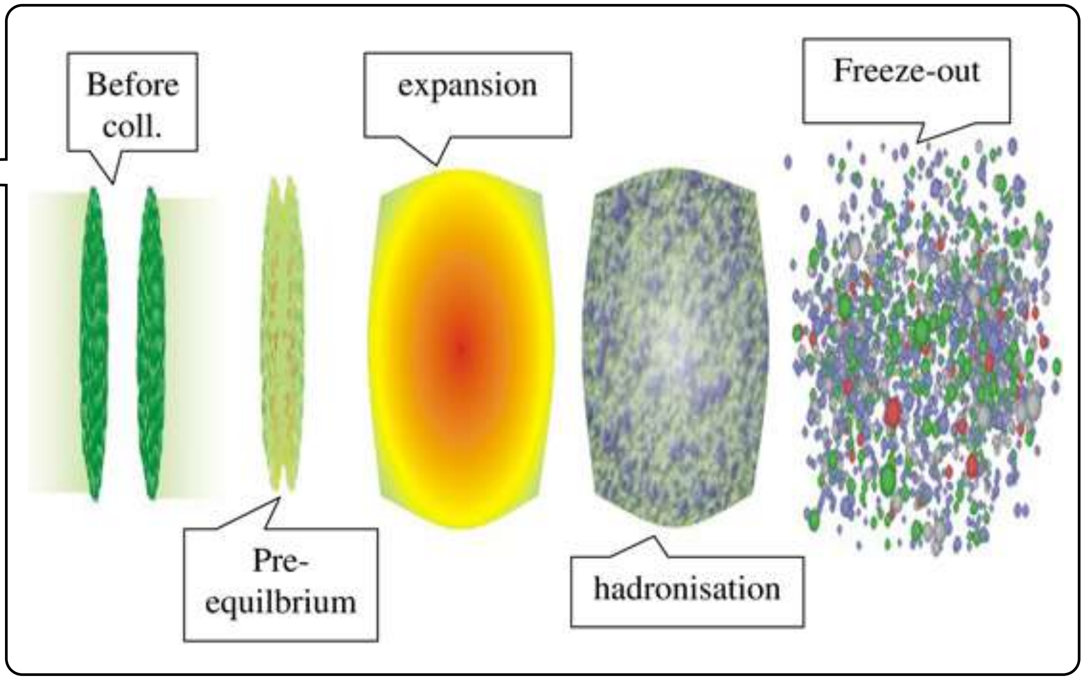
with a complex action:

$$\mathcal{L}_{\mathrm{QCD}} \to \mathcal{L}_{\mathrm{QCD}} - i\mu \sum_f \bar{q}_f \gamma^0 q_f$$

ADDITIONALLY THE SIGN PROBLEM FORBIDS:

ii) Real-time dynamics of matter in heavy-ion collisions or after Big Bang…





…and a wealth of dynamical response functions, transport properties, hadron distribution functions, and non-equilibrium physics of QCD.

Path integral formulation:

$$e^{iS[U,q\bar{q}]}$$

Hamiltonian evolution:

$$U(t) = e^{-iHt}$$

AN OPPORTUNITY TO EXPLORE NEW PARADIGMS AND NEW TECHNOLOGIES IN SIMULATION: QUANTUM SIMULATION?

QUANTUM SIMULATION FOR NUCLEAR AND HIGH-ENERGY PHYSICS: WHAT IT IMPLIES.

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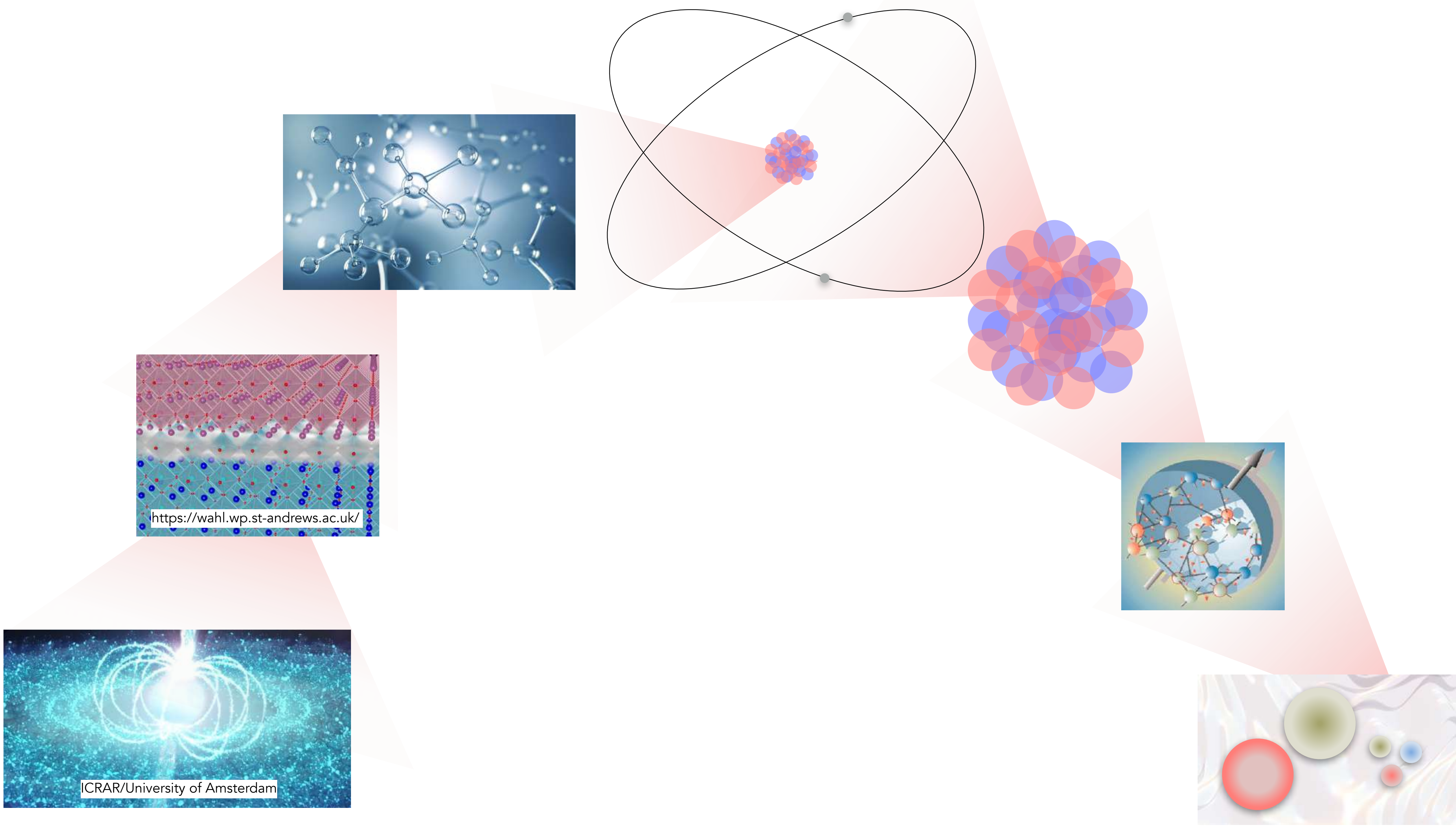
Quantum simulation amounts to leveraging a quantum system that can be controlled to study another quantum systems that is more elusive, experimentally or computationally.



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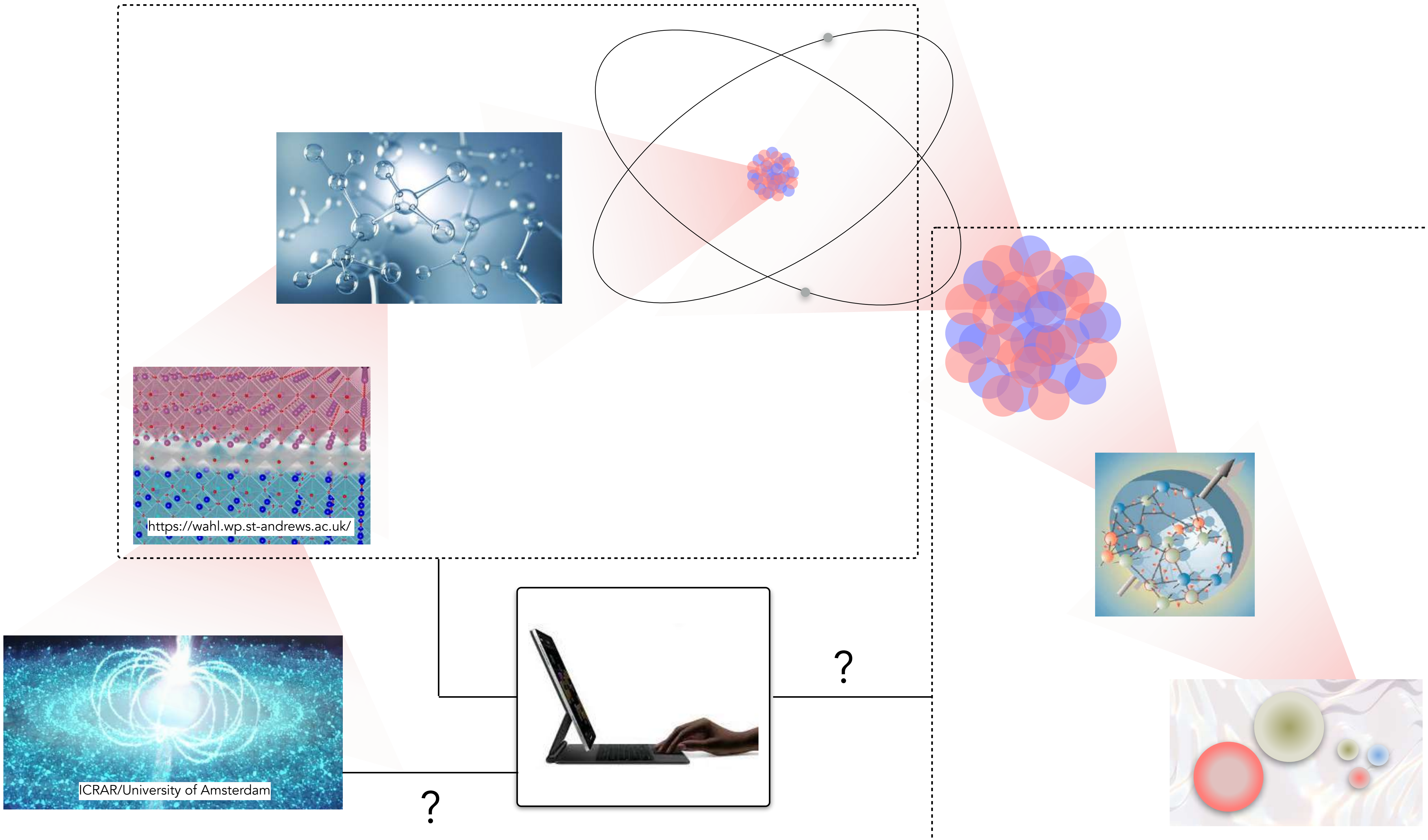

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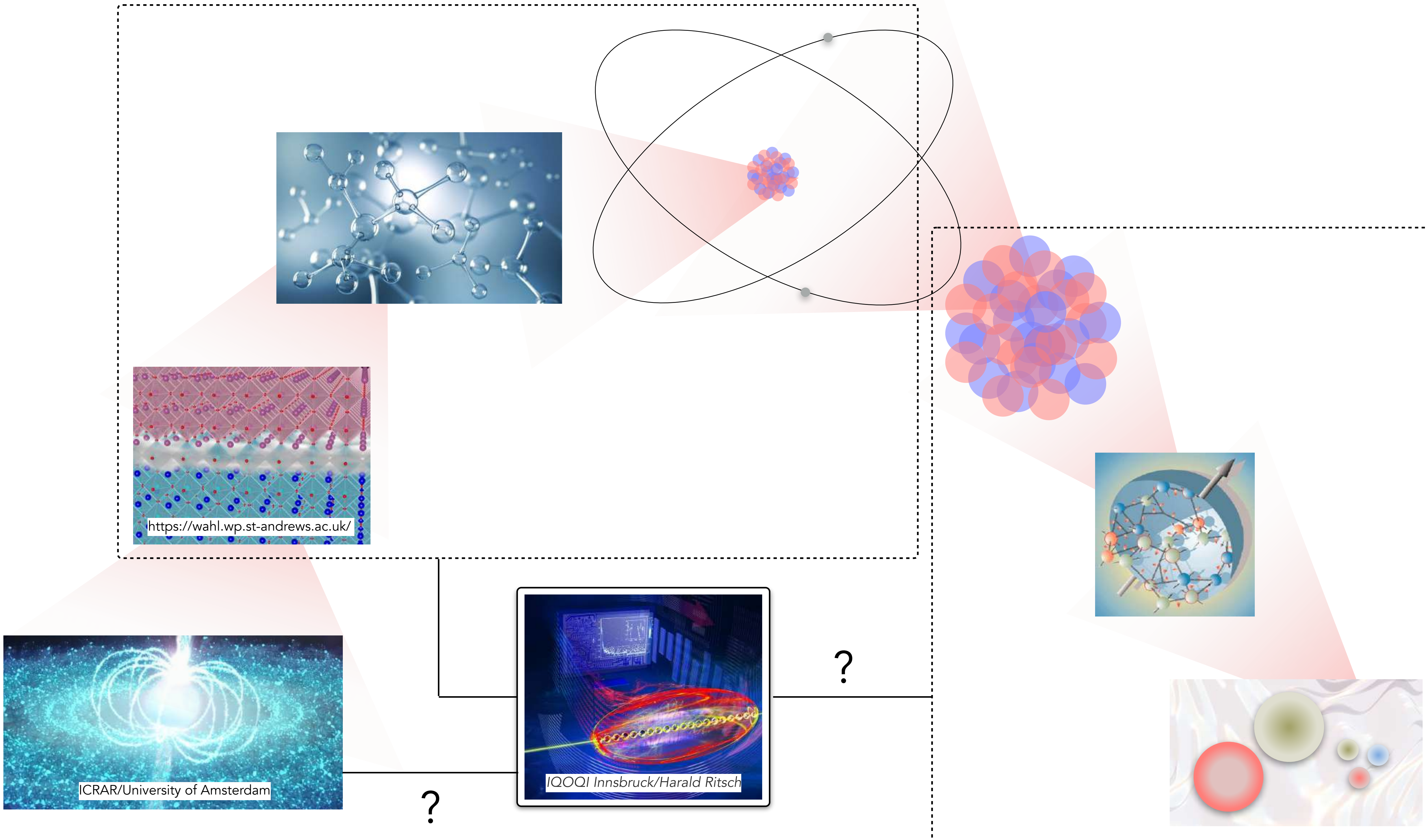
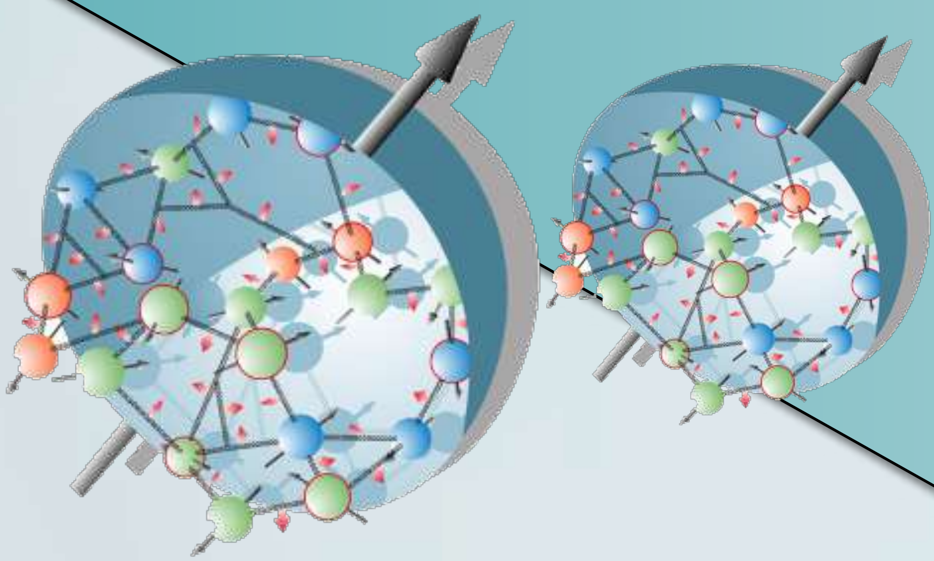


A RANGE OF QUANTUM SIMULATORS WITH VARING CAPACITY AND CAPABILITY IS AVAILABLE!

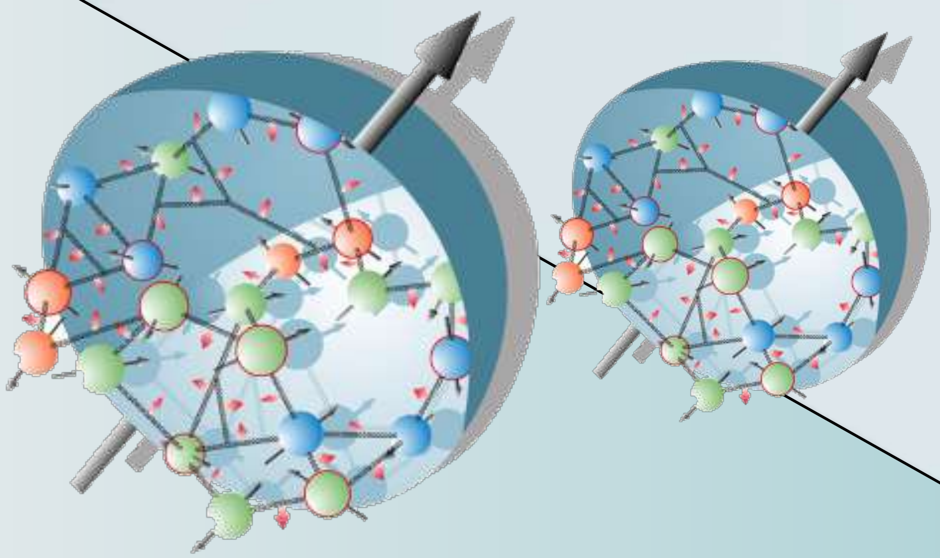
SOME SIMILARITIES BUT MAJOR DIFFERENCES WITH CONDENSED MATTER AND CHEMISTRY PROBLEMS



Starting from the nucelar Hamiltonian

More complex Hamiltonian, itself unknown with arbitrary accuracy, short, intermediate, and long-range interactions, three and multi-body interactions, pions (bosons) and other hadrons can become dynamical.

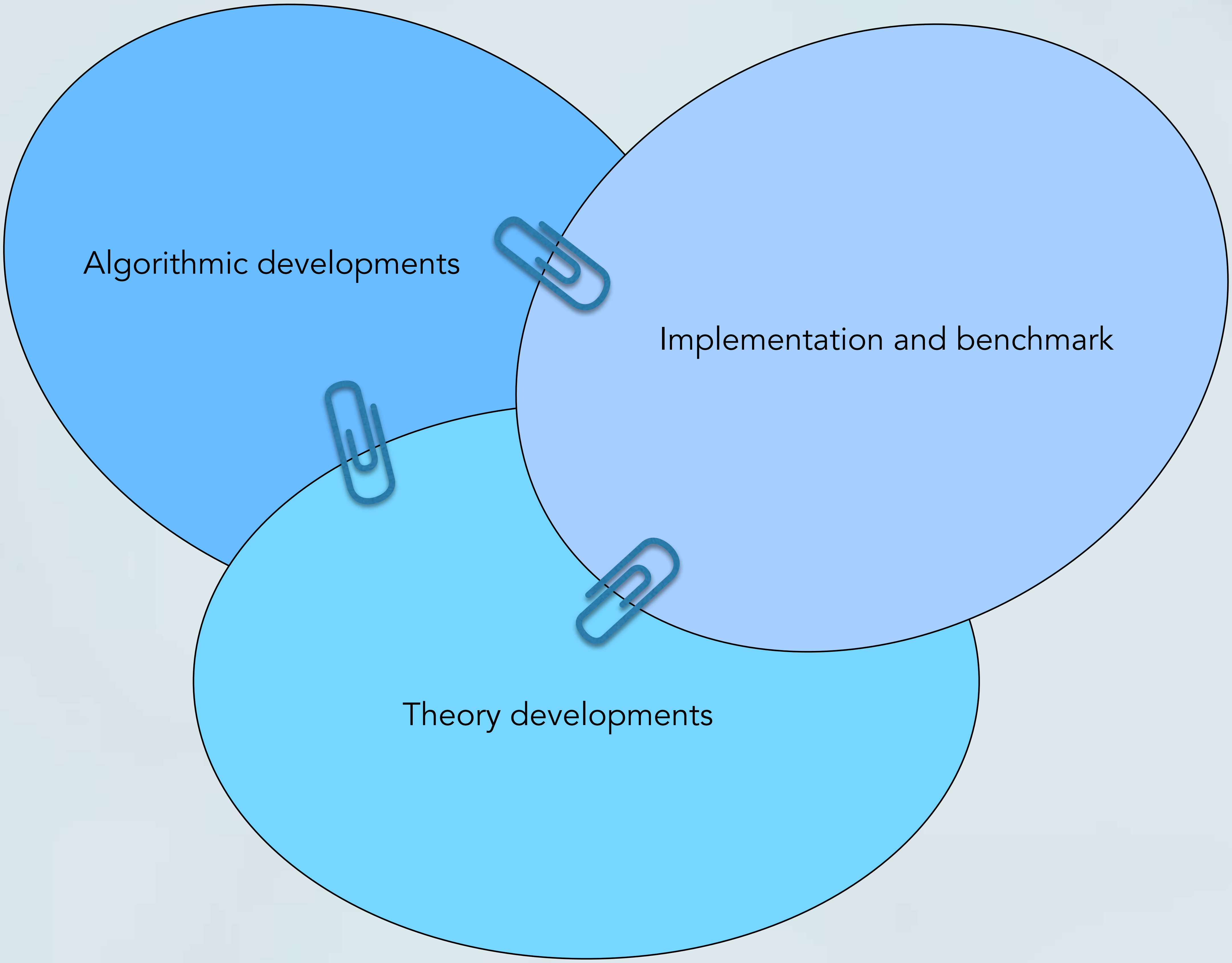
SOME SIMILARITIES BUT MAJOR DIFFERENCES WITH CONDENSED MATTER AND CHEMISTRY PROBLEMS



Starting from the Standard Model

Both bosonic and fermionic DOF are dynamical and coupled, exhibit both global and local (gauge) symmetries, relativistic hence particle number not conserved, vacuum state nontrivial in strongly interacting theories.

QUANTUM SIMULATION OF QUANTUM FIELD THEORIES INVOLVES:



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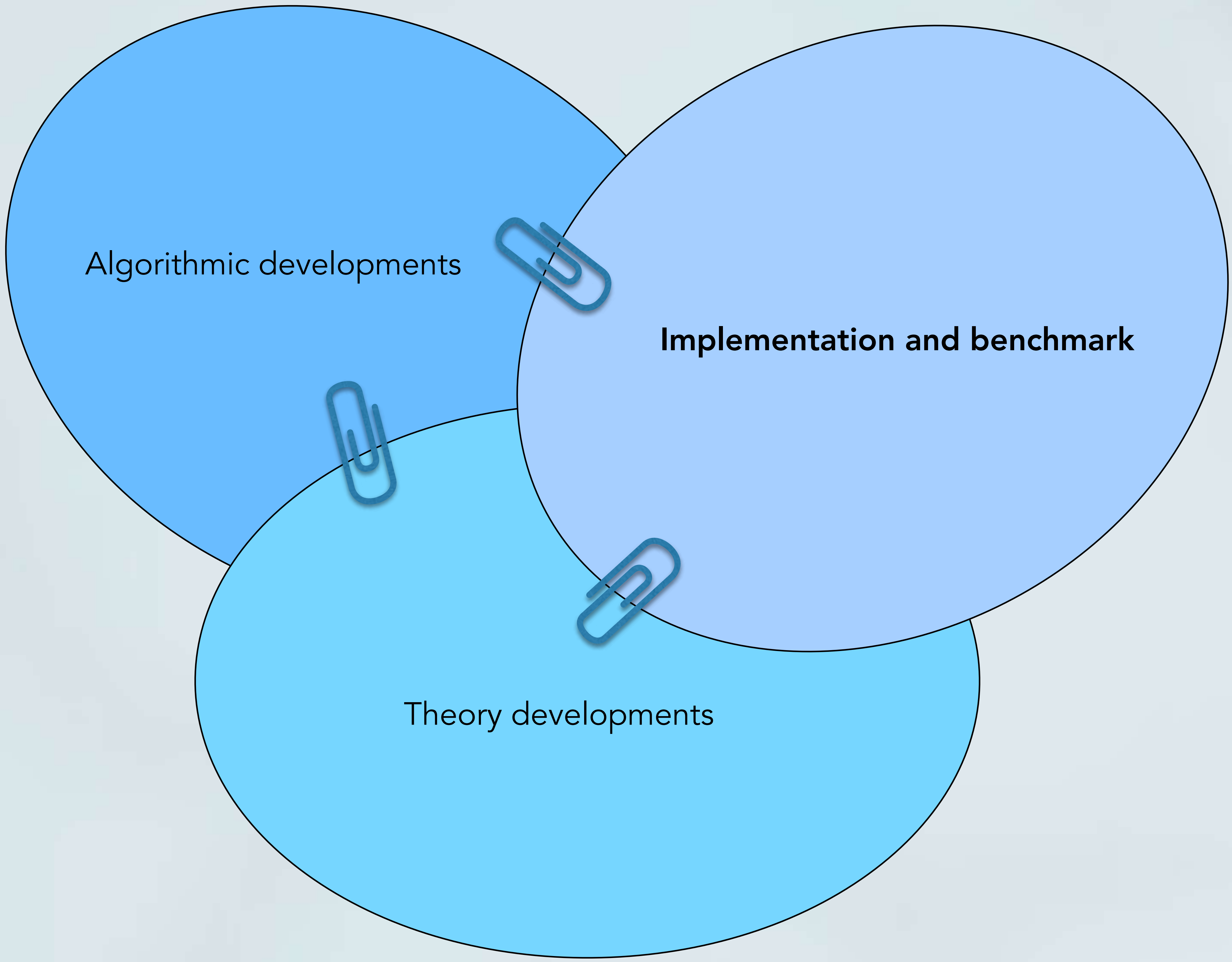
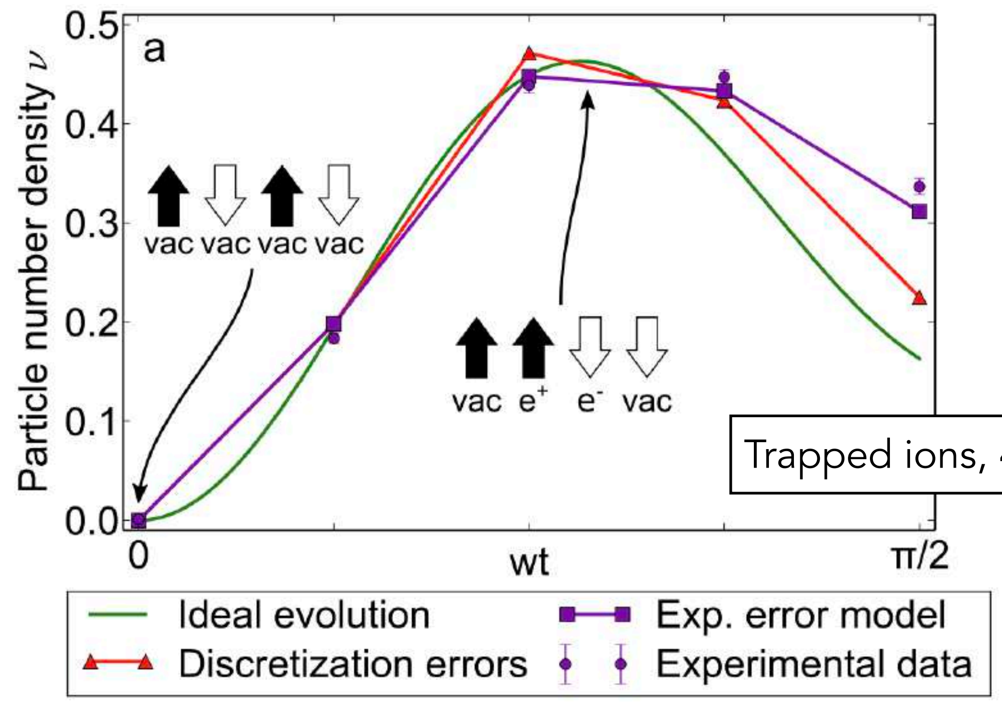
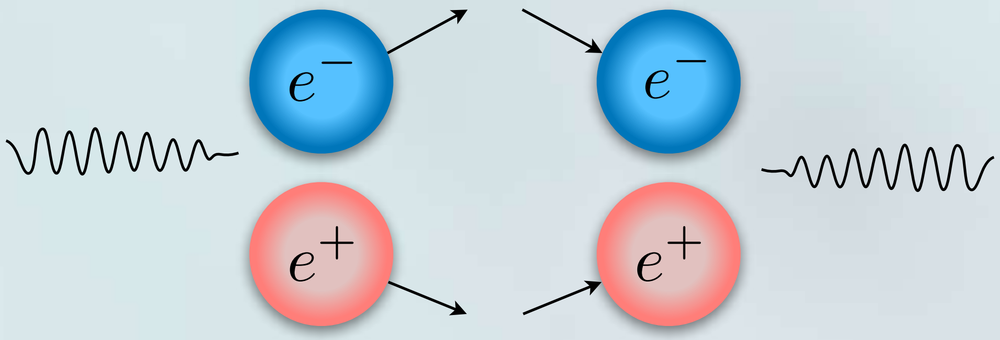


IMPLEMENTATION AND BENCHMARK: DIGITAL EXAMPLES





Martinez, Muschik, Schindler, Nigg, Erhard, Heyl, Hauke, Dalmonte, Monz, Zoller, Blatt, Nature 534, 516-519 (2016)

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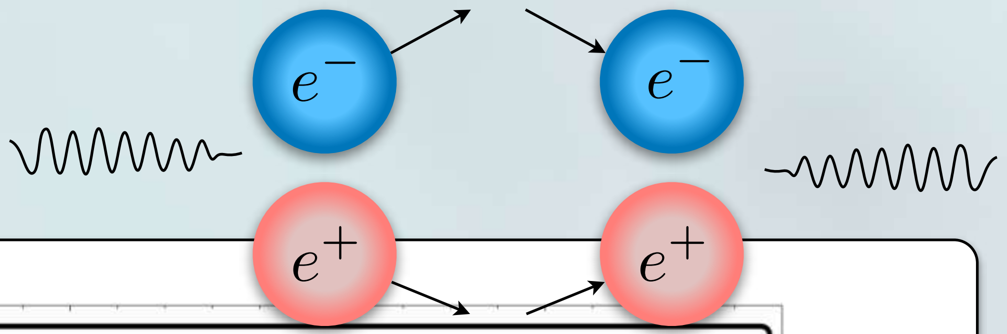
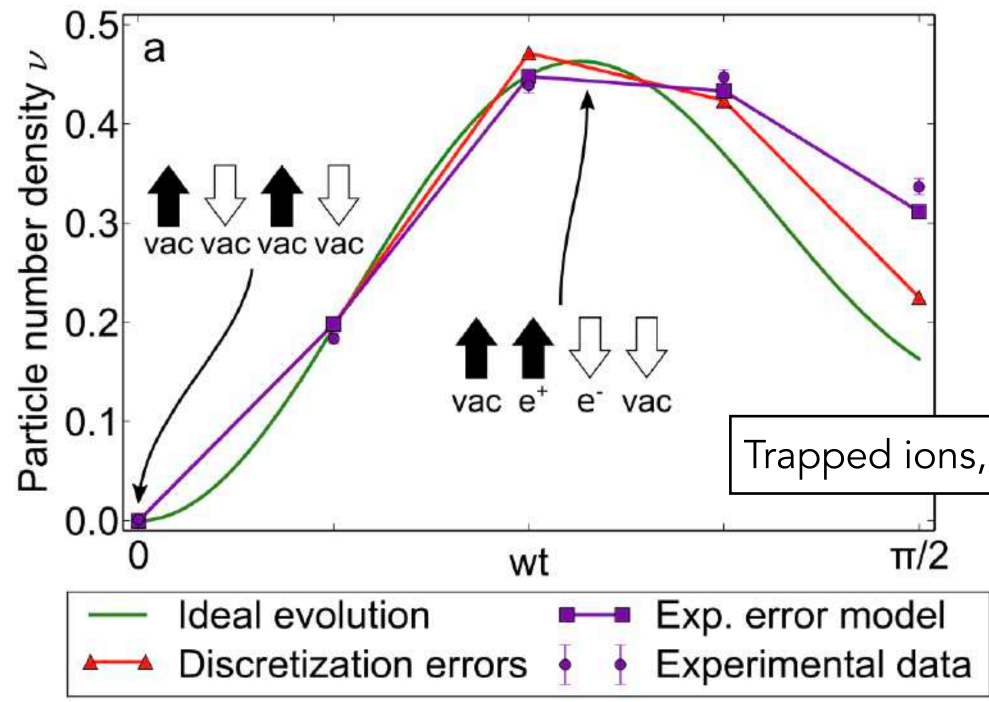
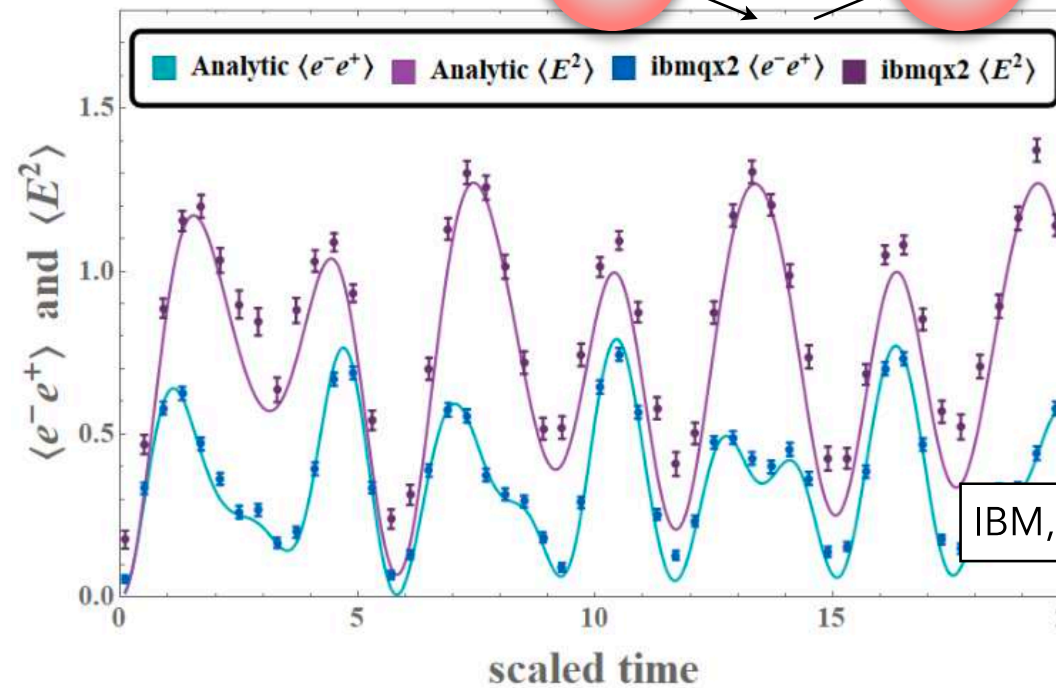




Trapped ions, 4 qubits

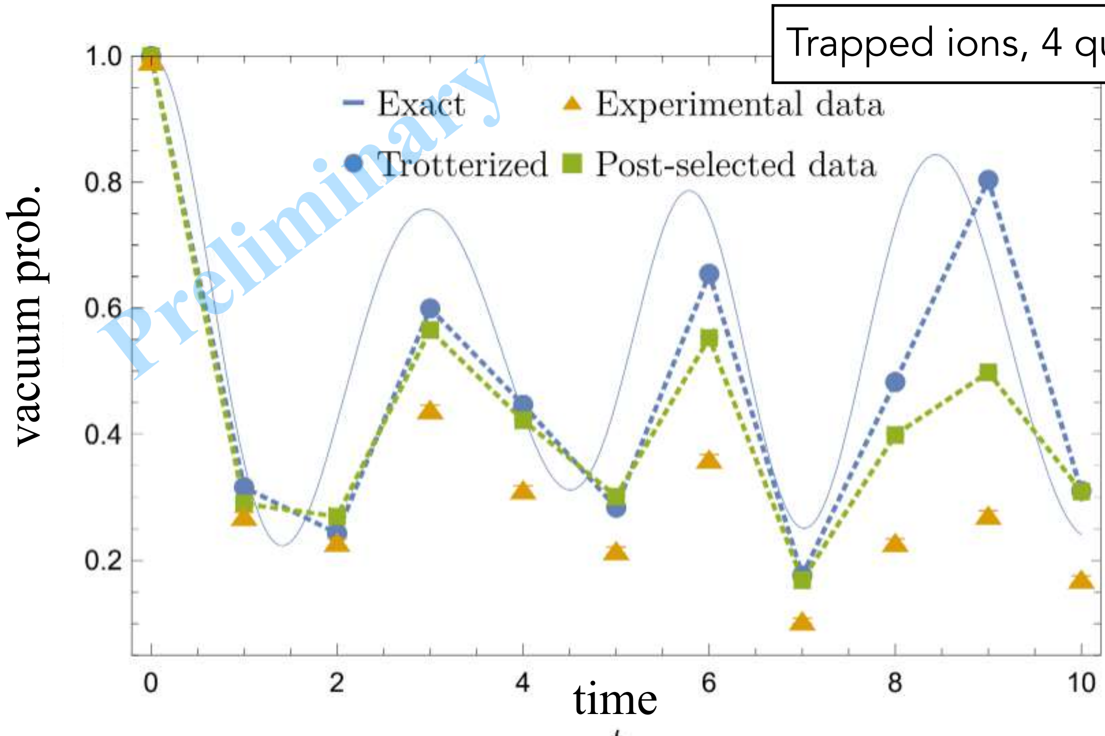
Martinez, Muschik, Schindler, Nigg, Erhard, Heyl, Hauke, Dalmonte, Monz, Zoller, Blatt, Nature 534, 516-519 (2016)



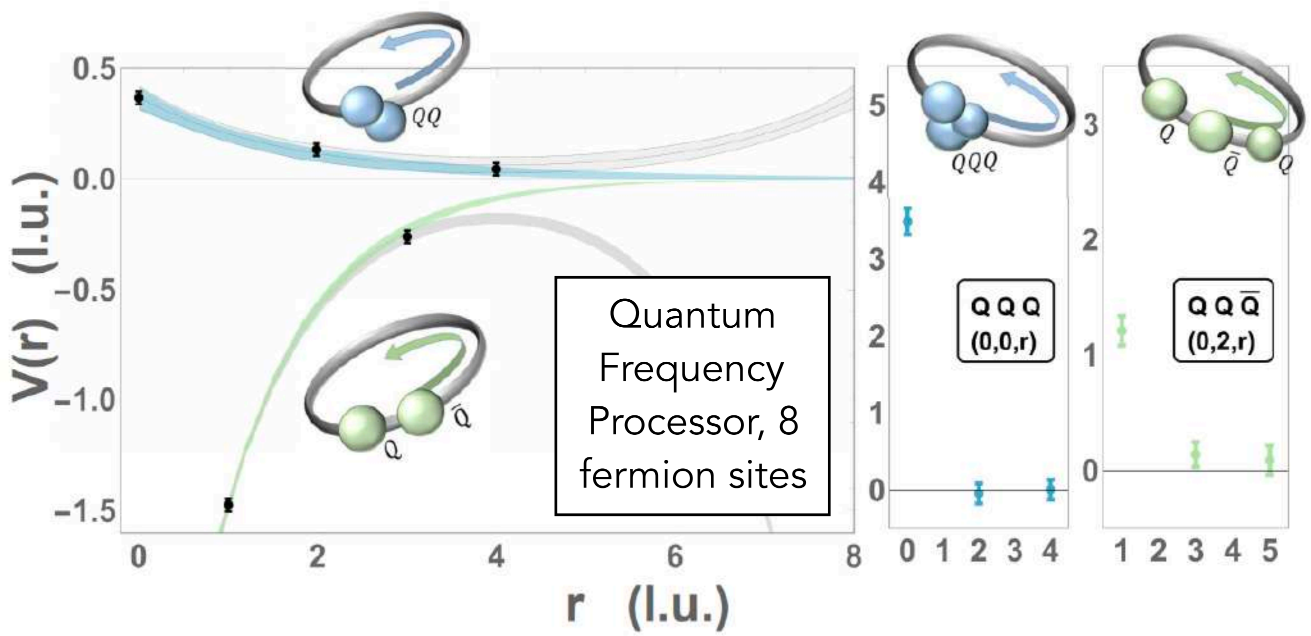
IBM, 2 qubits

Klco, Dumitrescu, McCaskey, Morris, Pooser, Sanz, Solano, Lougovski, Savage, Phys. Rev. A 98, 032331 (2018)

Trapped ions, 4 qubits



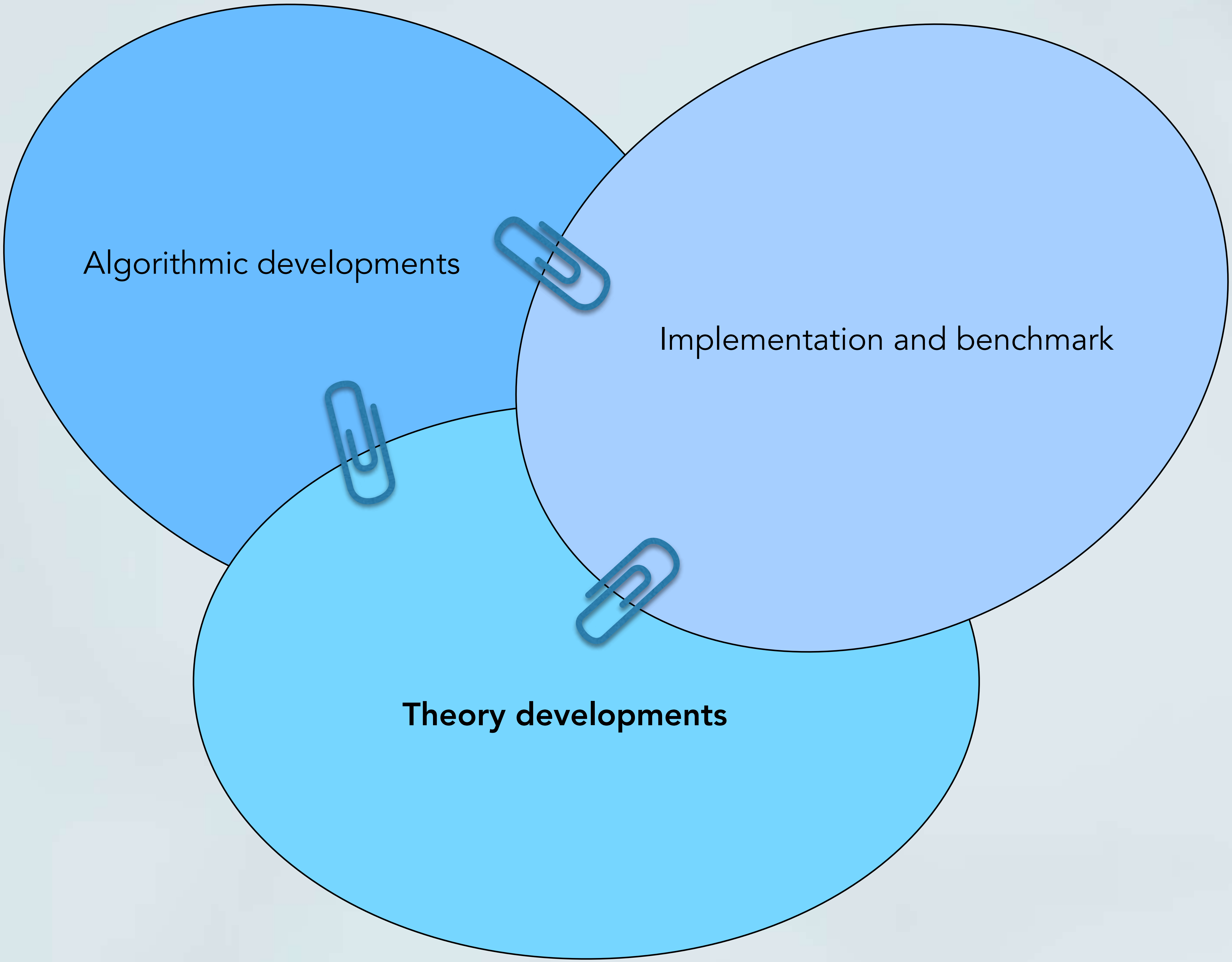
Nguyen, Shaw, Zhu, Huerta Alderete, ZD, Linke (2020)



Quantum Frequency Processor, 8 fermion sites

Lu, Klco, Lukens, Morris, Bansal, Ekström, Hagen, Papenbrock, Weiner, Savage, Lougovski, Phys. Rev. A 100, 012320 (2019)

QUANTUM SIMULATION OF QUANTUM FIELD THEORIES INVOLVES:



Hamiltonian formalism maybe more natural than the path integral formalism for quantum simulation/computation:

Kogut and Susskind formulation:

$$H_{\rm QCD} = -t\sum_{\langle xy\rangle} s_{xy}\left(\psi_x^\dagger U_{xy}\psi_y + \psi_y^\dagger U_{xy}^\dagger \psi_x\right) + m\sum_x s_x \psi_x^\dagger \psi_x + \frac{g^2}{2}\sum_{\langle xy\rangle}\left(L_{xy}^2 + R_{xy}^2\right) - \frac{1}{4g^2}\sum_{\Box} {\rm Tr}\left(U_\Box + U_\Box^\dagger\right).$$

Fermion hopping term | Fermion mass | Energy of color electric field | Energy of color magnetic field

Generator of infinitesimal gauge transformation $G_x^a = \psi_x^{i\dagger}\lambda_{ij}^a\psi_x^j + \sum_k \left(L^a_{x,x+\hat{k}} + R^a_{x-\hat{k},x}\right) \Longrightarrow G_x^i|\psi(\{q_x^{(i)}\})\rangle = q_x^{(i)}|\psi(\{q_x^{(i)}\})\rangle$

EXAMPLES OF THEORY DEVELOPMENTS

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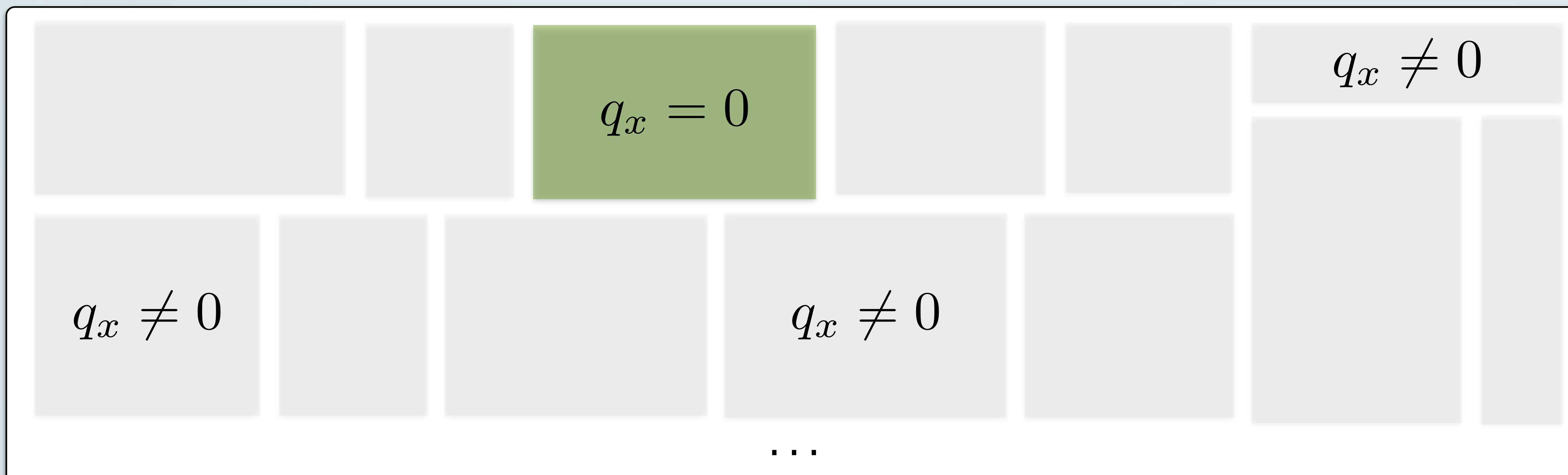

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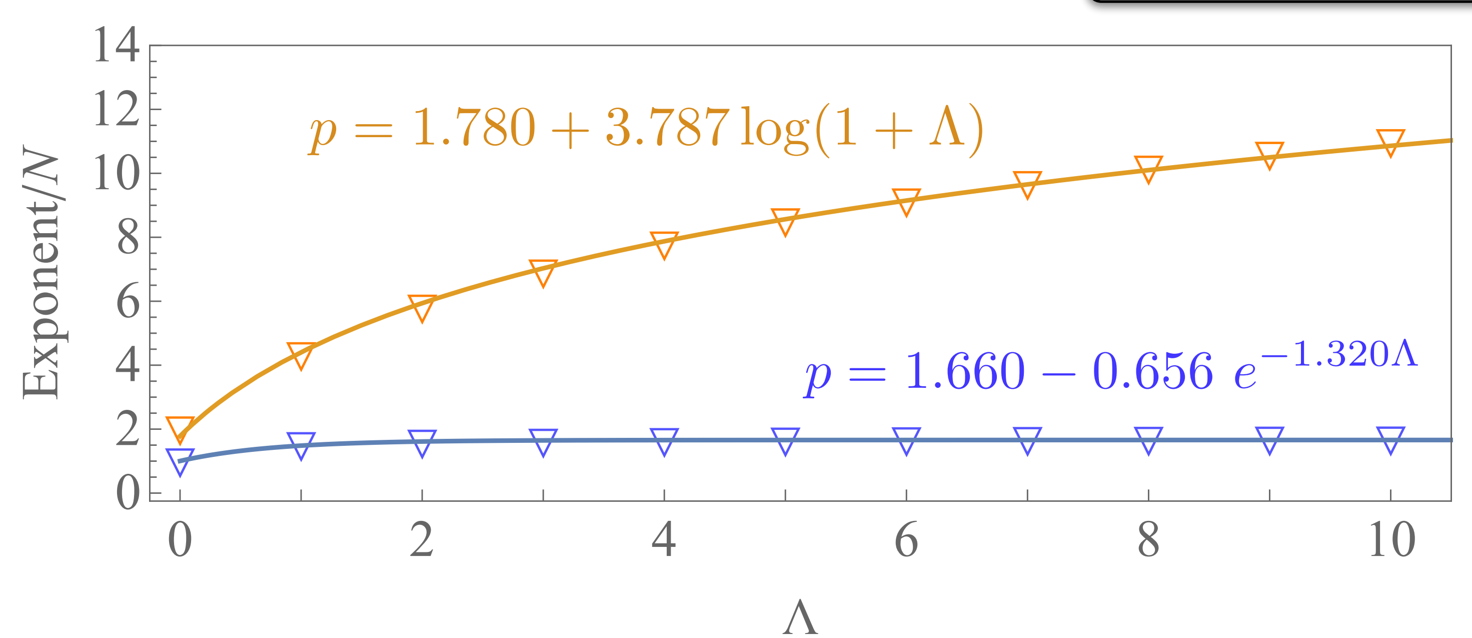
$N_{\rm state} \sim e^{pN}$

SU(2) gauge theory with matter in 1+1D

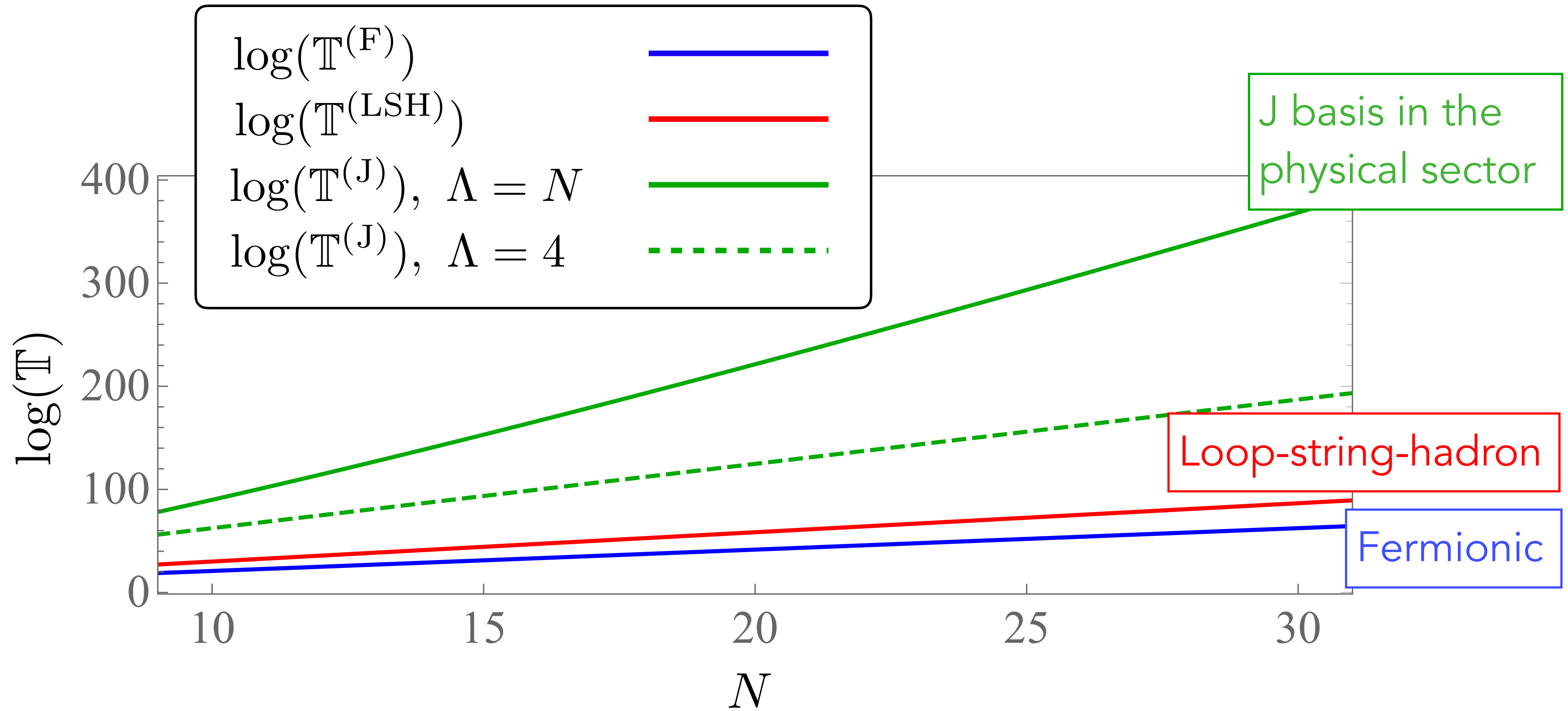


ZD, Raychowdhury, and Shaw, arXiv:2009.11802 [hep-lat]

EXAMPLES OF THEORY DEVELOPMENTS

ZD, Raychowdhury, and Shaw, arXiv:2009.11802 [hep-lat]

The time complexity of classical Hamiltonian-simulation algorithms for each formulation.



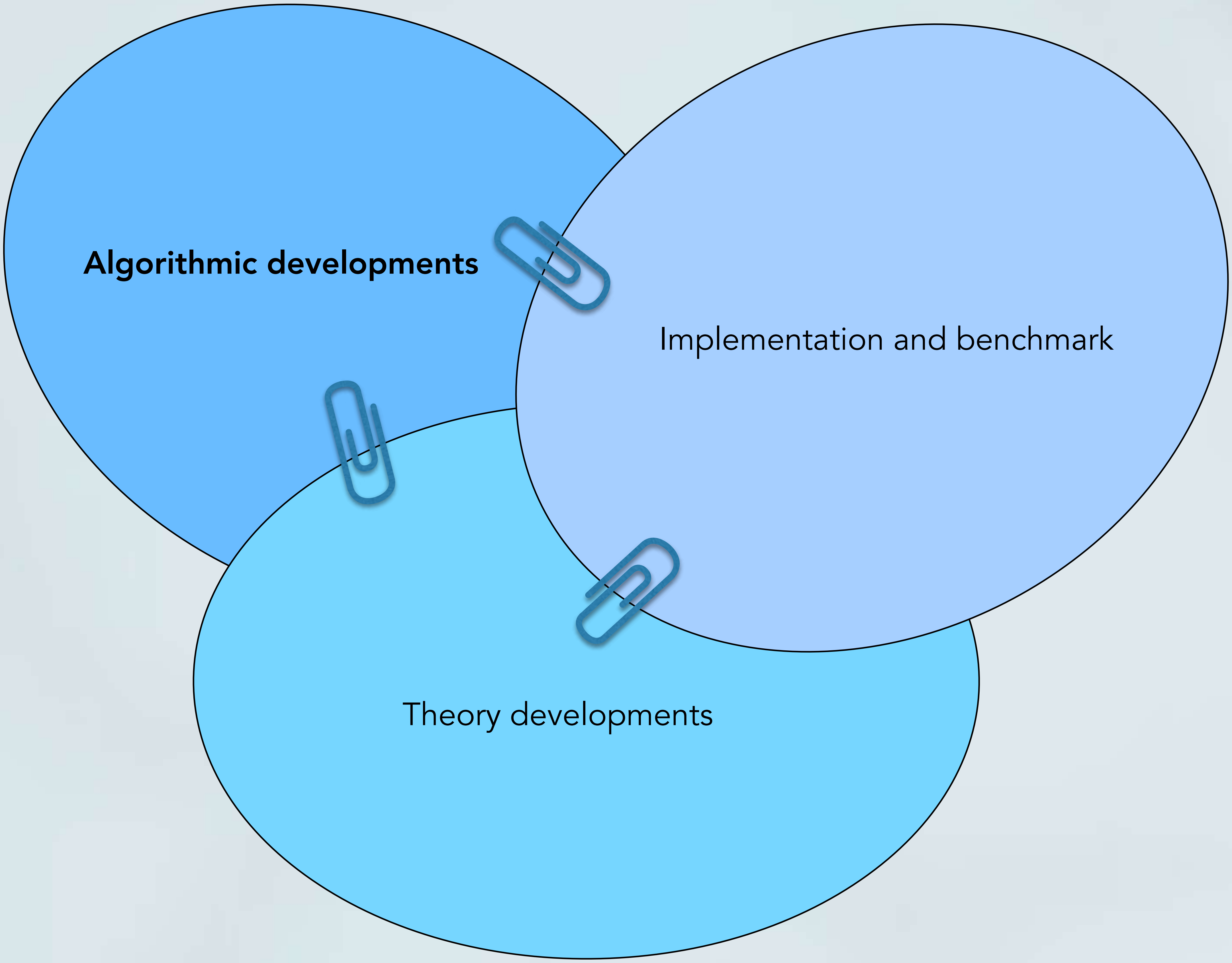
SU(2) LGT formulation for quantum simulation: Raychowdhury, Stryker, Phys. Rev. D 101, 114502 (2020).

For progress in 2+1 D U(1) gauge theory, see:
Haase, Dellantonio, Celi, Paulson, Kan, Jansen, Muschik, arXiv:2006.14160 [quant-ph]
Paulson, Dellantonio, Haase, Celi, Kan, Jena, Kokail, van Bijnen, Jansen, Zoller, Muschik, arXiv:2008.09252 [quant-ph].

Other digitization ideas:
Brower et al, Phys. Rev. D 60, 094502 (1999).
Alexandru et l, Phys. Rev. D 100, 114501 (2019).

Halimeh, Lang, Mildenberger, Jiang, Hauke, arXiv:2007.00668 [quant-ph], Stannigel, Hauke, Marcos, Hafezi, Diehl, Dalmonte, Zoller, Phys. Rev. Lett. 112, 120406, and Lamm, Lawrence, Yamauchi, arXiv:2005.12688 [quant-ph] for similar symmetry-protection ideas.

QUANTUM SIMULATION OF QUANTUM FIELD THEORIES INVOLVES:



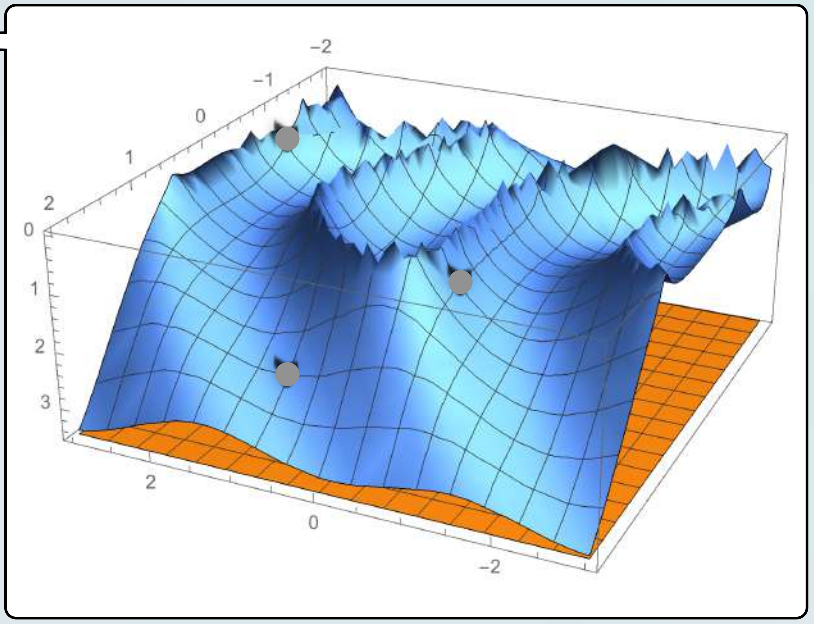
QUANTUM SIMULATION OF QUANTUM FIELD THEORIES: ALGORITHMIC DEVELOPMENTS

Scalar field theory

Jordan, Lee, and Preskill, Quant. Inf. Comput.14,1014(2014)

Klco, Savage, Phys. Rev. A 99, 052335 (2019).

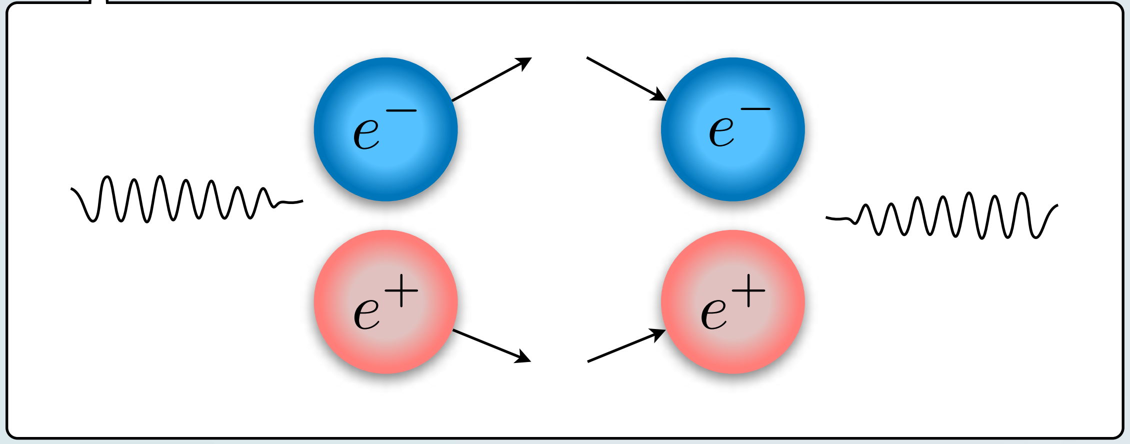
Barata , Mueller, Tarasov, Venugopalan (2020).



1+1 D quantum electrodynamics

$$\hat{H}_{\text{spin}} = w \sum_{n=1}^{N-1} \left[\hat{\sigma}_n^+ e^{i\hat{\theta}_n} \hat{\sigma}_{n+1}^- + \text{H.c.} \right] + \frac{m}{2} \sum_{n=1}^{N} (-1)^n \hat{\sigma}_n^z + J \sum_{n=1}^{N-1} \hat{L}_n^2$$

Shaw, Lougovski, Stryker, Wiebe, Quantum 4, 306 (2020)



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Shaw, Lougovski, Stryker, Wiebe, Quantum 4, 306 (2020)

Recourse analysis for lattice Schwinger model

Near term

	$\delta_g = 10^{-3}$		$\delta_g = 10^{-4}$		$\delta_g = 10^{-5}$		$\delta_g = 10^{-6}$		$\delta_g = 10^{-7}$	
	$\tilde{\epsilon}^2$	CNOT	$\tilde{\epsilon}^2$	CNOT	$\tilde{\epsilon}^2$	CNOT	$\tilde{\epsilon}^2$	CNOT	$\tilde{\epsilon}^2$	CNOT
$x = 10^{-2}$	—	7.3e4	—	1.6e5	—	3.4e5	—	7.3e5	5.6e-2	1.6e6
$x = 10^{-1}$	—	1.6e4	—	3.5e4	—	7.5e4	5.9e-2	1.6e5	2.7e-3	3.5e5
$x = 1$	—	4.6e3	—	9.9e3	1.0e-1	2.1e4	4.7e-3	4.6e4	2.2e-4	9.9e4
$x = 10^2$	—	2.8e3	8.3e-1	6.1e3	3.8e-2	1.3e4	1.8e-3	2.8e4	8.2e-5	6.0e4

Far term

Upper Bounds on T-gate Cost of Specific Simulations ($\mu = 1,\ \tilde{\epsilon}^2 = 0.1$)

	Short Time ($T = 10/x$)		Long Time ($T = 1000/x$)	
	Sampling	Estimating	Sampling	Estimating
$N = 4,\ \Lambda = 2$				
Strong Coupling ($x = 0.1$)	$6.5 \cdot 10^7$	$2.4 \cdot 10^{11}$	$8.8 \cdot 10^{10}$	$3.3 \cdot 10^{14}$
Weak Coupling ($x = 10$)	$5.0 \cdot 10^6$	$1.8 \cdot 10^{10}$	$7.0 \cdot 10^9$	$2.6 \cdot 10^{13}$
$N = 16,\ \Lambda = 2$				
Strong Coupling ($x = 0.1$)	$7.2 \cdot 10^8$	$2.5 \cdot 10^{12}$	$9.4 \cdot 10^{11}$	$3.3 \cdot 10^{15}$
Weak Coupling ($x = 10$)	$5.6 \cdot 10^7$	$1.9 \cdot 10^{11}$	$7.6 \cdot 10^{10}$	$2.7 \cdot 10^{14}$
$N = 16,\ \Lambda = 4$				
Strong Coupling ($x = 0.1$)	$1.9 \cdot 10^9$	$6.3 \cdot 10^{12}$	$2.3 \cdot 10^{12}$	$8.1 \cdot 10^{15}$
Weak Coupling ($x = 10$)	$9.6 \cdot 10^7$	$3.2 \cdot 10^{11}$	$1.2 \cdot 10^{11}$	$4.2 \cdot 10^{14}$

THEORY-EXPERIMENT CO-DEVELOPMENT IS A KEY TO PROGRESS.

CAN NUCLEAR AND HIGH-ENERGY IMPACT QUANTUM-SIMULATION HARDWARE DEVELOPMENTS?

ATOMS AND IONS AS ANALOG QUANTUM SIMULATORS OF LATTICE GAUGE THEORIES?

ATOMS AND **IONS** AS ANALOG QUANTUM SIMULATORS OF LATTICE GAUGE THEORIES?

Ion-laser Hamiltonian

Wineland et al, J.Res.Natl.Inst.Stand.Tech. 103 (1998) 259, Schneider et al, Rep. Prog. Phys. 75 024401 (2012)

$$H_I = -\mu \cdot \mathbf{E}$$

Ion-laser Hamiltonian

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$$H_I = \sum_{i=1}^{N} \left[\left(\sum_{I=1}^{n_L} \frac{1}{2} \Omega_I^{(i)} e^{-i(\omega_I - \omega_{\uparrow\downarrow})t + i\phi_I^{(i)}} \right) \left(e^{i \sum_{m=1}^{3N} \eta_m^{(i)} (a_m e^{-i\omega_m t} + a_m^\dagger e^{i\omega_m t})} \right) (\alpha_0 \mathbb{I} + \alpha_1 \sigma_x^{(i)} + \alpha_2 \sigma_y^{(i)} + \alpha_3 \sigma_z^{(i)}) \right]$$

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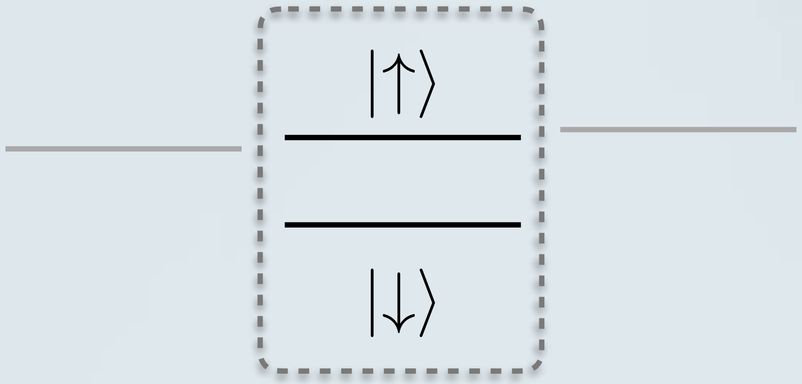
Acts on the internal states of each ion; a pseudo-spin



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Acts on the internal states of each ion; a pseudo-spin

Quantize $e^{i\mathbf{k}^{(i)} \cdot \mathbf{x}^{(i)}}$ operator in terms of the normal modes of the motion of the chain.

Ion-laser Hamiltonian

Wineland et al, J.Res.Natl.Inst.Stand.Tech. 103 (1998) 259, Schneider et al, Rep. Prog. Phys. 75 024401 (2012)

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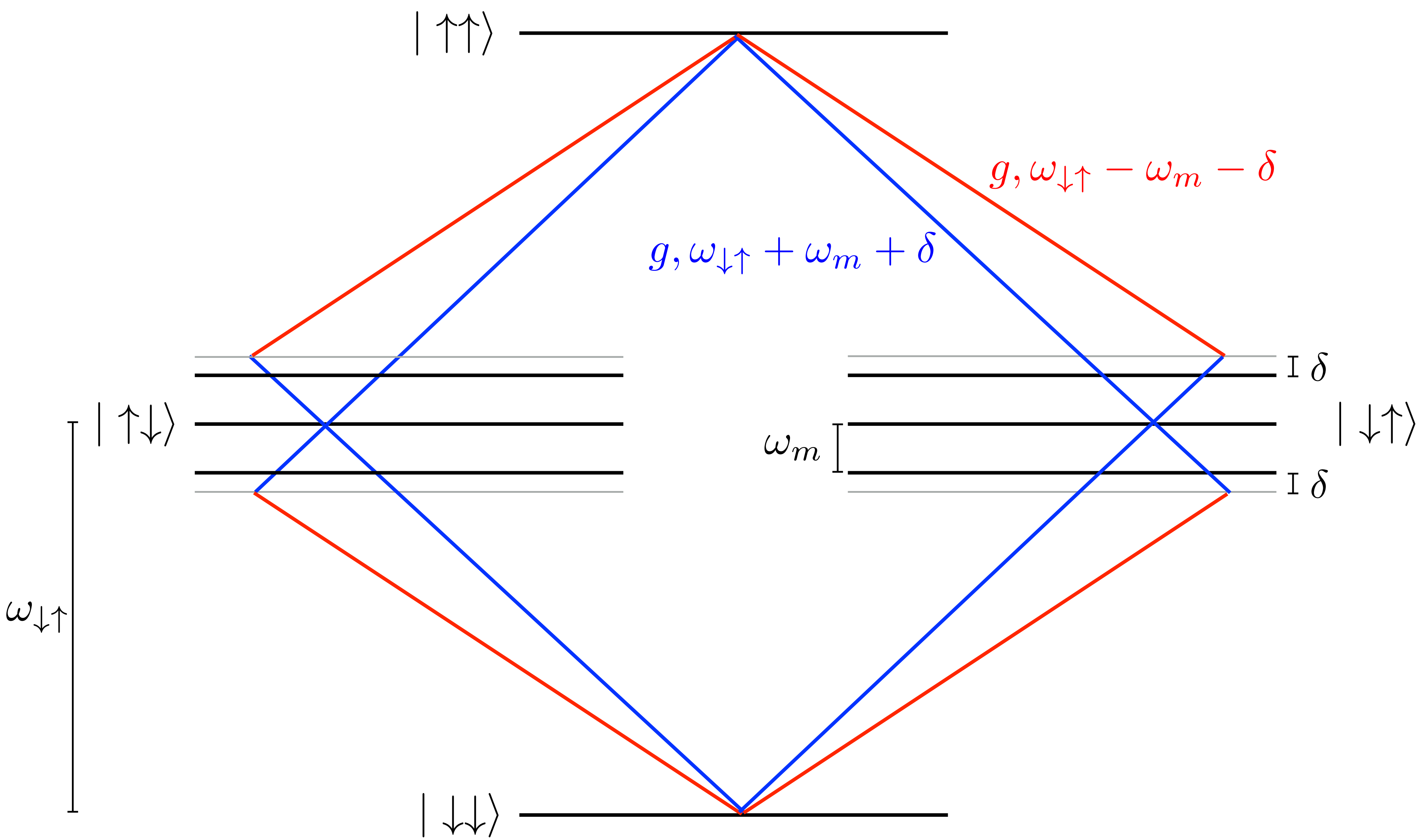
Acts on the internal states of each ion; a pseudo-spin

Quantize $e^{i\mathbf{k}^{(i)} \cdot \mathbf{x}^{(i)}}$ operator in terms of the normal modes of the motion of the chain.

Depends on intensity and phases of the lasers. Note that ideally ions can be addressed by individual lasers.

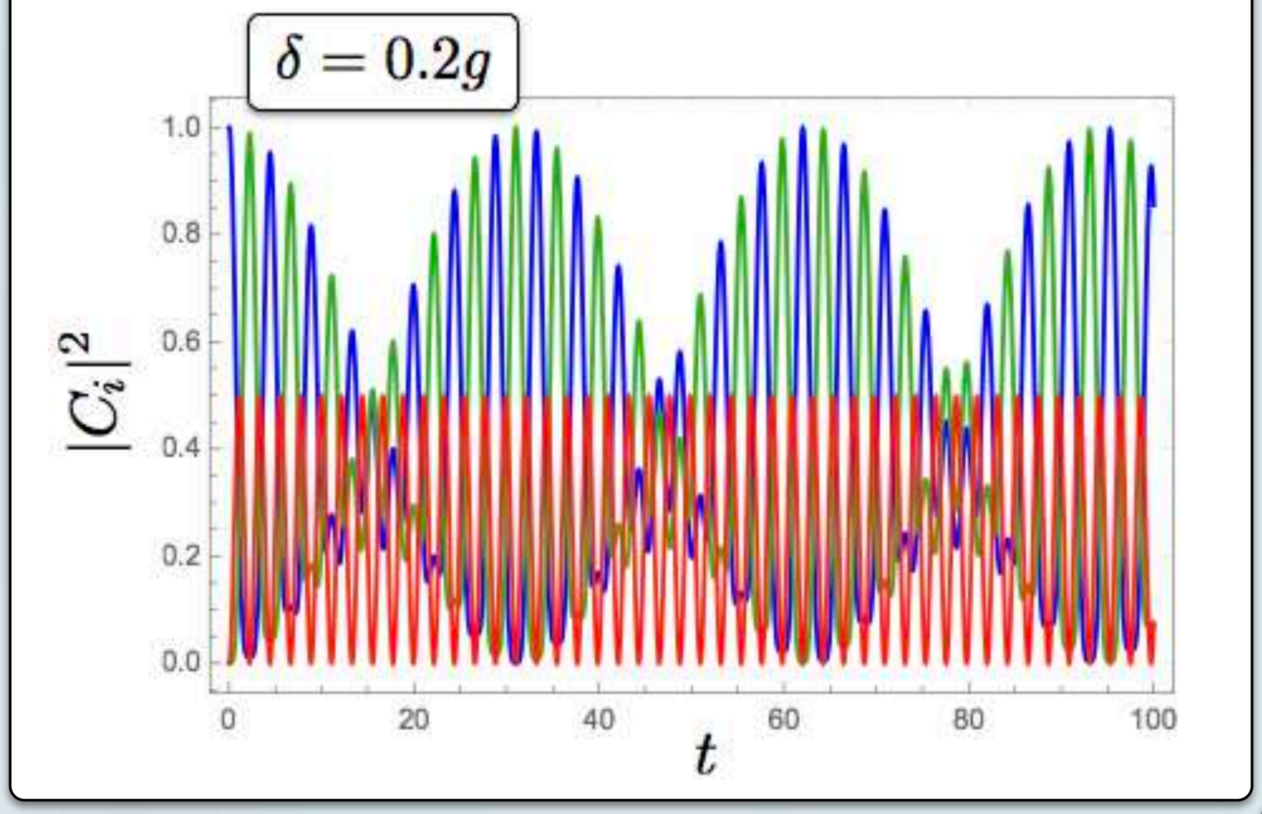
TWO-QUBIT ENTANGLING OPERATION

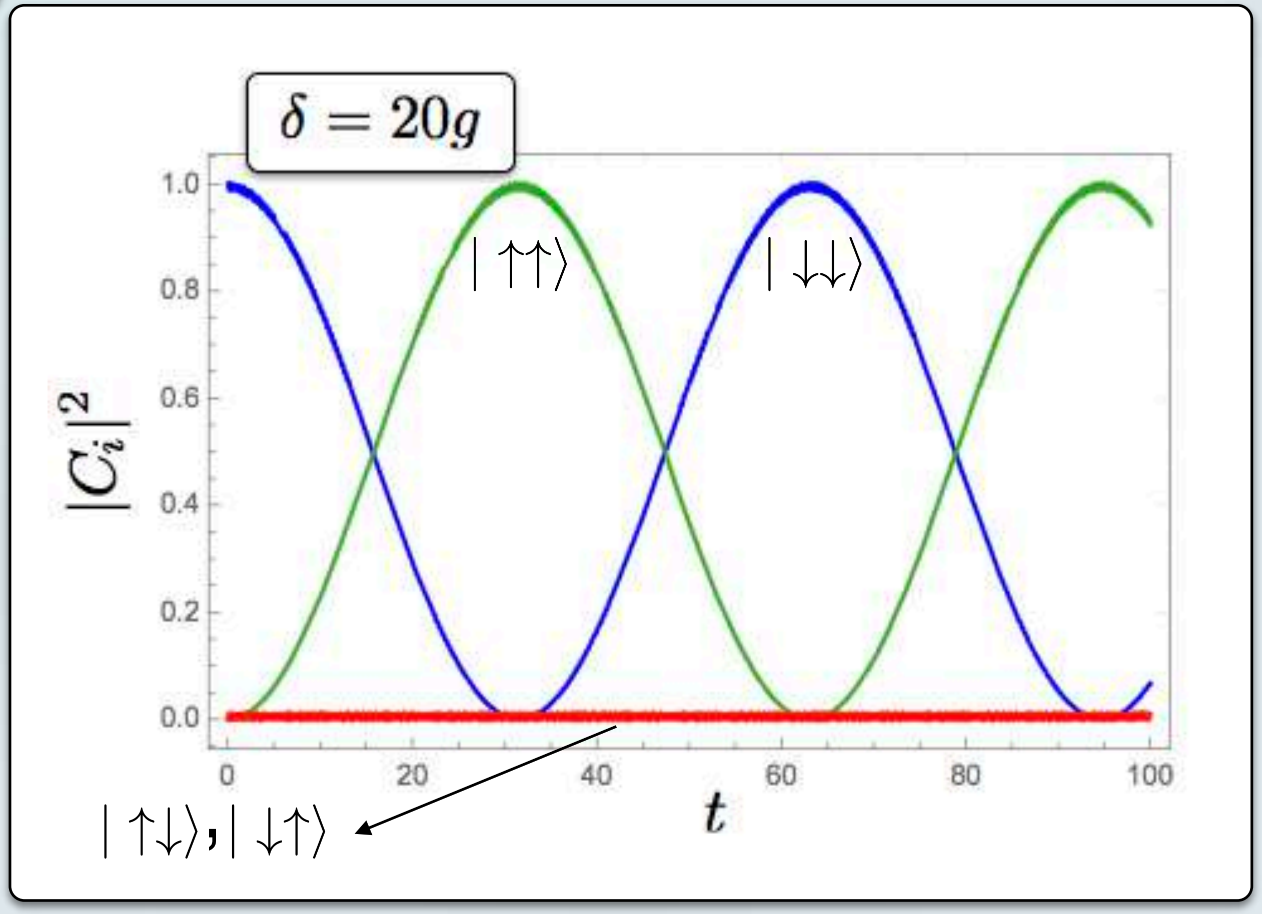
Adiabatic elimination technique and the use of sideband transitions effectively couples two spins and is independent of phonon occupation.



Cirac and Zoller, Phys.Rev.Lett.74, 4091 (1995),
Sorenson and Molmer, Phys. Rev. A 62, 022311 (2000)

Adiabatic elimination technique for a four-level system

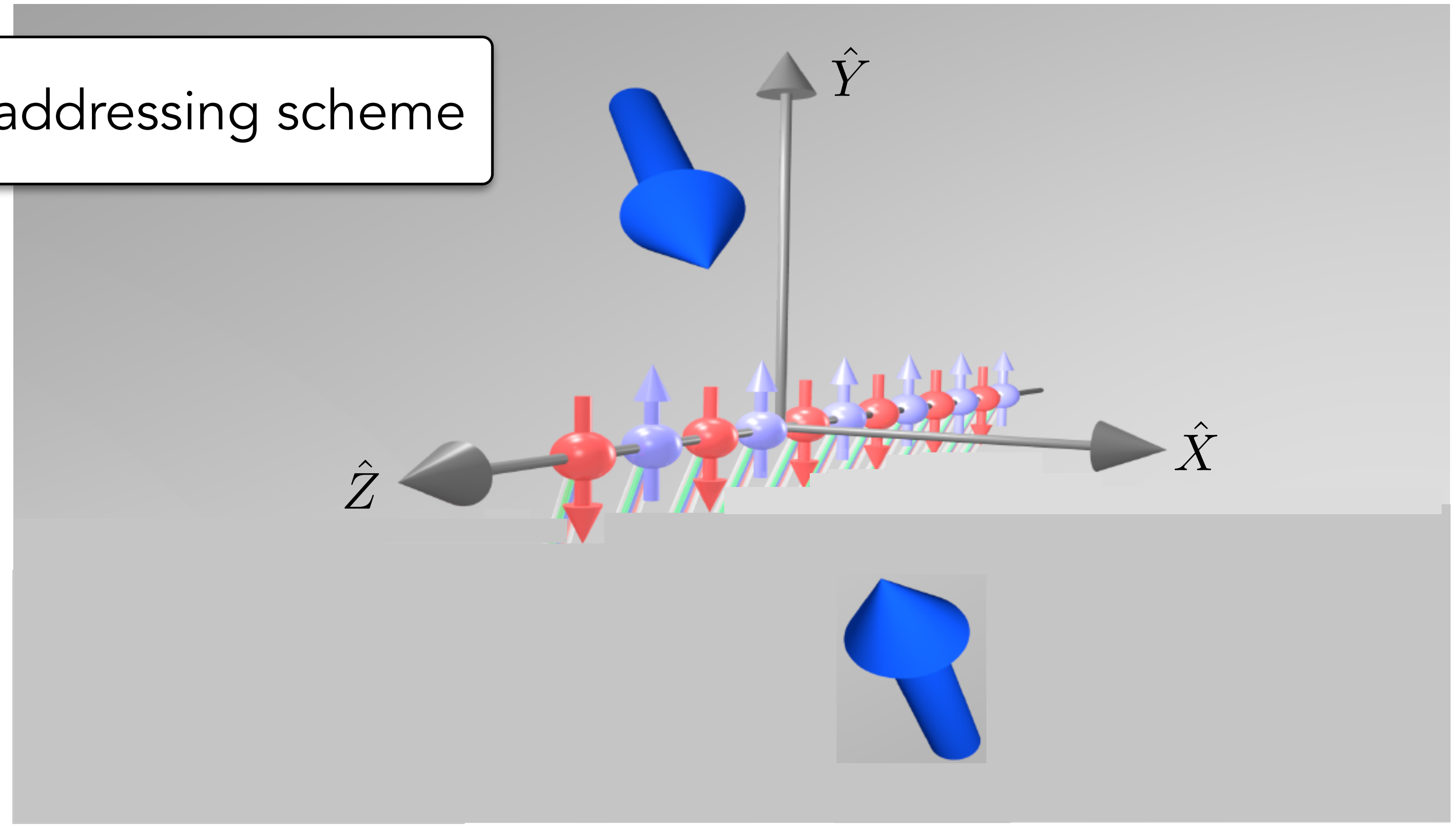




A TRAPPED-ION **ANALOG** SIMULATOR

A TRAPPED-ION **ANALOG** SIMULATOR

A global addressing scheme



A TRAPPED-ION **ANALOG** SIMULATOR

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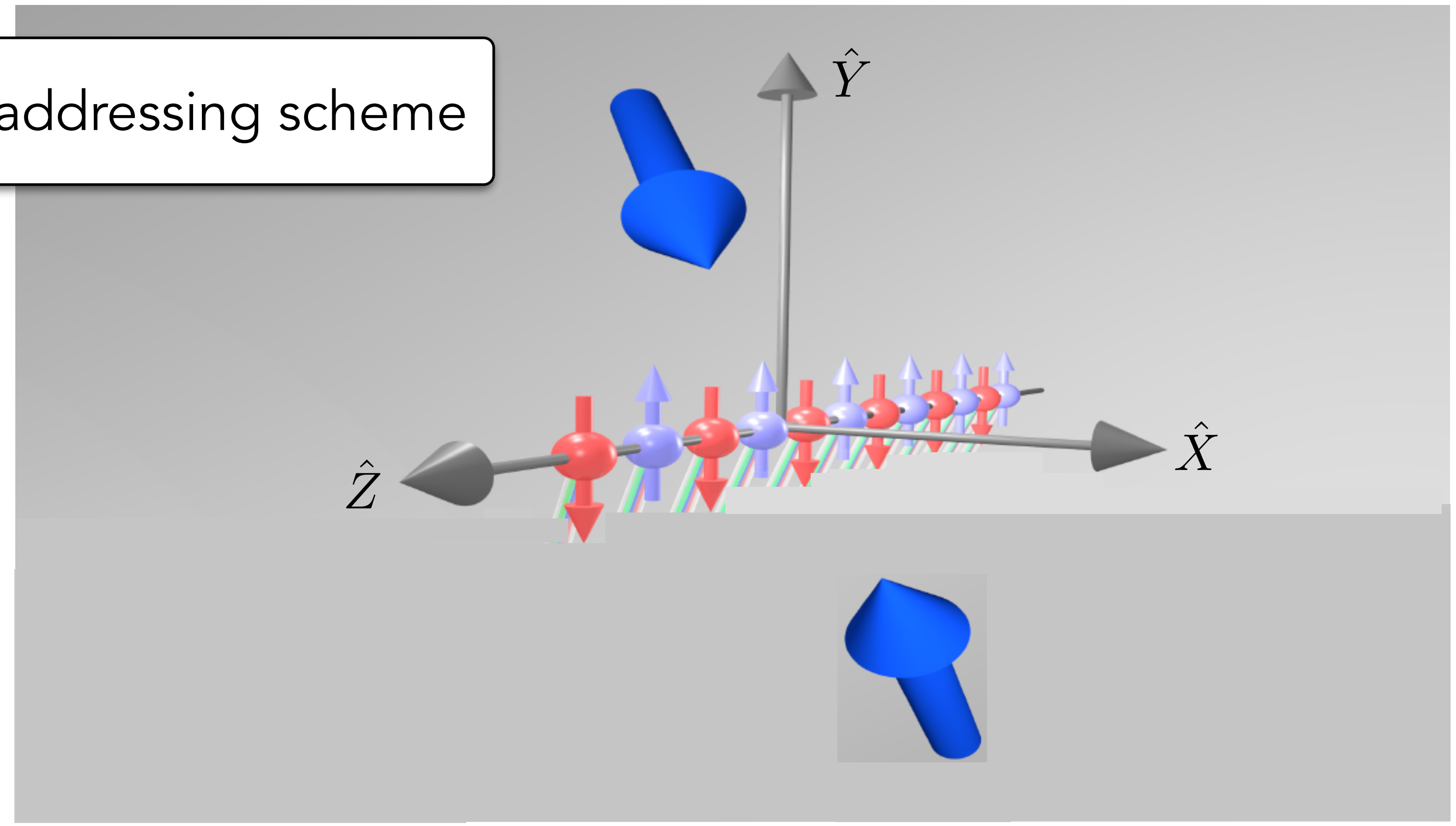
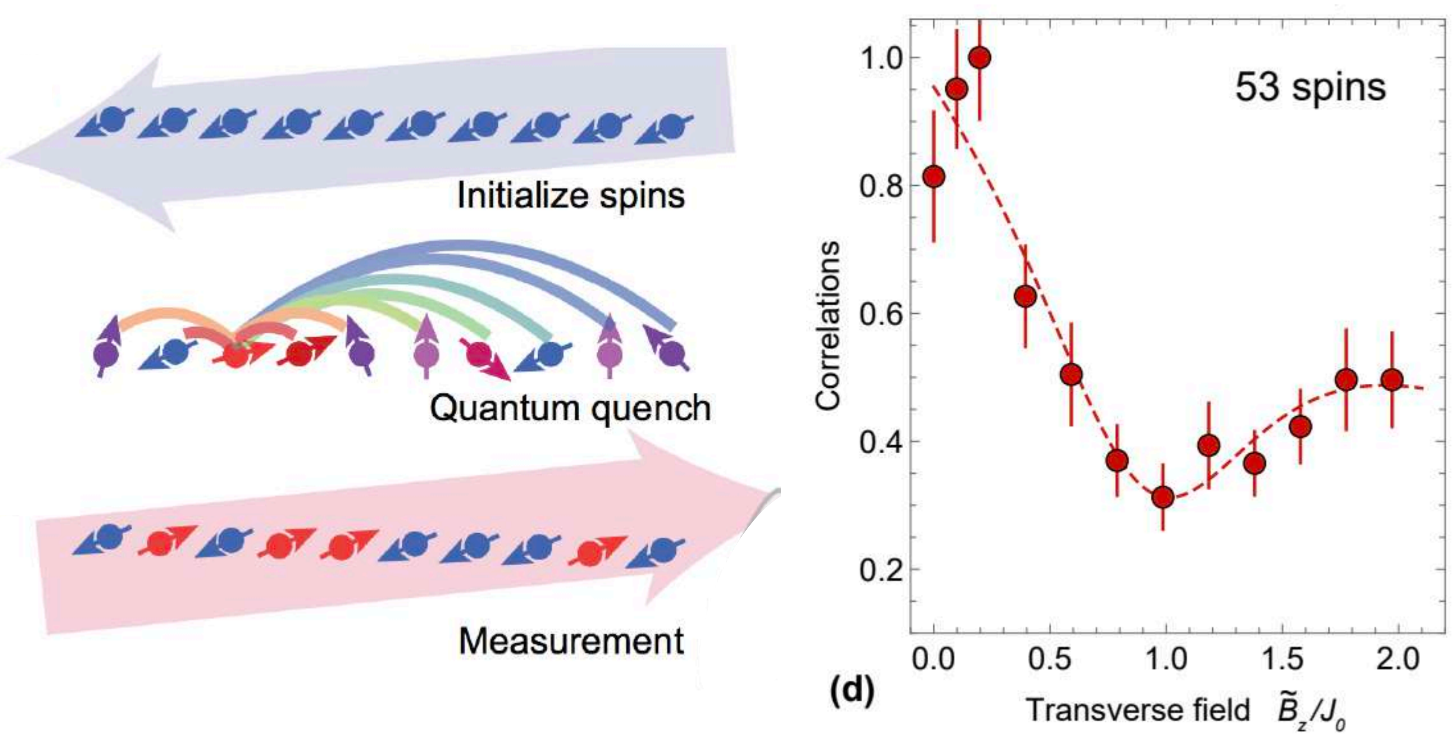


Effective Hamiltonian

$$H_{\text{eff}} = \sum_{i,j} J_{i,j}^{(xx)} \sigma_x^{(i)} \otimes \sigma_x^{(j)} - \frac{B_z}{2} \sum_i \sigma_z^{(i)}$$

with coupling:

$$J_{i,j}^{(xx)} \sim \frac{1}{|i-j|^{\alpha}}, \; 0 < \alpha < 3$$



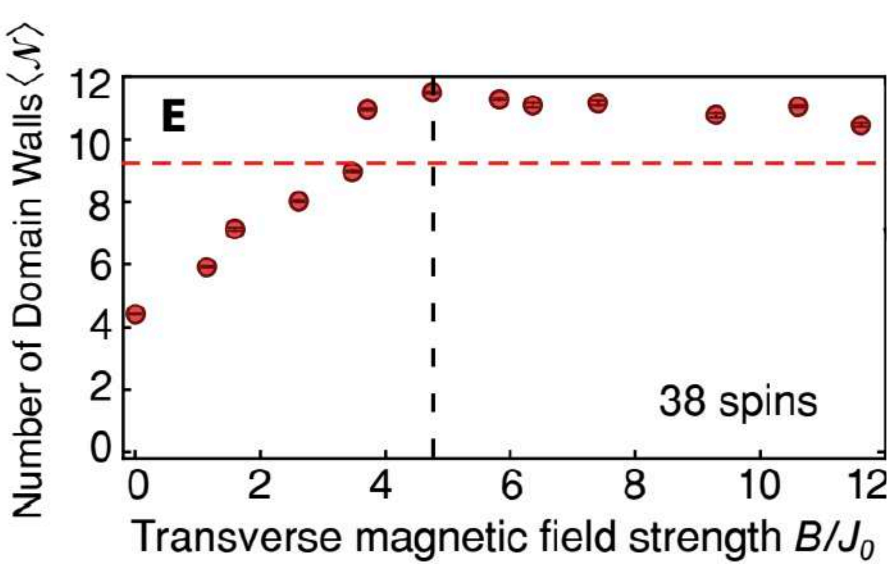
Zhang et al, Nature 551, 601–604 (2017).

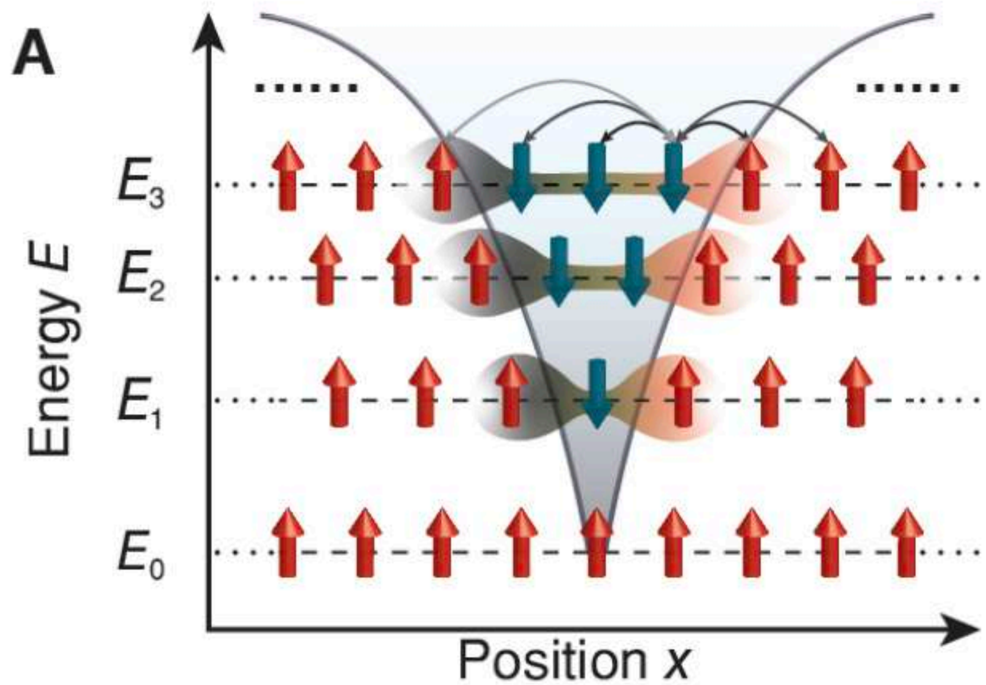
ANOTHER EXAMPLE: SPIN MODELS AS PROTOTYPES OF QCD? CAN THEY REVEAL ENTANGLEMENT ASPECTS OF CONFINEMENT AND COLLISIONS?

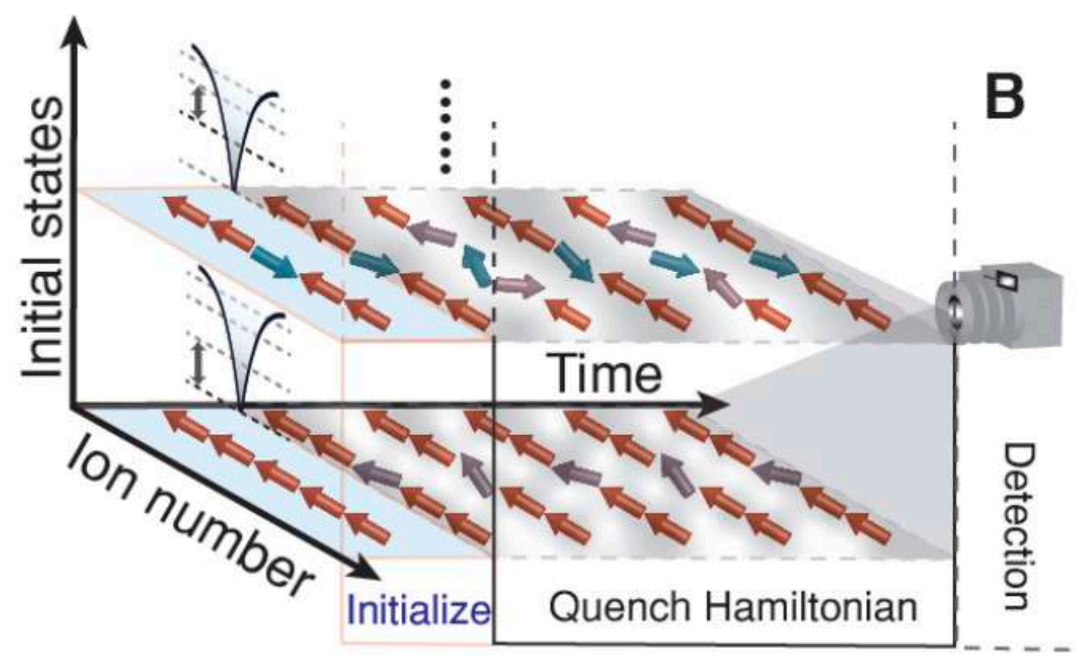
Transverse-field Ising model with long-range interactions in 1+1D exhibits an effective confining potential among domain walls: the “mesons”!

$$H = -\sum_{i<j}^{L} J_{i,j}\sigma_i^x\sigma_j^x - B\sum_i^L \sigma_i^z.$$

Native Hamiltonian in a trapped-ion simulator!







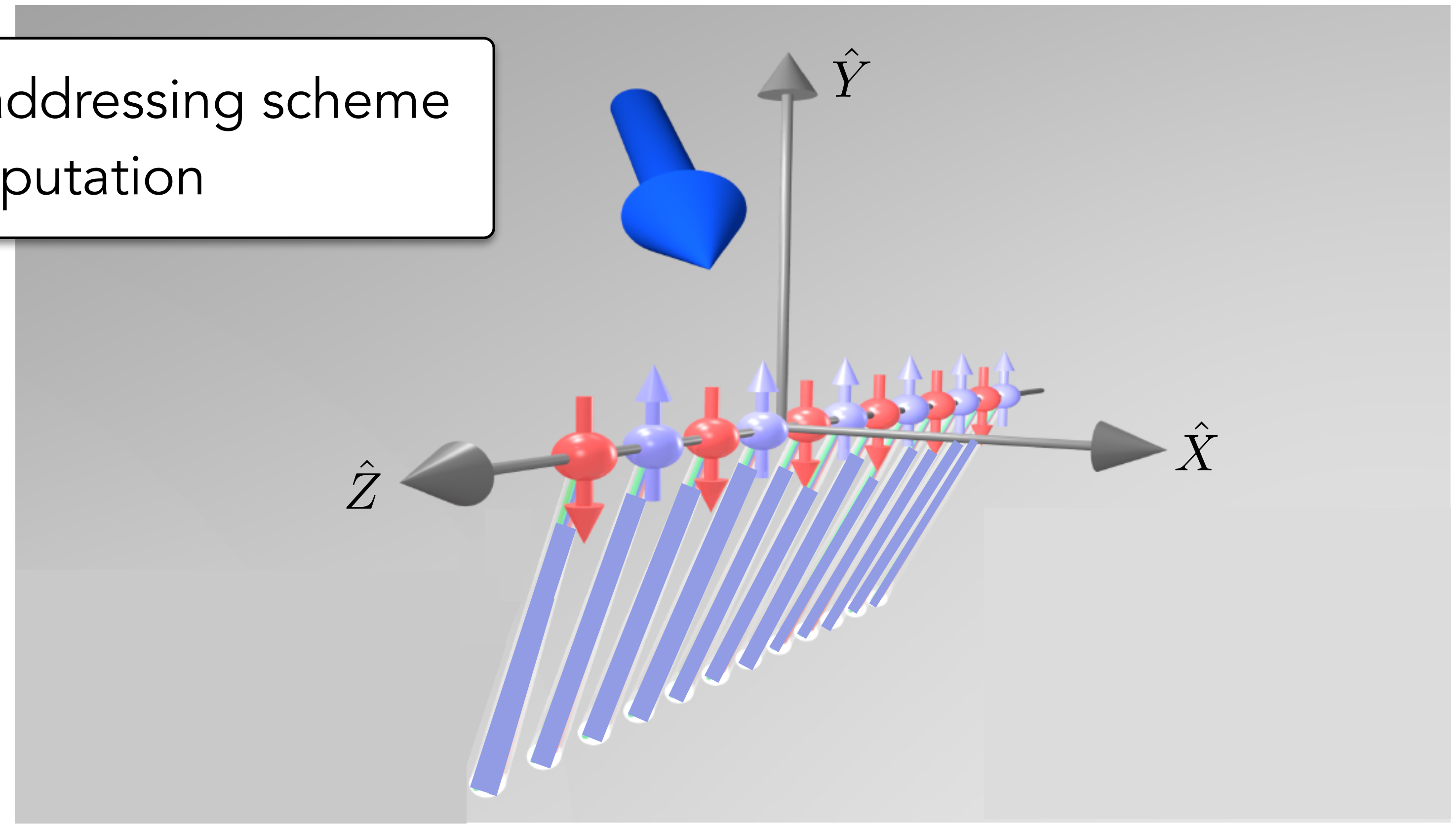
Tan, Becker, Liu, Pagano, Collins, De, Feng, Kaplan, Kyprianidis, Lundgren, Morong, Whitsitt, Gorshkov, Monroe, arXiv:1912.11117 [quant-ph]

See also: Milsted, Liu, Preskill, Vidal, arXiv:2012.07243 [quant-ph].

A TRAPPED-ION **DIGITAL** SIMULATOR

A TRAPPED-ION **DIGITAL** SIMULATOR

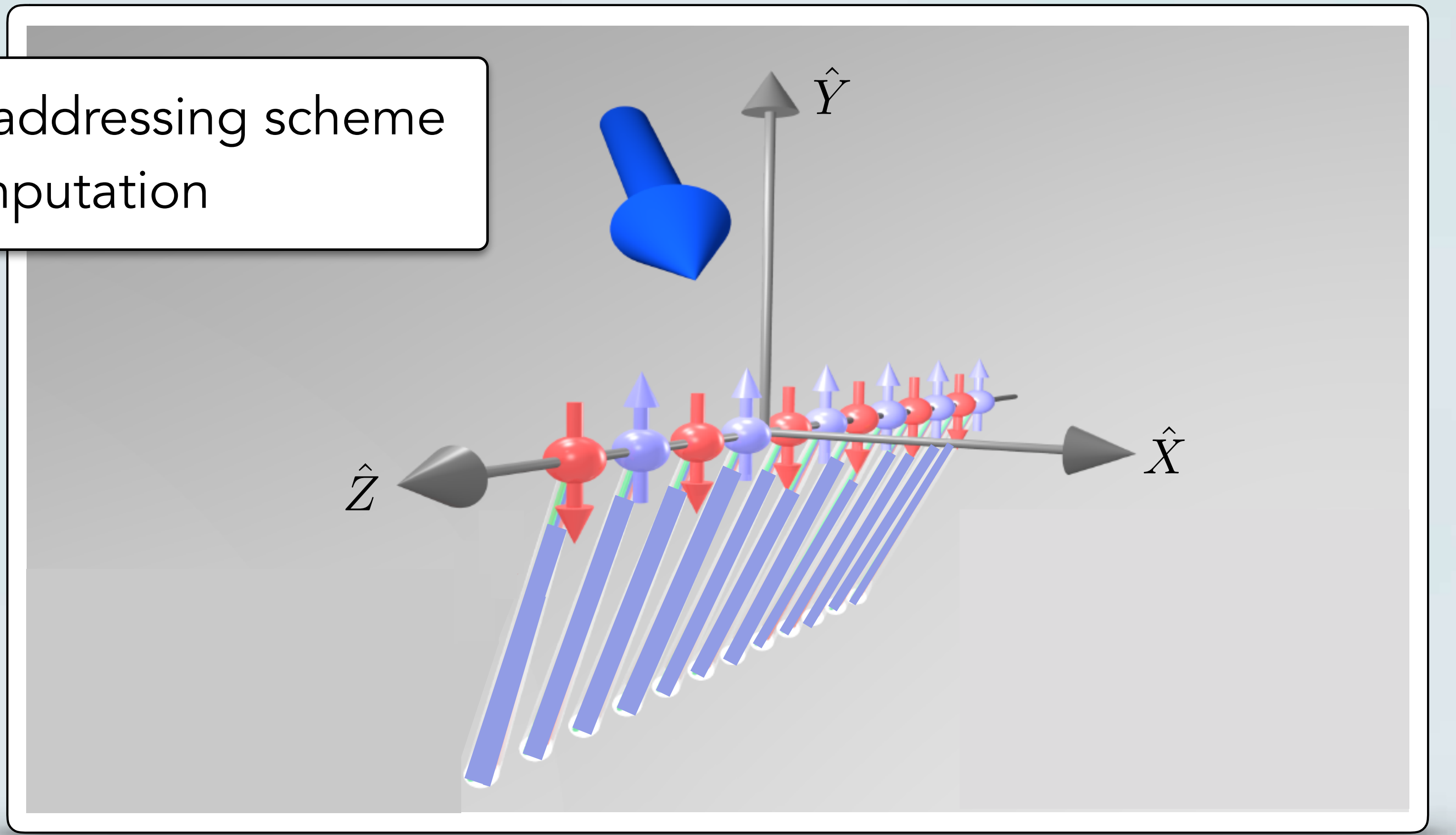
An individual addressing scheme for digital computation



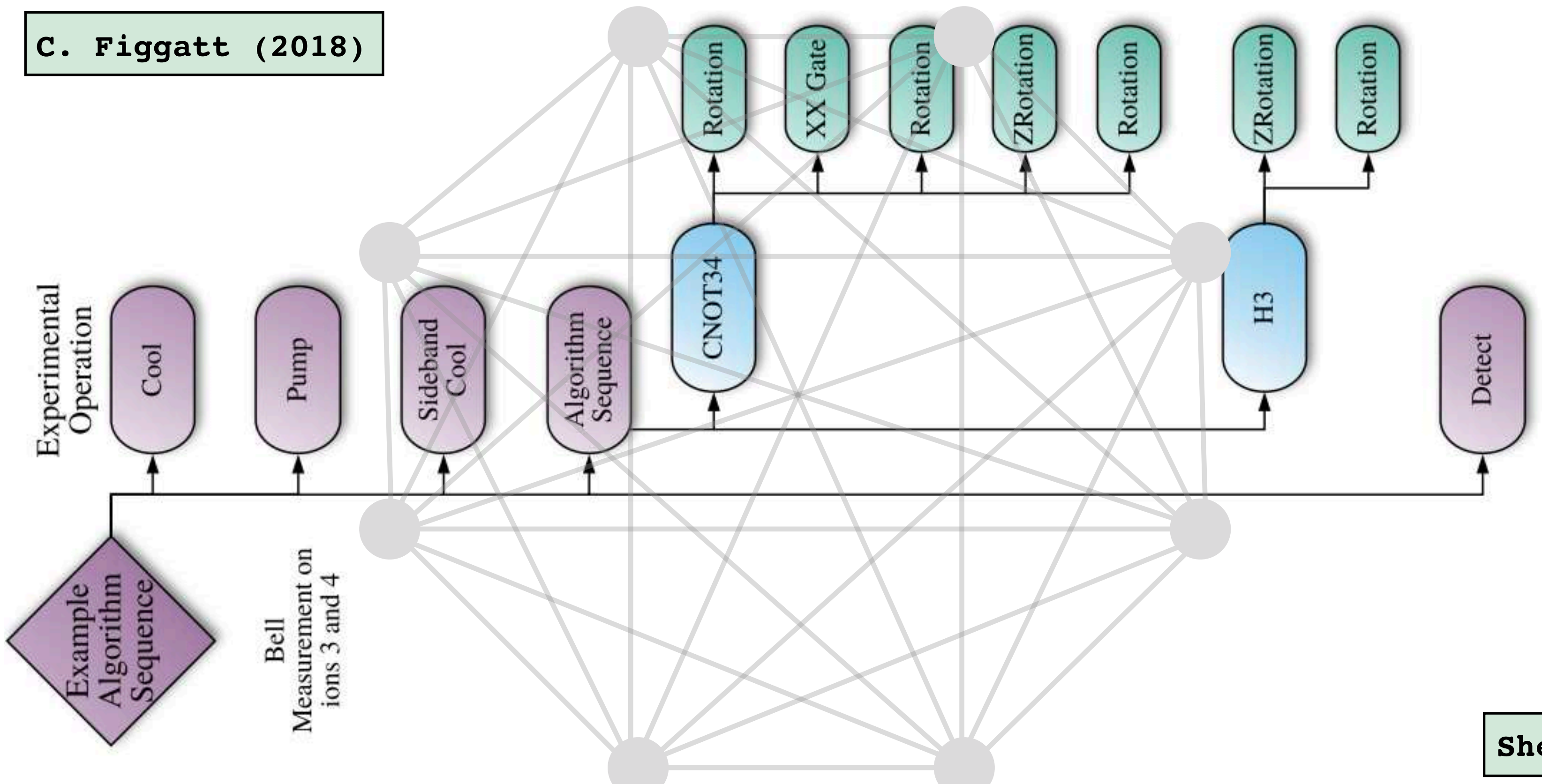
A highly tunable analog simulator is achievable with this set up too: Teoh, Drygala, Melko, Islam arXiv:1910.02496 [quant-ph], Korenblit, Islam, Monroe et al, New Journal of Physics 14, 095024 (2012).

A TRAPPED-ION **DIGITAL** SIMULATOR

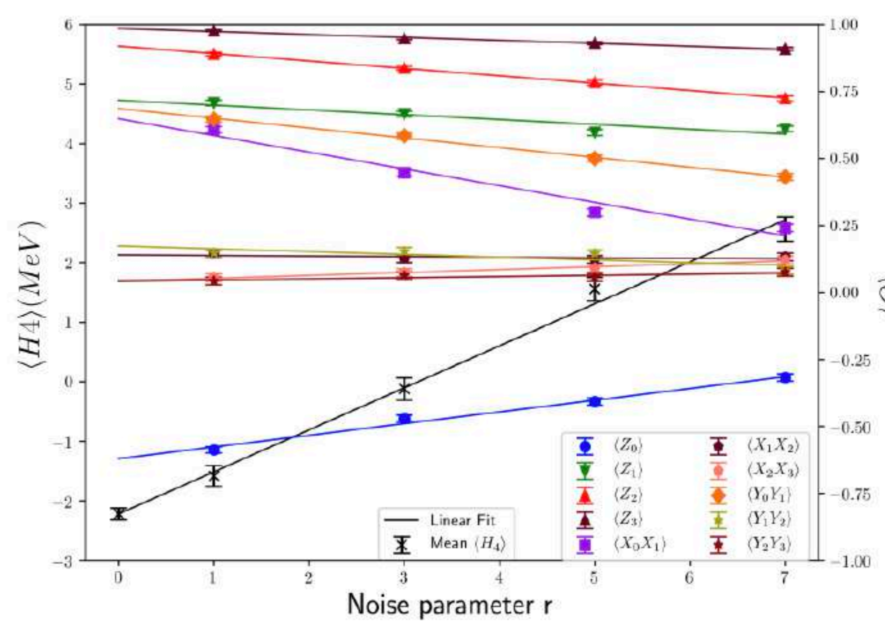
An individual addressing scheme for digital computation



C. Figgatt (2018)



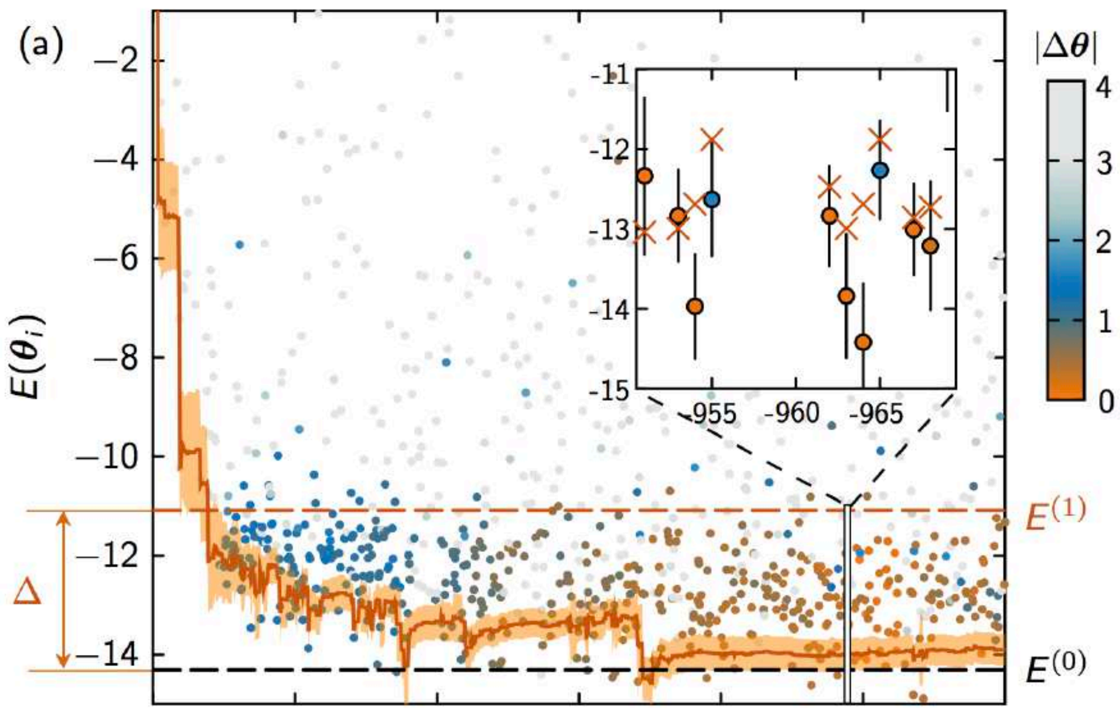
VQE for finding deuteron's binding



Shehab et al, Phys. Rev. A 100, 062319 (2019)

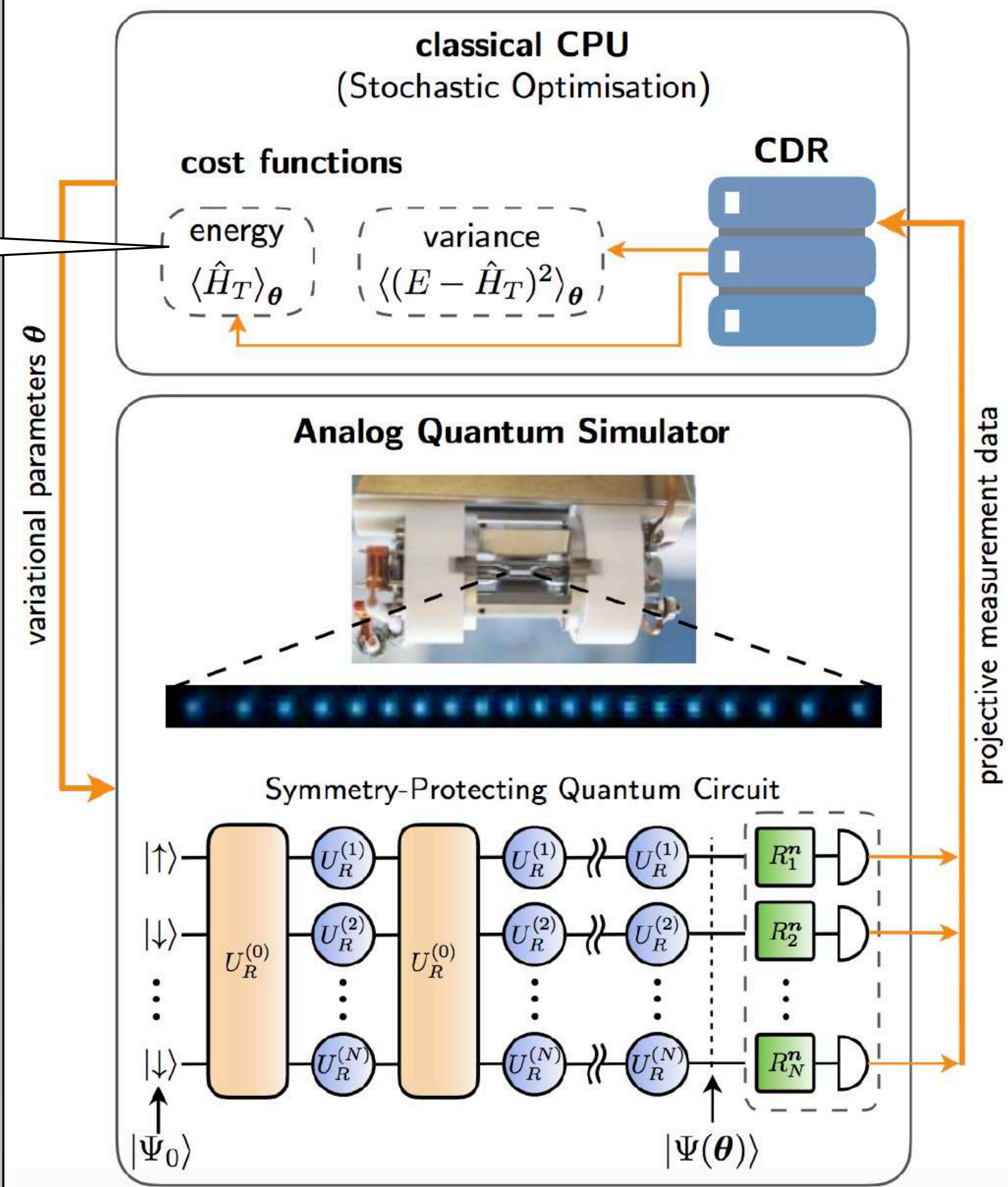
ANOTHER EXAMPLE I: VARIATIONAL QUANTUM SIMULATION OF LATTICE SCHWINGER MODEL

Hamiltonian under which the system evolves respects some symmetries of the original theory and is implemented in an analog fashion.



Kokail et al, Nature 569, 355 (2019).

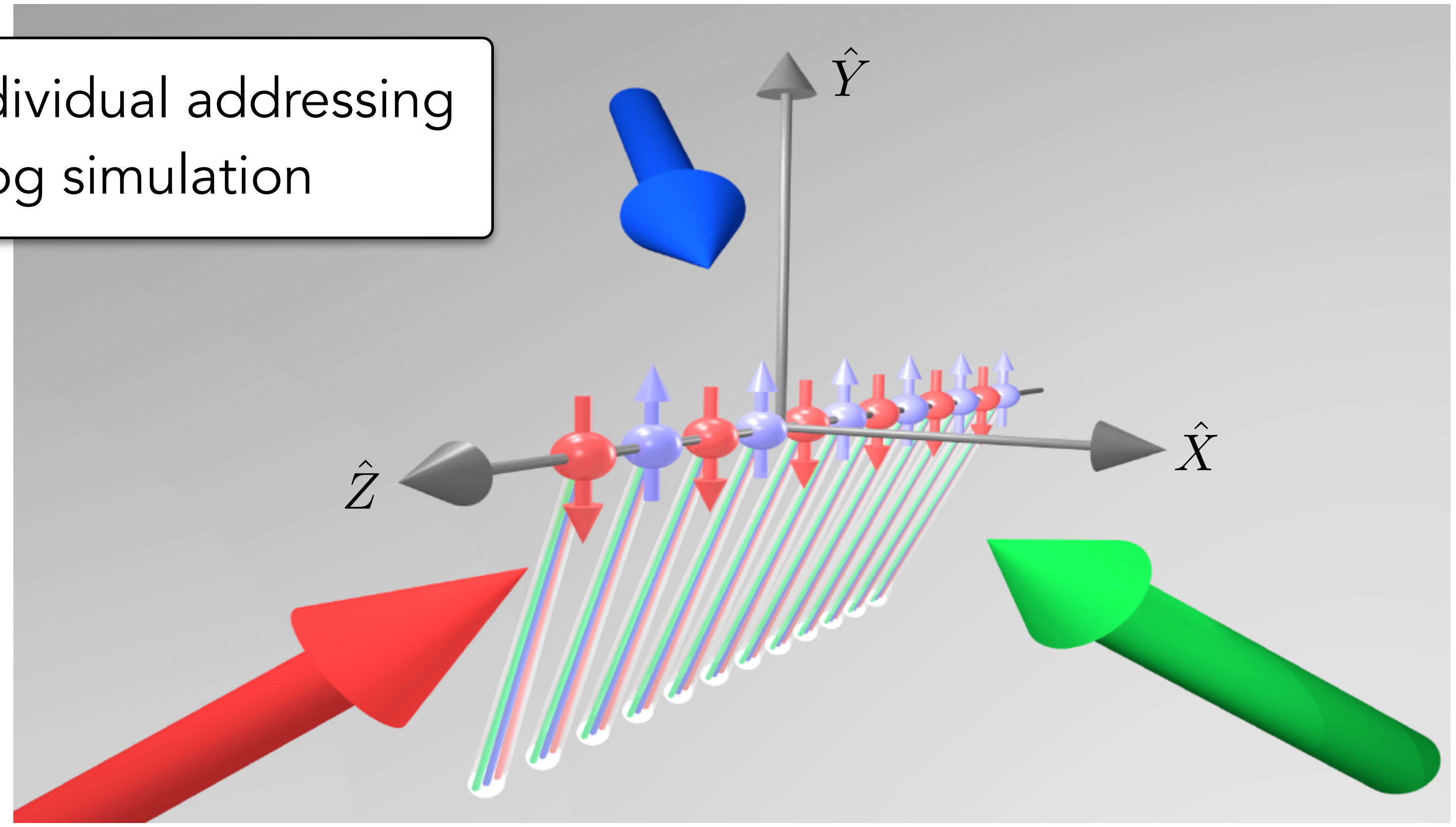
See alSo the VQE applied to calculation of neutron binding in Dumitrescu, McCaskey, Hagen, Jansen, Morris, Papenbrock, Pooser, Dean, Lougovski Phys. Rev. Lett. 120, 210501 (2018)



AN ADVANCED TRAPPED-ION **ANALOG** SIMULATOR

AN ADVANCED TRAPPED-ION **ANALOG** SIMULATOR

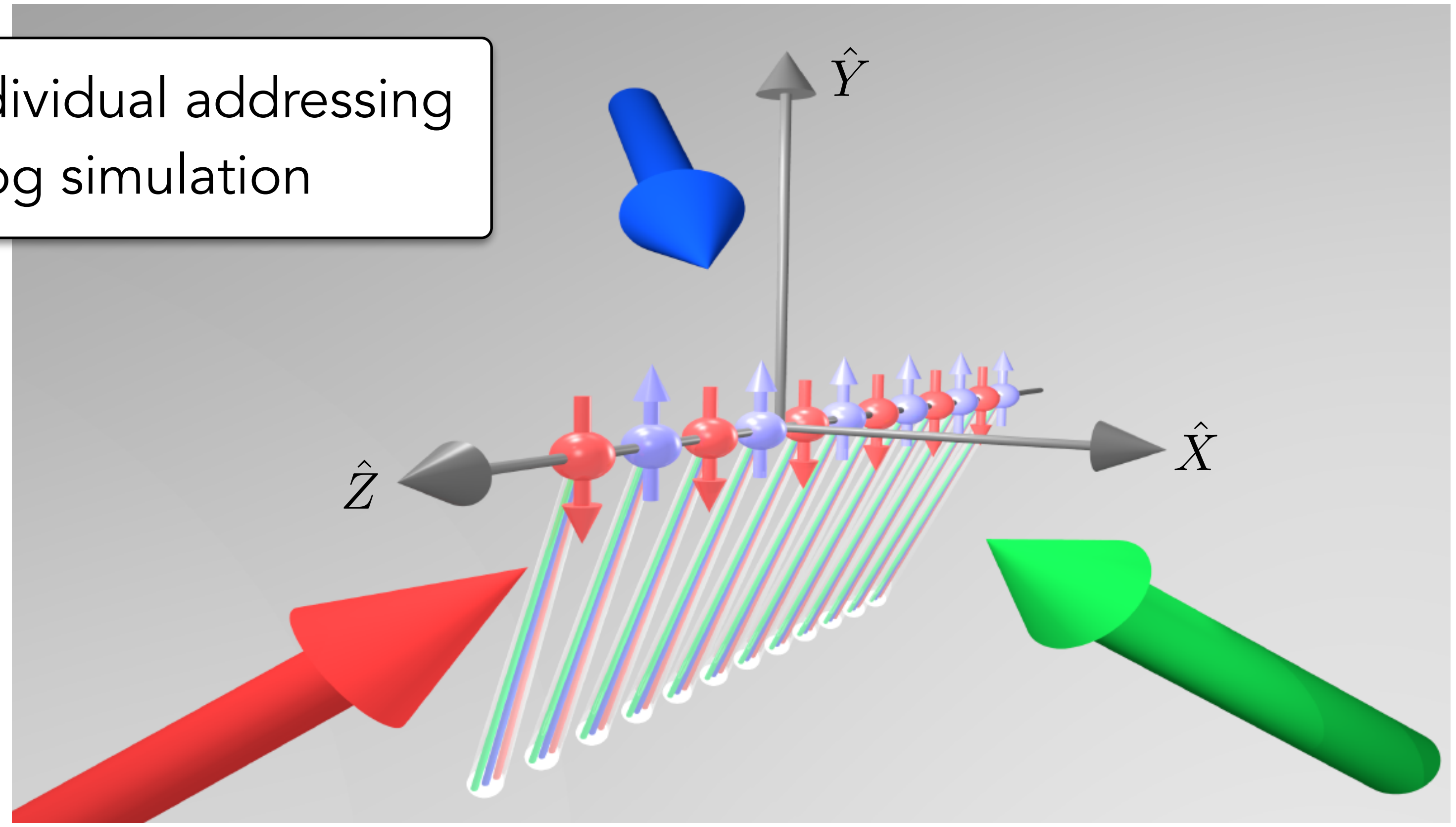
An enhanced individual addressing scheme for analog simulation



ZD, HAFEZI, MONROE, PAGANO, SEIF AND SHAW, Phys. Rev. R 2, 023015 (2020)

AN ADVANCED TRAPPED-ION **ANALOG** SIMULATOR

An enhanced individual addressing scheme for analog simulation



ZD, HAFEZI, MONROE, PAGANO, SEIF AND SHAW, Phys. Rev. R 2, 023015 (2020)

Heisenberg model Hamiltonian can be obtained under certain conditions:

$$H_{\text{eff}} = \sum_{\substack{i,j \\ j<i}} \left[J_{i,j}^{(xx)} \sigma_x^{(i)} \otimes \sigma_x^{(j)} + J_{i,j}^{(yy)} \sigma_y^{(i)} \otimes \sigma_y^{(j)} + J_{i,j}^{(zz)} \sigma_z^{(i)} \otimes \sigma_z^{(j)} \right] - \frac{1}{2} \sum_{i=1}^{N} B_z^{(i)} \sigma_z^{(i)}.$$

This can be matched to the Hamiltonian of Schwinger Model

$$\hat{H}_s = \frac{\mu}{2}\sum_{n=1}^{N}(-1)^n\sigma_n^z + x\sum_{n=1}^{N-1}\{\sigma_n^+\sigma_{n+1}^- + \text{h.c.}\} + \frac{1}{4}\sum_{n=1}^{N-1}\left\{\sum_{m=1}^{n}\left[\sigma_m^z + (-1)^m\right]\right\}^2$$

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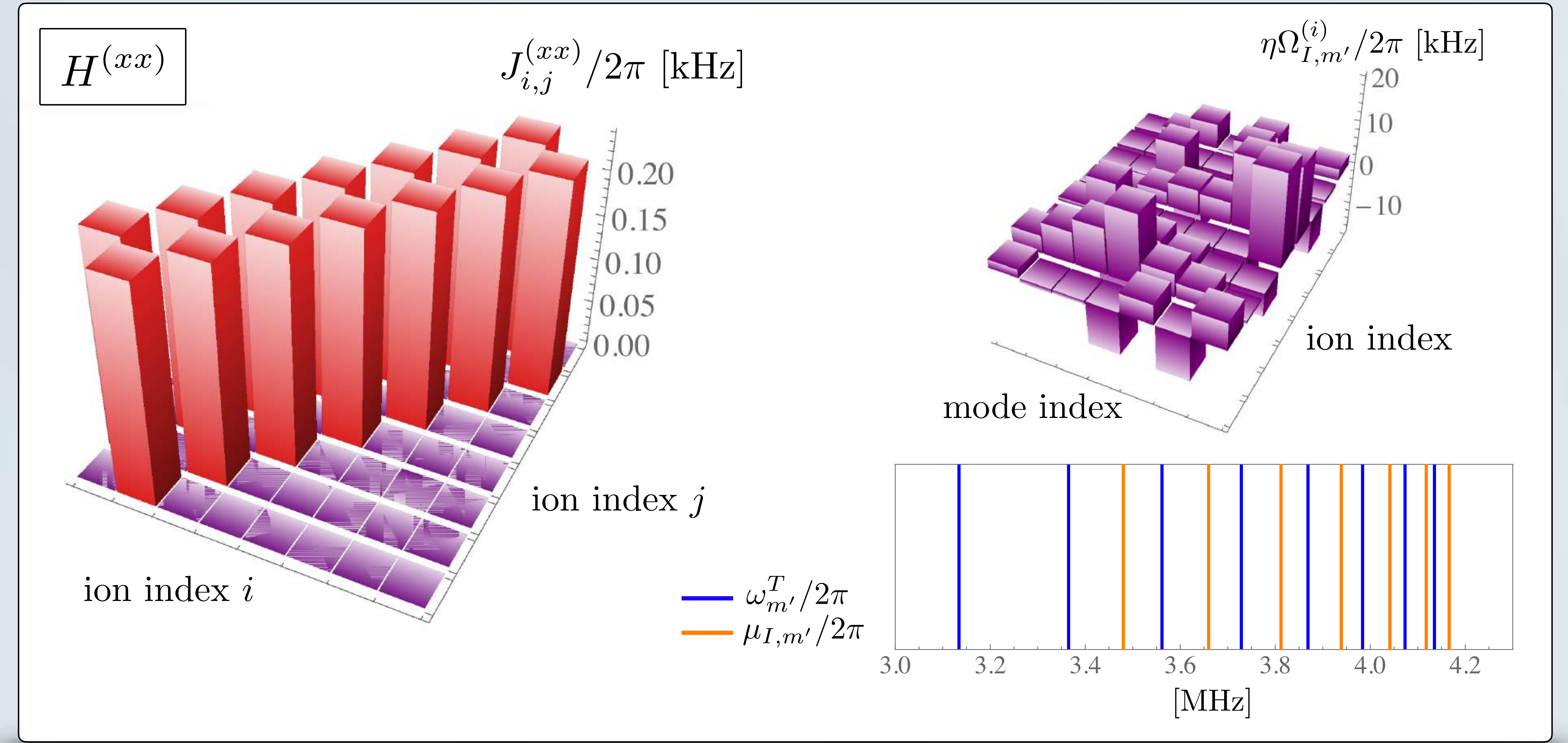

Eight-fermion site theory

ZD, HAFEZI, MONROE, PAGANO, SEIF AND SHAW, Phys. Rev. R 2, 023015 (2020)

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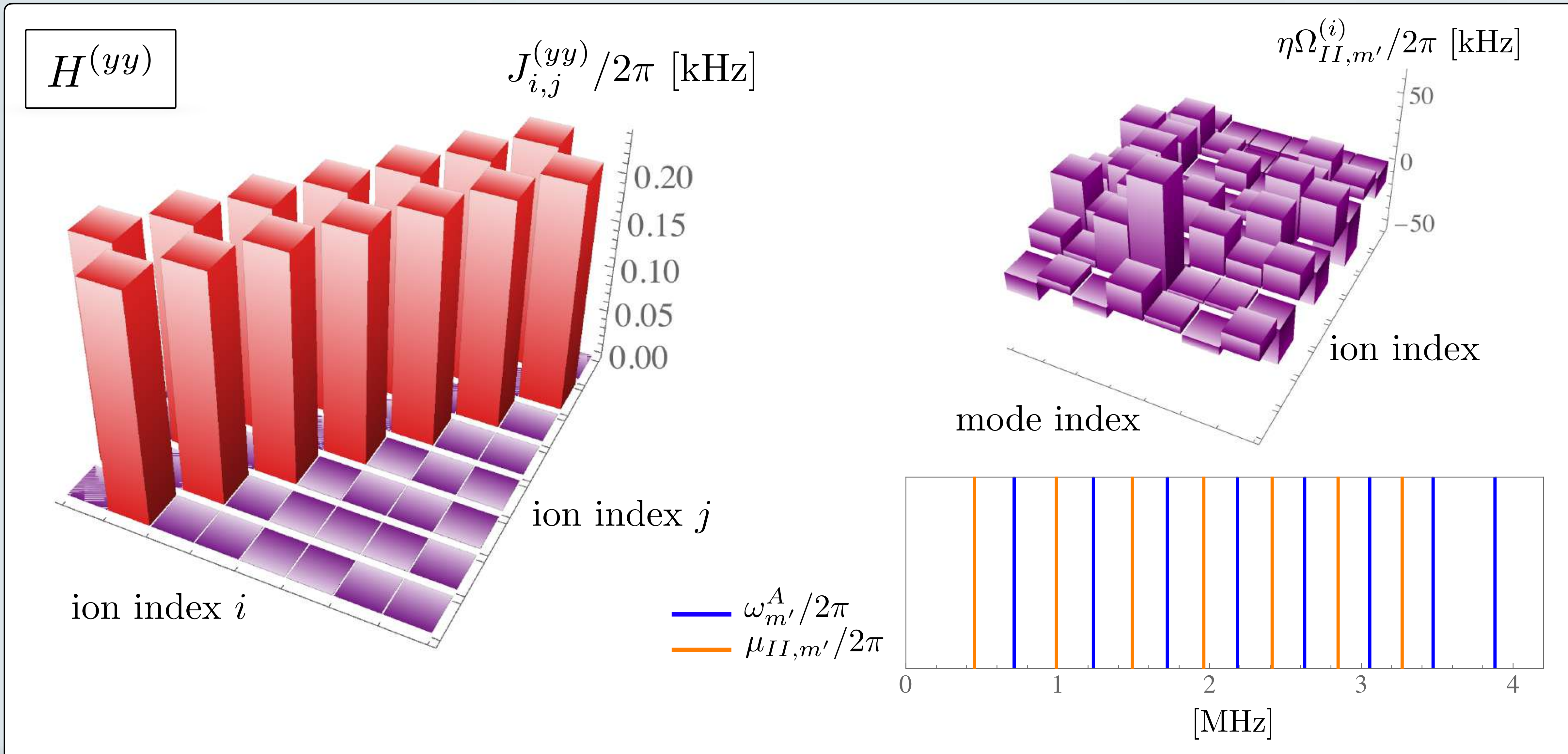

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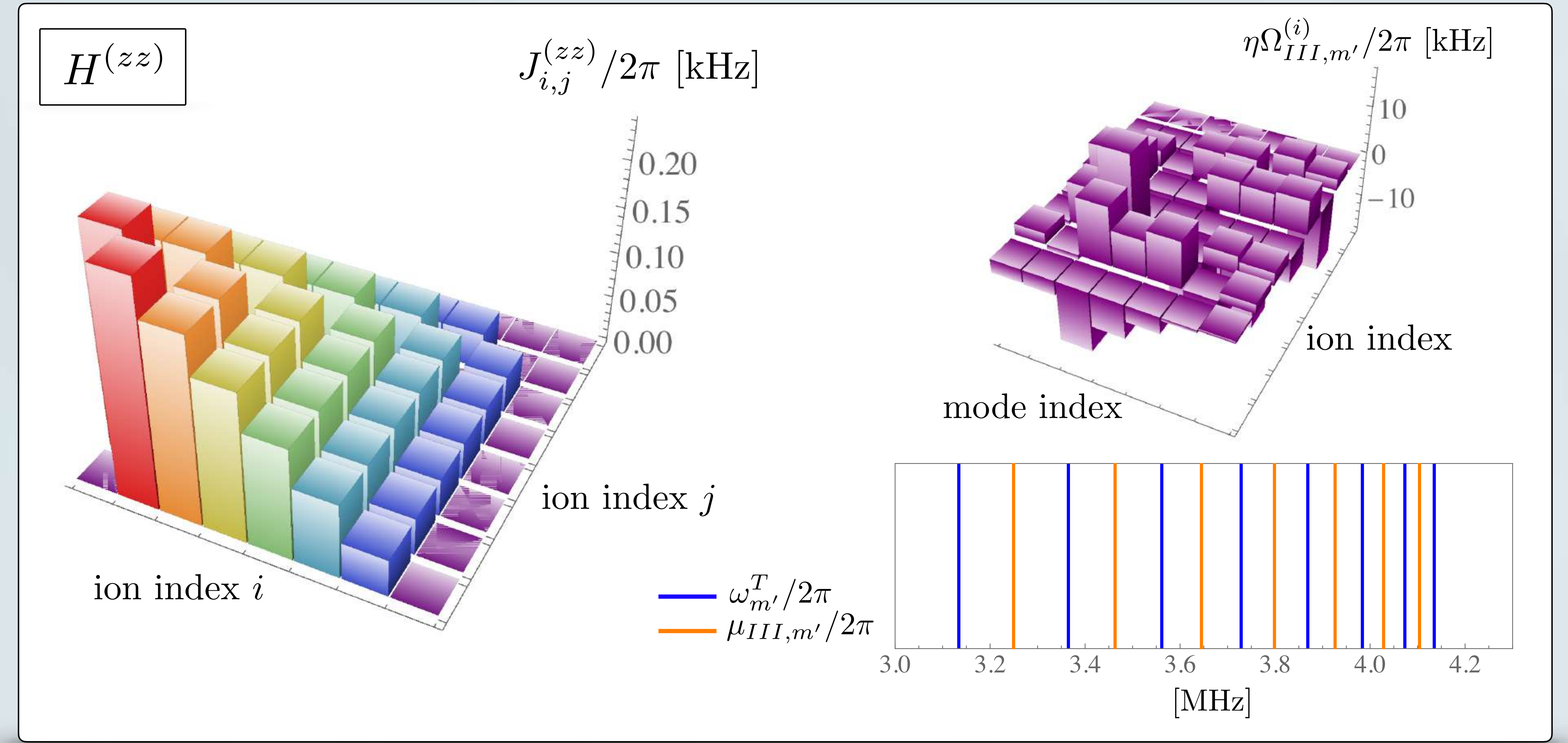


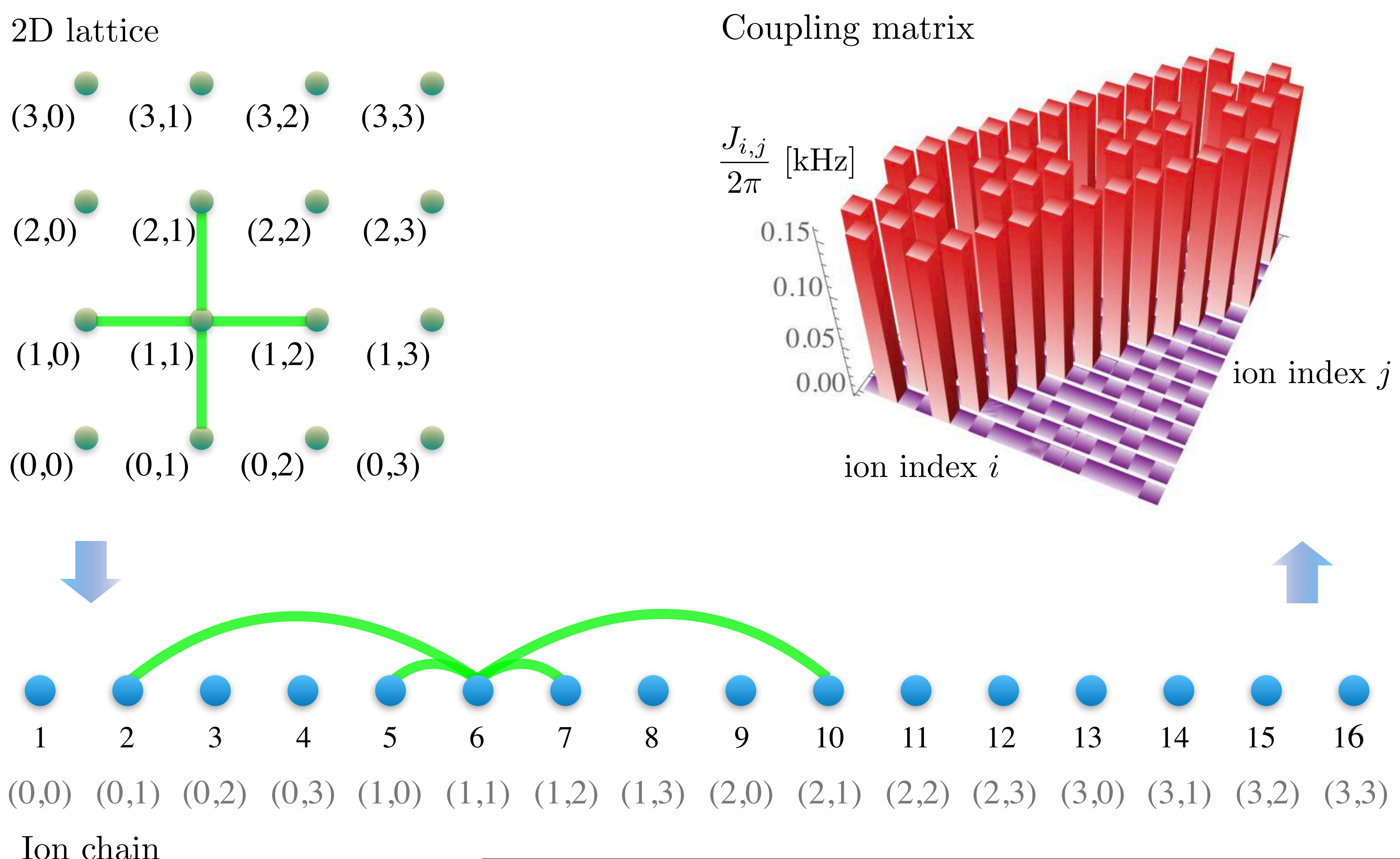
Eight-fermion site theory

ZD, HAFEZI, MONROE, PAGANO, SEIF AND SHAW, Phys. Rev. R 2, 023015 (2020)

The same scheme can be applied to Chern-Simons theory in 2+1 d:

$$\mathcal{L}_{\rm CS} = a^\dagger(x) i D_0 a(x) - \sum_{j=1,2}\left[a^\dagger(x) e^{iA_j(x)} a(x+\hat{\boldsymbol{n}}_j) + \text{h.c.}\right] - \frac{\theta}{4}\epsilon^{\mu\nu\lambda} A_\mu(x) F_{\nu\lambda}(x) \qquad (24)$$

$$H_{\rm CS} = \sum_{\boldsymbol{n}} \sum_{j=1,2}\left[\sigma_+^{(\boldsymbol{n})}\sigma_-^{(\boldsymbol{n}+\hat{\boldsymbol{n}}_j)} + \text{h.c.}\right]$$



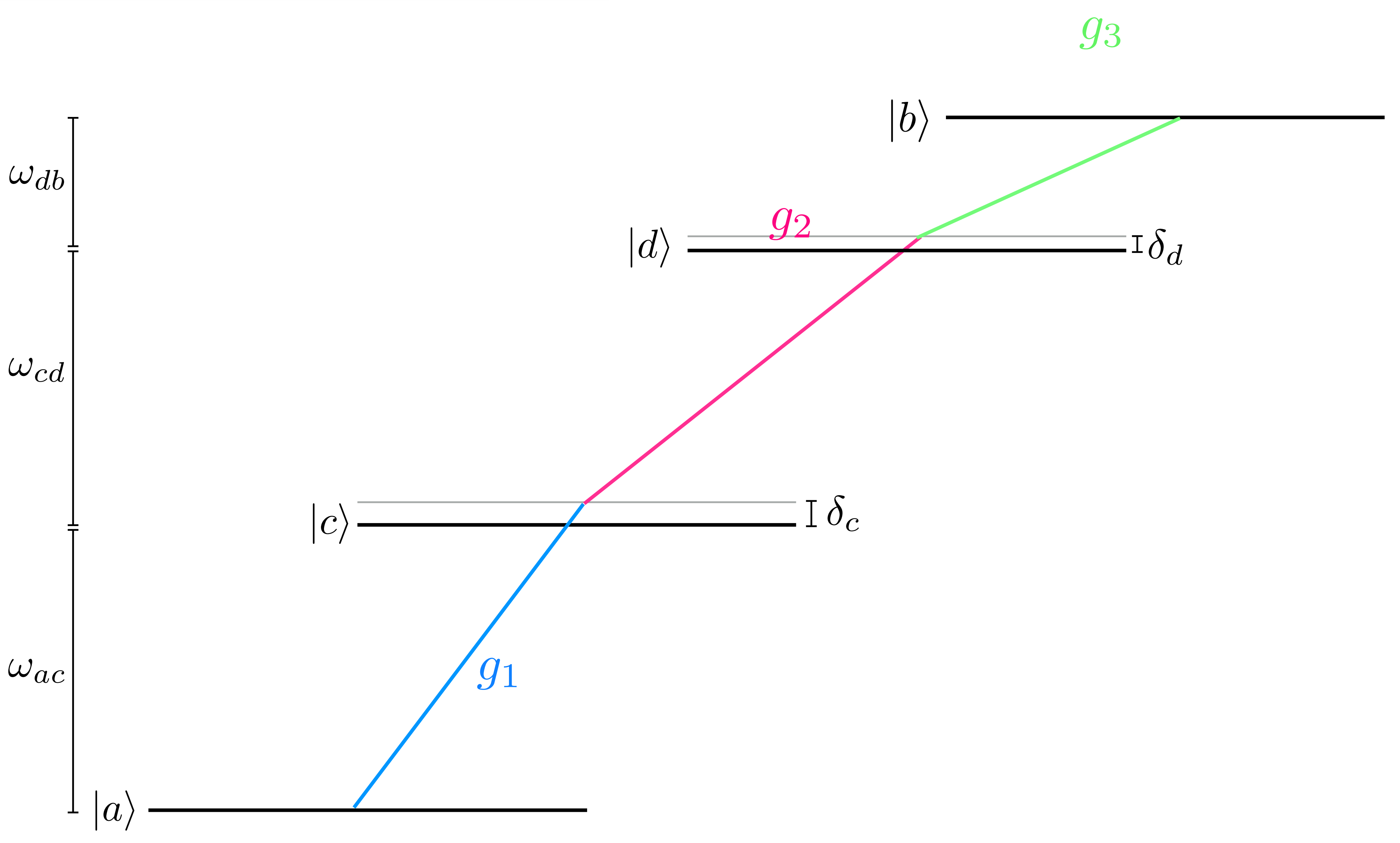
ZD, HAFEZI, MONROE, PAGANO, SEIF AND SHAW, Phys. Rev. R 2, 023015 (2020)

HOW OTHER GAUGE THEORIES? OR NUCLEAR HAMILTONIAN?

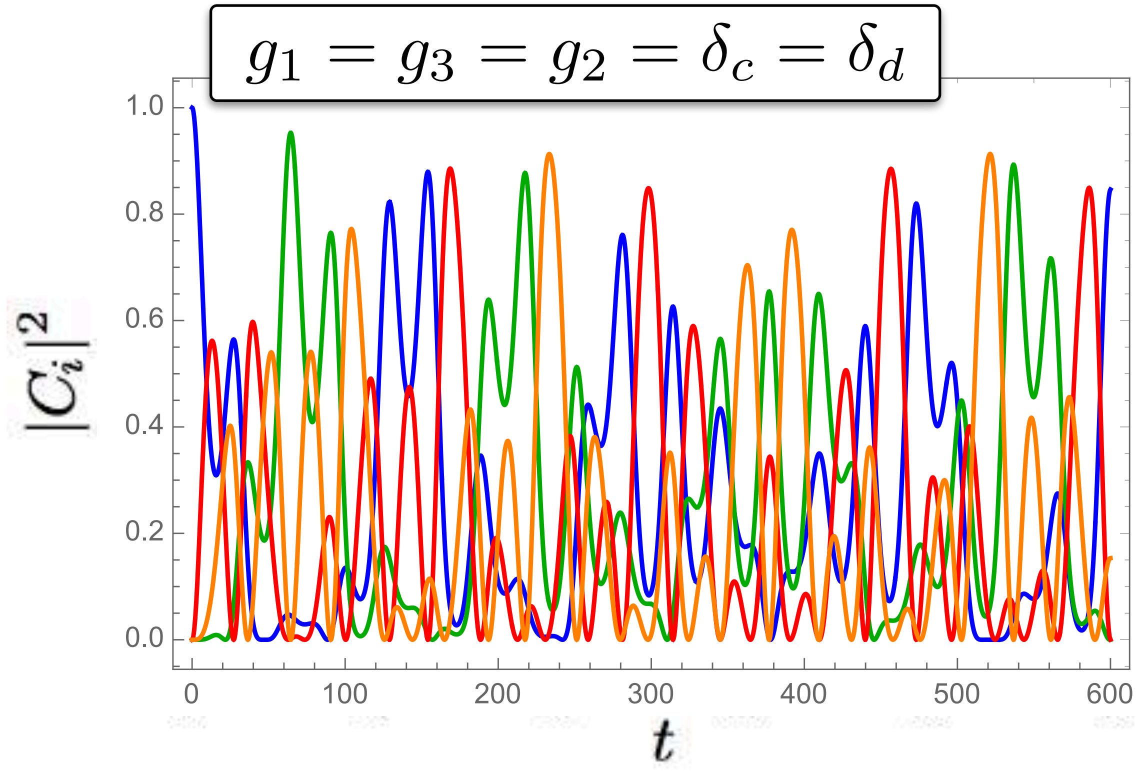
CAN WE EXPAND THE TRAPPED-ION TOOLKIT EVEN FURTHER FOR ANALOG SIMULATIONS OF NUCLEAR AND HIGH-ENERGY PHYSICS?

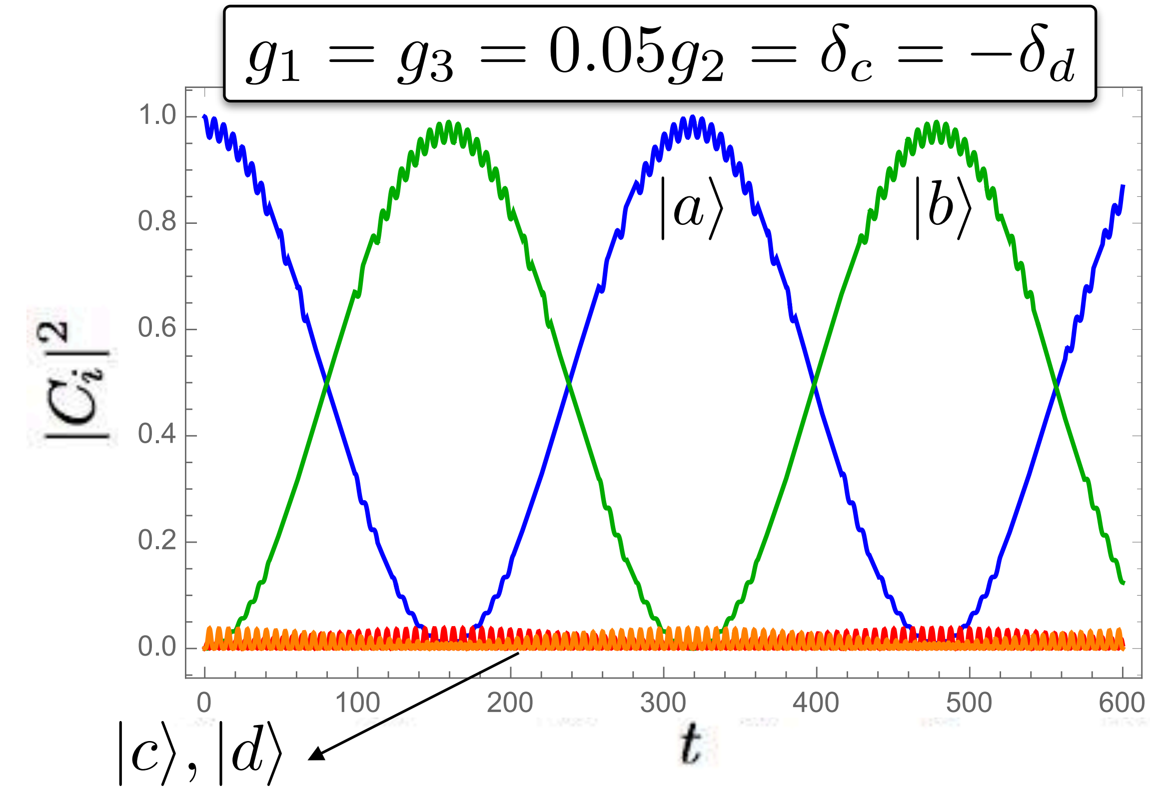
I) MORE COMPLEX SPIN INTERACTIONS?

Adiabatic elimination technique for a four-level system

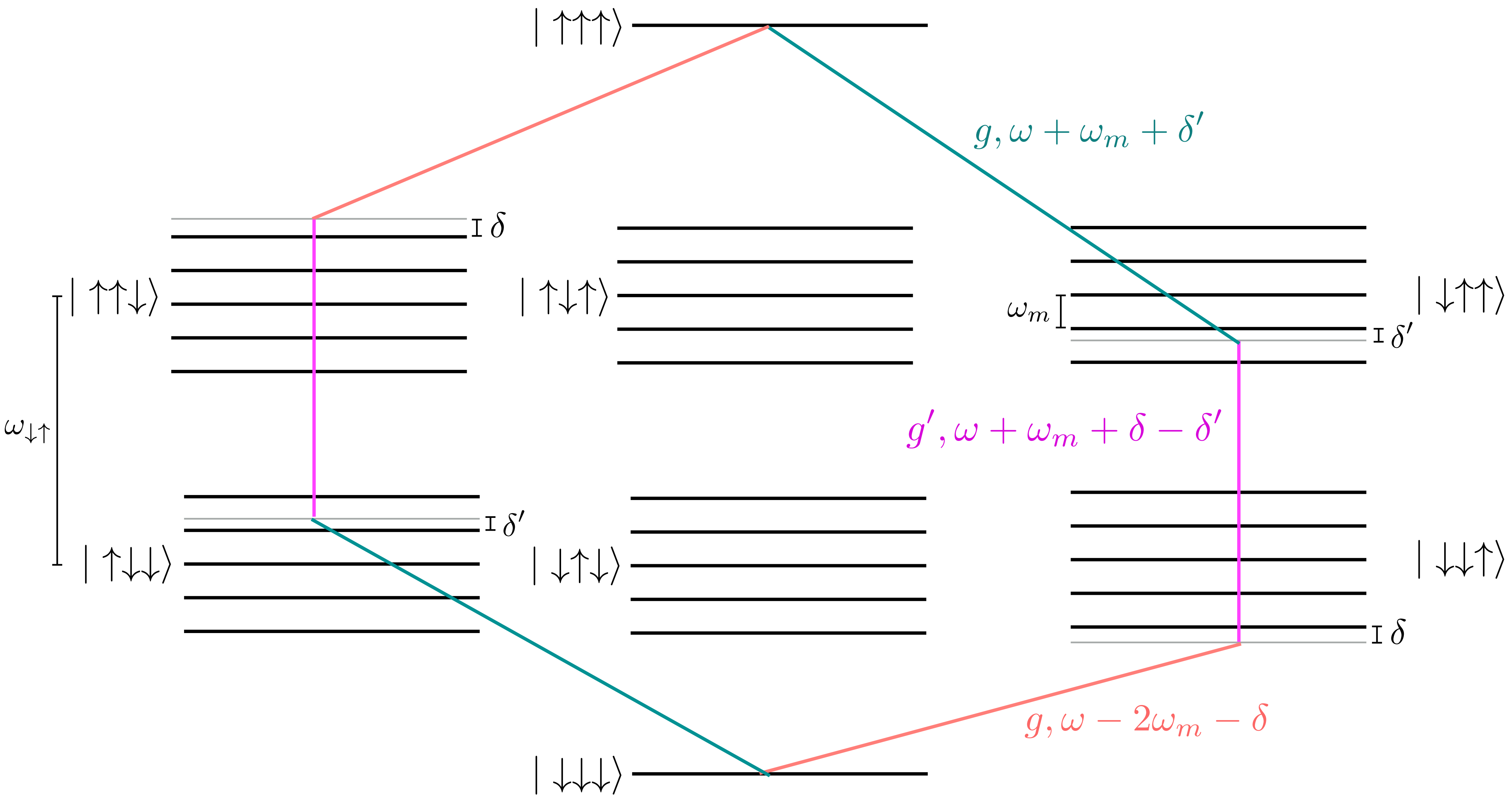


Adiabatic elimination technique
for a four-level system





A BICHROMATIC LASER PLUS A MONOCHROMATIC LASER OFF-TUNED FROM SINGLE AND DOUBLE SIDEBANDS CAN INDUCE THREE-SPIN INTERACTIONS.



18 paths contribute! $\delta = 2\delta'$ eliminates dependence on phonon occupation and makes it very robust.

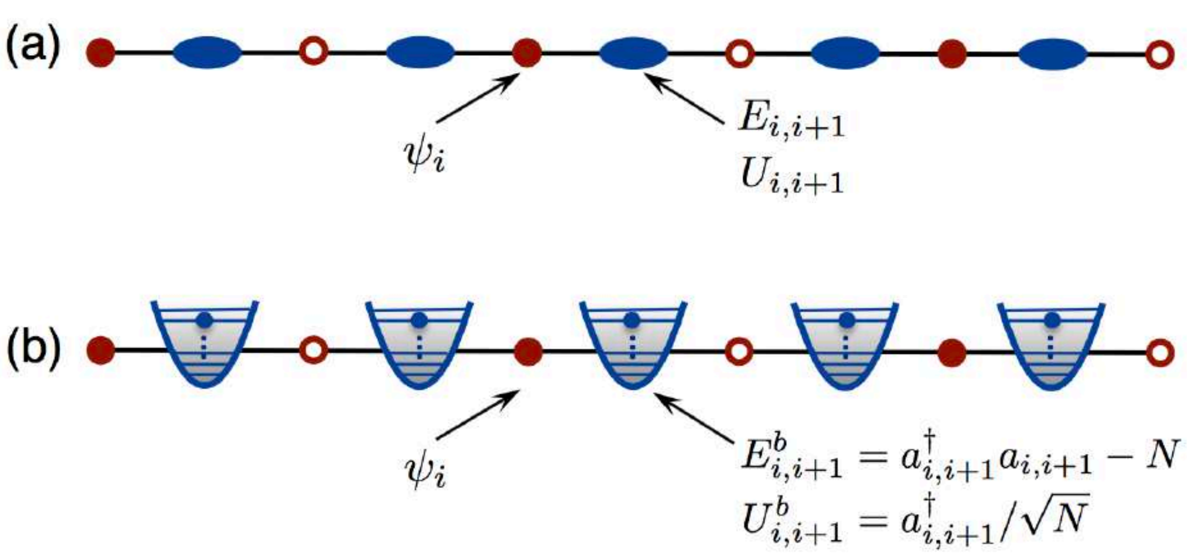
Can augment it with multi-level ion simulators in Low, White, Cox, Day, Senko, Phys. Rev. Research 2, 033128 (2020)

See also: Bermudez et al, Pays.Rev.A79, 060303 R (2009)

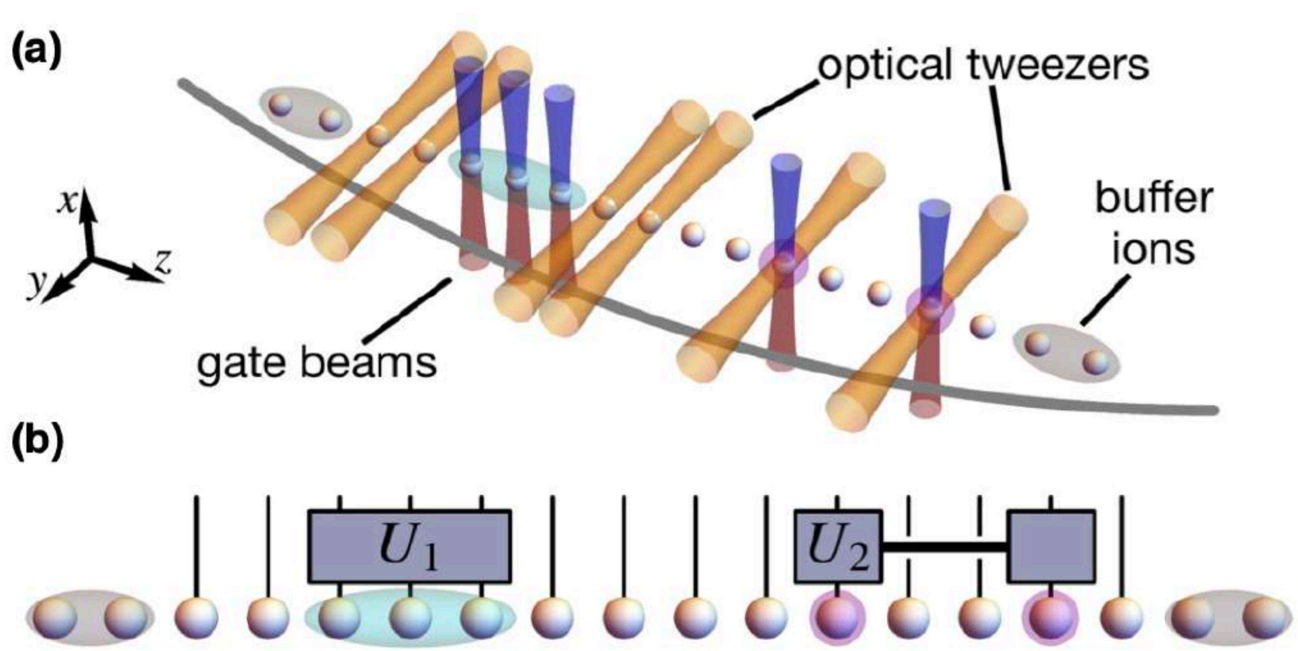
II) LEVERAGING PHONON MODES FOR SIMULATING GAUGE DEGREES OF FREEDOM?

Micro trap technology…

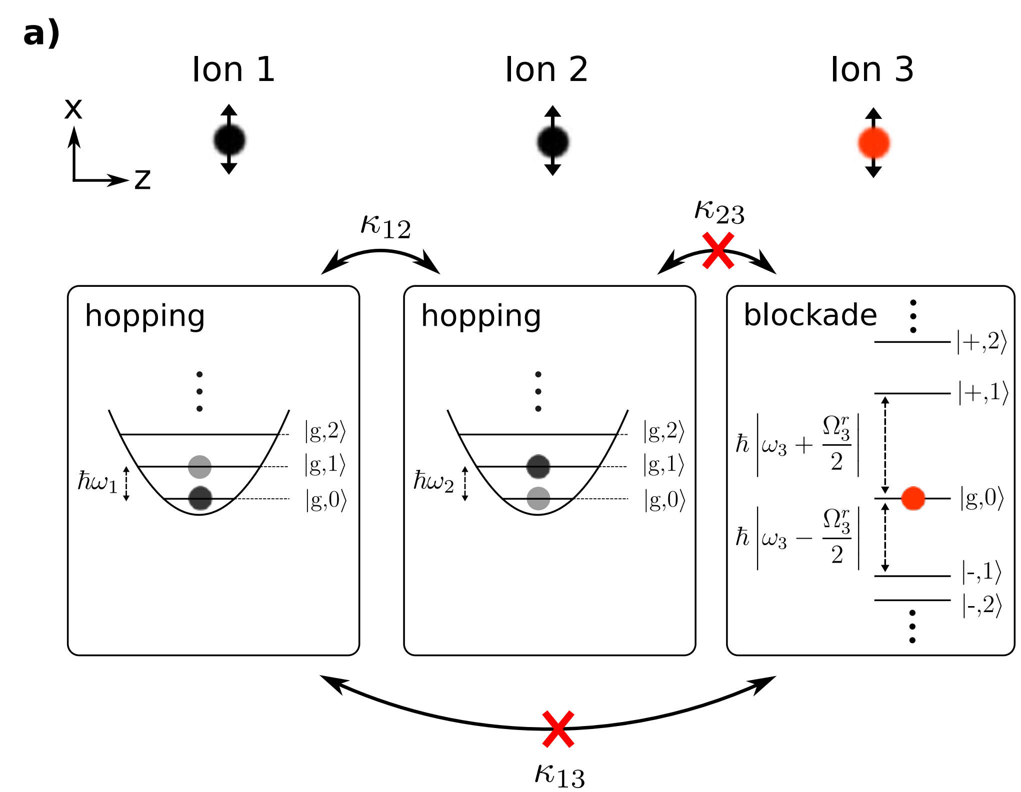
Yang et al, Phys. Rev. A 94, 052321 (2016).



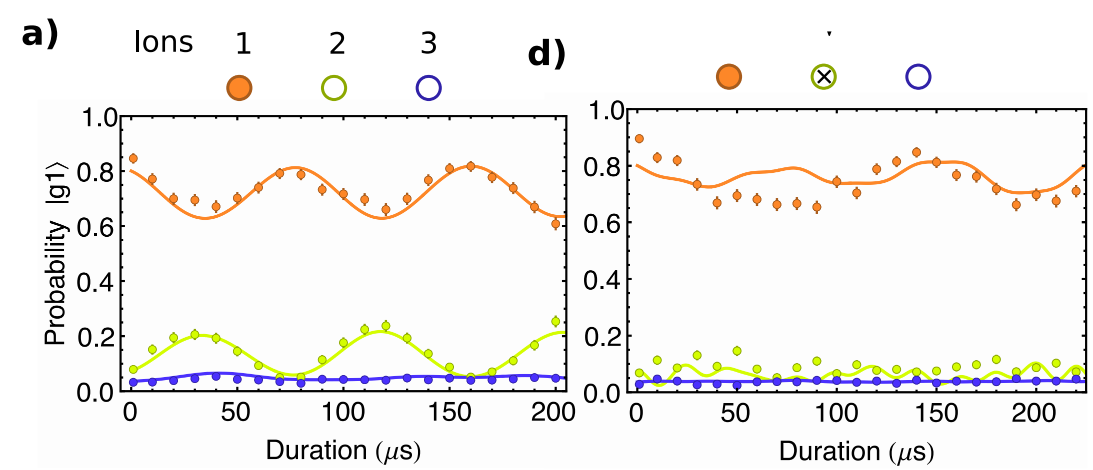
…or new ideas based on pinned ions with optical tweezers: Olsacher et al, PRX Quantum 1, 020316 (2020).



Or simply manipulate phonons on a shorter time scale than effective spin interactions.

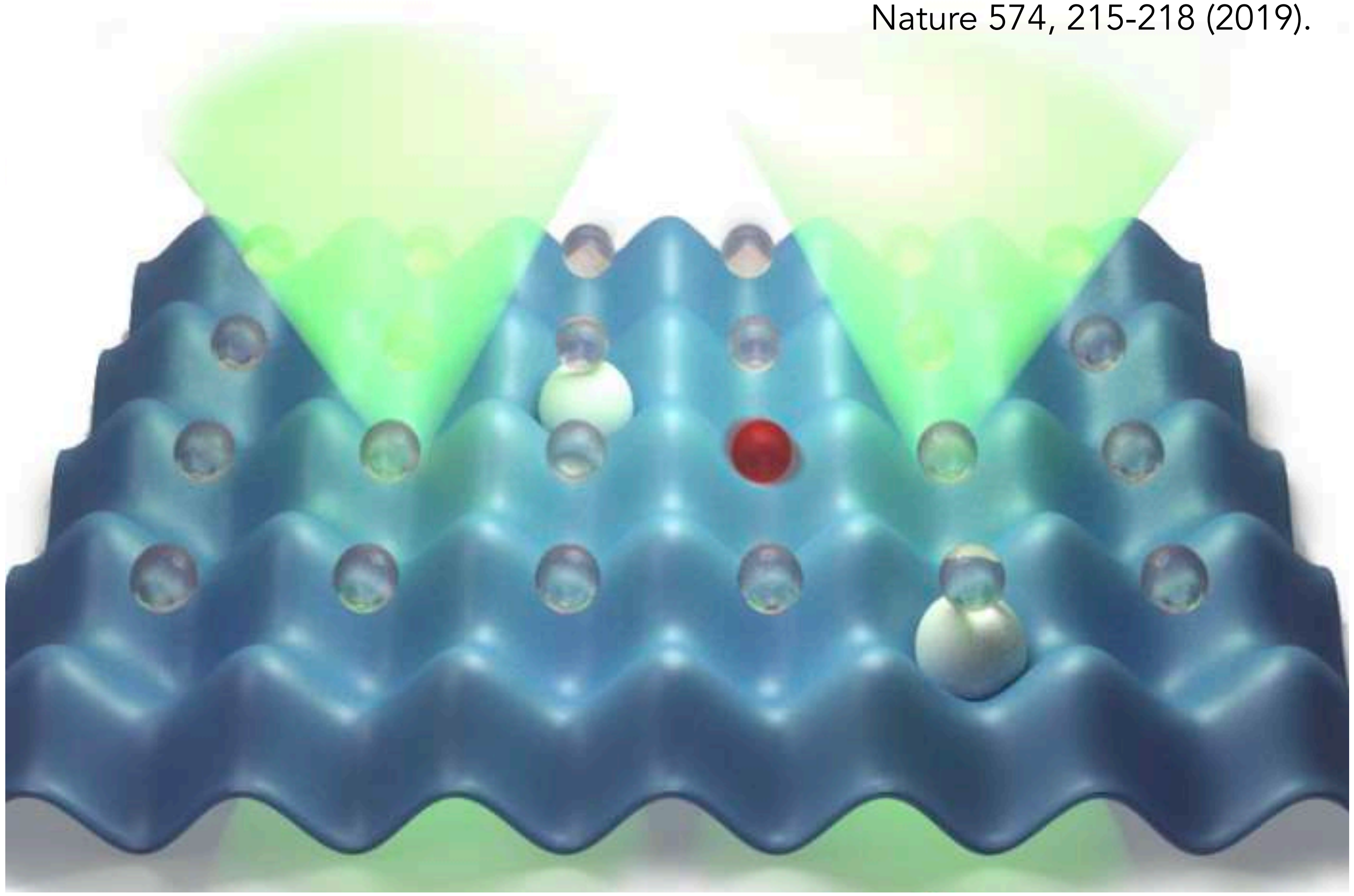


Debnath et al, Phys. Rev. Lett. 120, 073001 (2018).

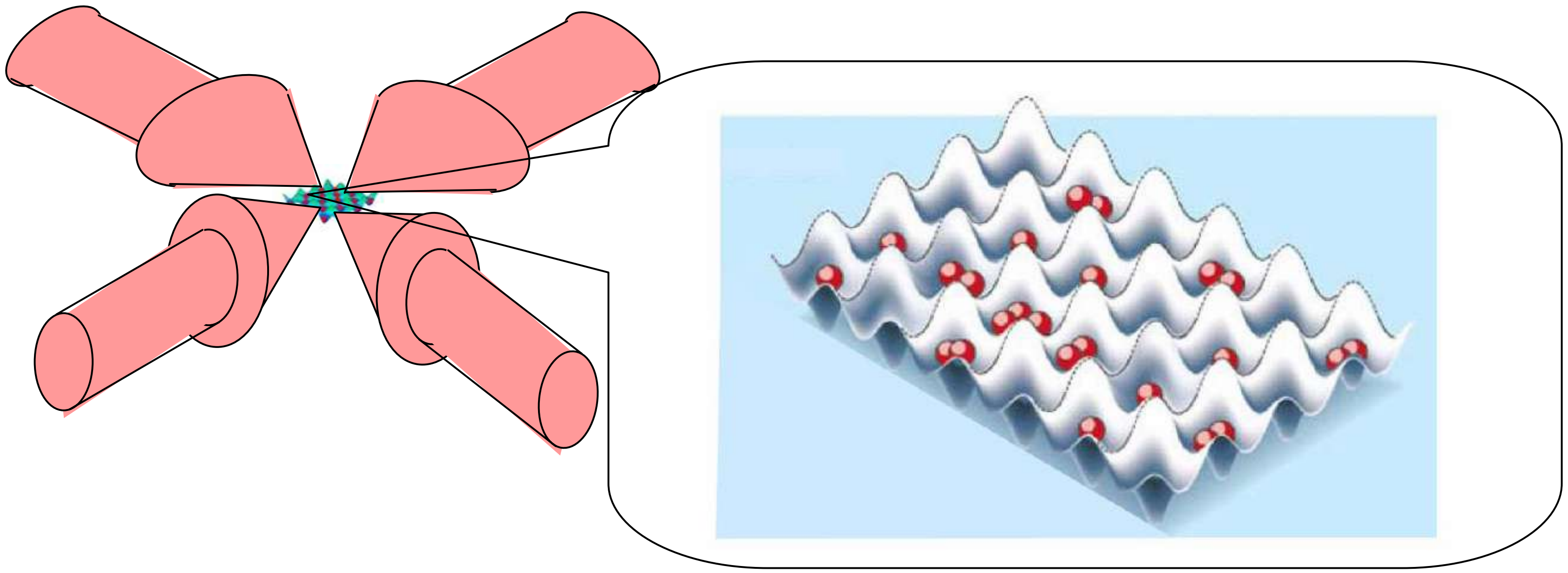


ATOMS AND IONS AS ANALOG QUANTUM SIMULATORS OF LATTICE GAUGE THEORIES?

Nature 574, 215-218 (2019).



An optical lattice is an artificial crystal created by focused laser beams…



…where either fermionic or bosonic atoms or a mixture of both can be trapped.

Effective microscopic Hamiltonian:

Eugene Demler lectures, Harvard University.

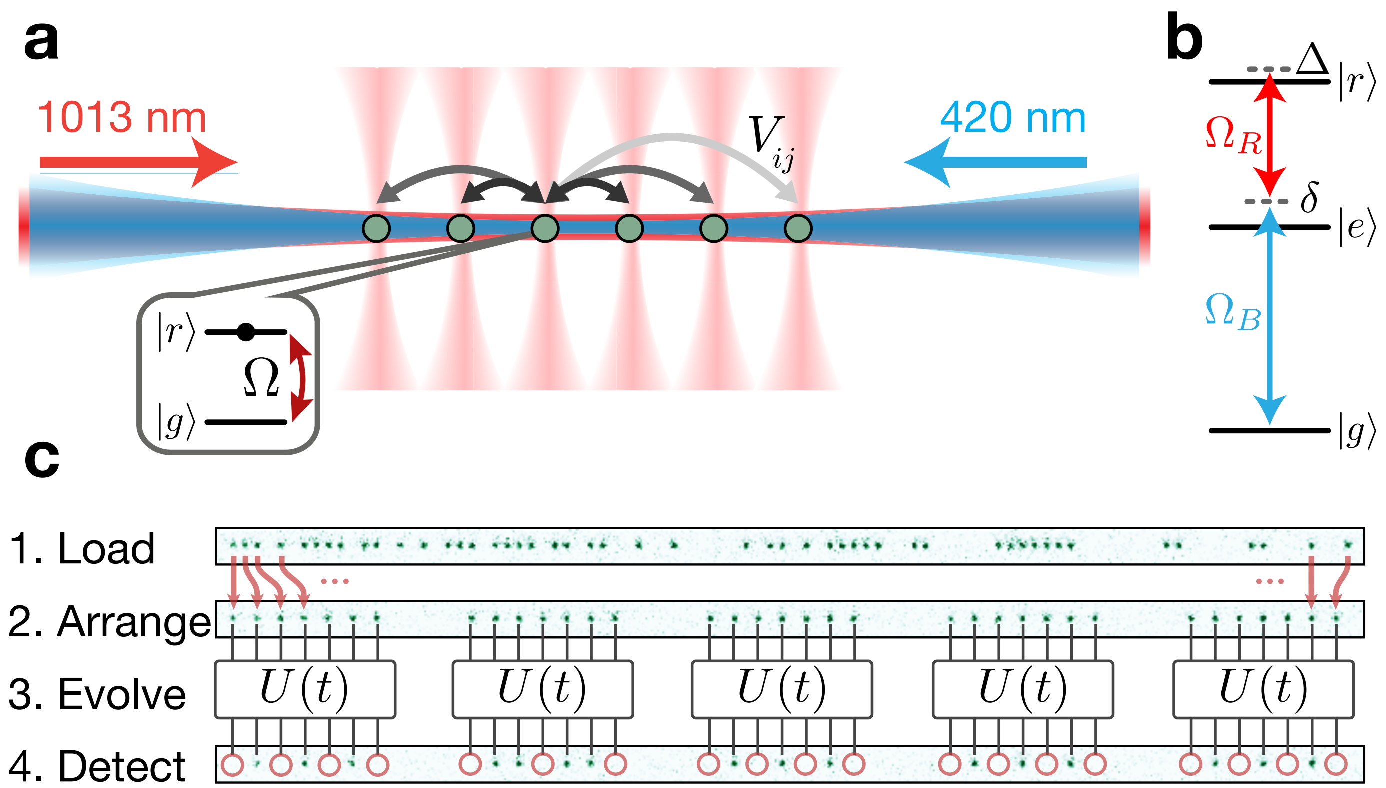
$$\mathcal{H} = -t \sum_{\langle ij \rangle\, \sigma} c^{\dagger}_{i\sigma} c_{j\sigma} + U \sum_{i} n_{i\uparrow} n_{i\downarrow} - \mu \sum_{i} n_i$$

Many variants of this setup exists, including super-lattices, and Rydberg atom arrays in optical tweezers, etc, cable of simulating Hubbard model, Ising model, and simple lattice gauge theories.

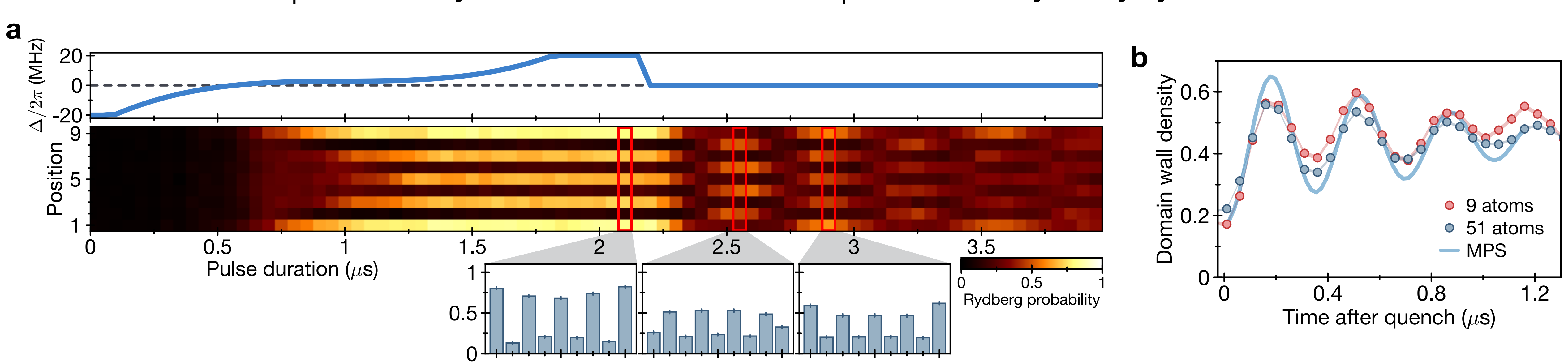
EXAMPLE: PROBING MANY-BODY DYNAMICS ON A 51-ATOM QUANTUM SIMULATOR

Bernien et al, *Nature* 551, 579–584 (2017).

An array of programmable Rydberg atoms…



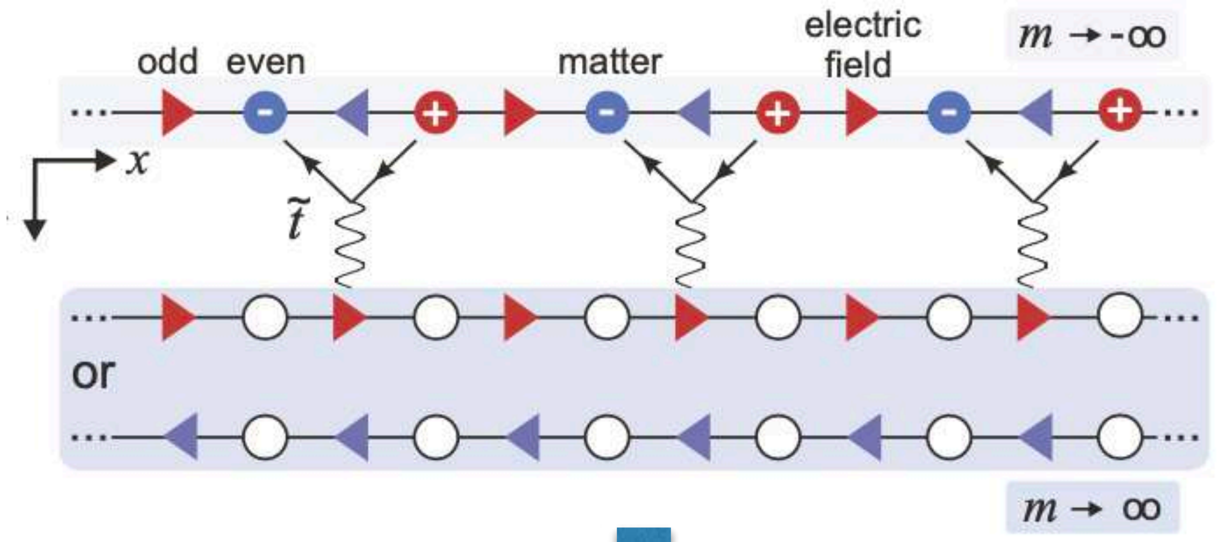
…can simulate the quenched dynamics of a constrained quantum-many body system.



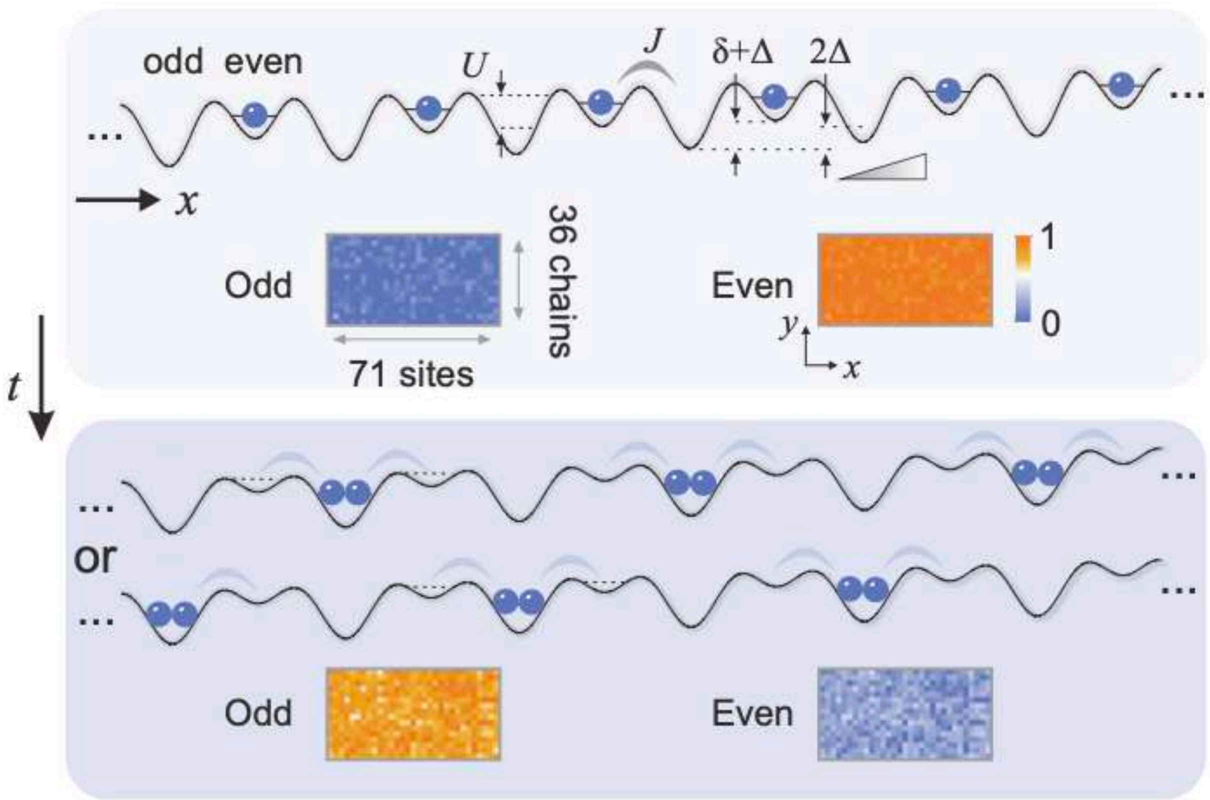
EXAMPLE: OBSERVATION OF GAUGE INVARIANCE IN A 71-SITE BOSE-HUBBARD QUANTUM SIMULATOR

Yang et al, *Nature* 587 (2020) 7834, 392-396.

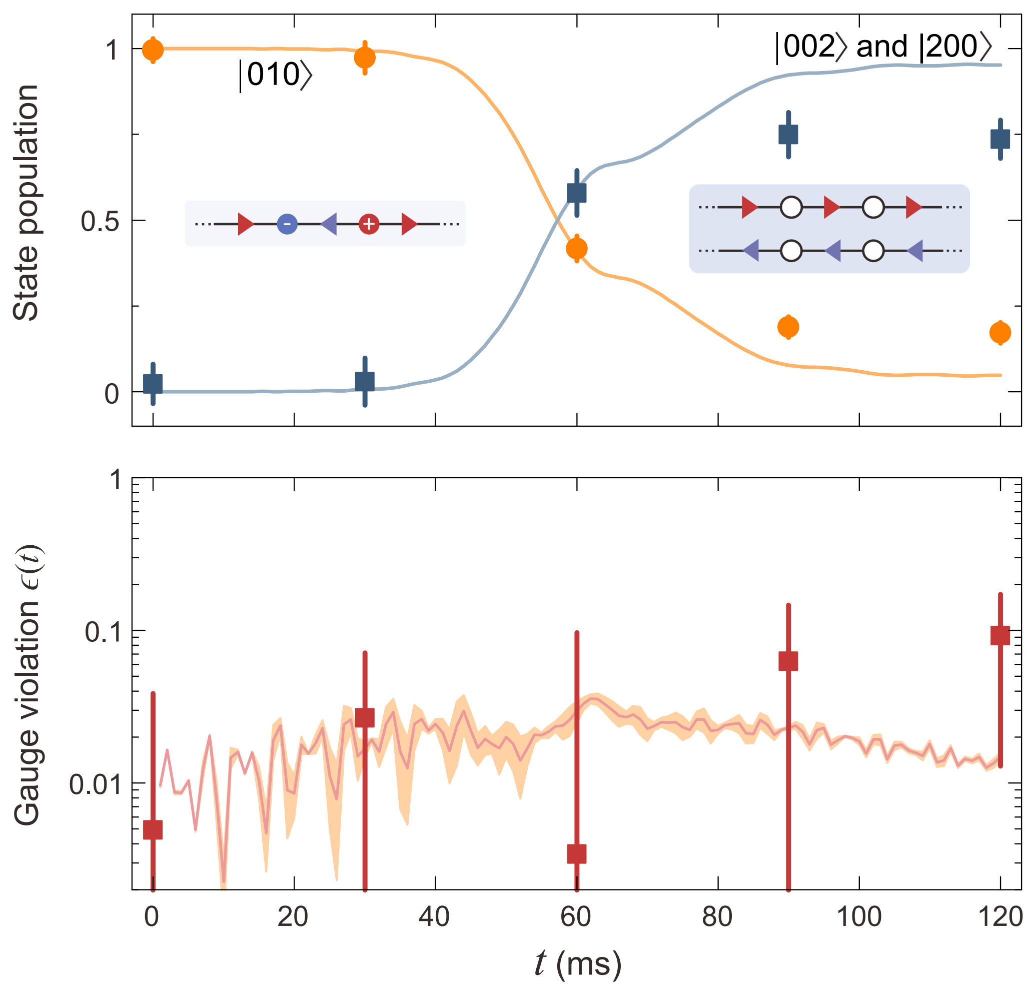
Schwinger model within quantum link model formulation…



…mapped to an atomic Hubbard simulator:



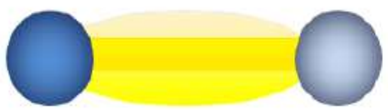
Gauss's law violating effects are suppressed:

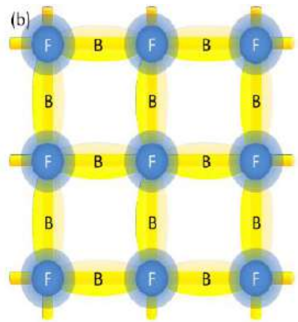


EXAMPLE: WHAT ABOUT NON-ABELIAN SYMMETRIES? SLOW BUT STEADY PROGRESS.

In the electric-field basis, non-trivial interactions are:

$$\psi_L^\dagger U \psi_R \qquad \sum_{\text{plaquettes}} \left(\mathrm{Tr}\left(U_1 U_2 U_3^\dagger U_4^\dagger\right) + h.c. \right)$$

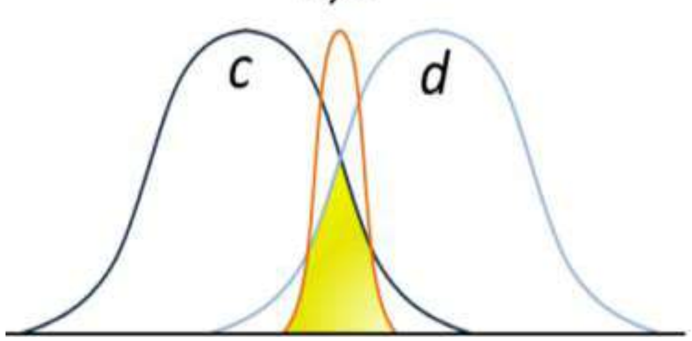




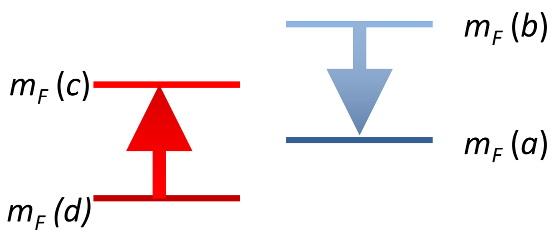
Some non-Abelian gauge theory proposals:
Zohar, Cirac, Reznik, Phys. Rev. Lett. 110, 125304 (2013), Phys. Rev. A 88 023617 (2013), Rep. Prog. Phys. 79, 014401 (2016).
González Cuadra, Zohar, Cirac, New J. Phys. 19 063038 (2017).
Dasgupta and Raychowdhury, arXiv:2009.13969 [hep-lat].

A few proposals are developed including one based on cold Bose-Fermi mixture in optical lattices…

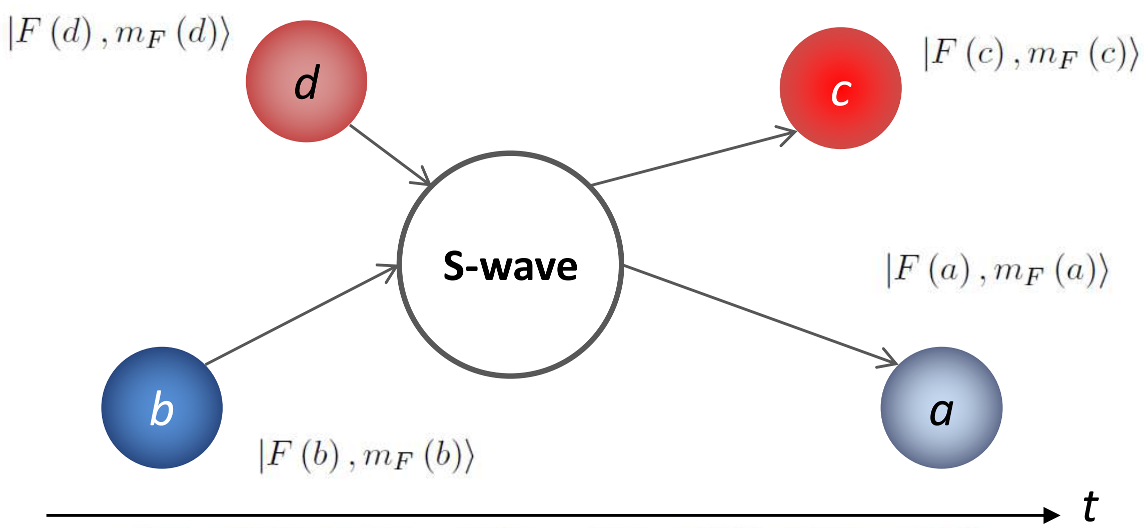
e.g.,



$$\psi_L^\dagger U \psi_R \sim \psi_L^\dagger L_+ \psi_R = c^\dagger a^\dagger b d$$



Zohar, Cirac, Reznik, Phys. Rev. A 88 023617 (2013).

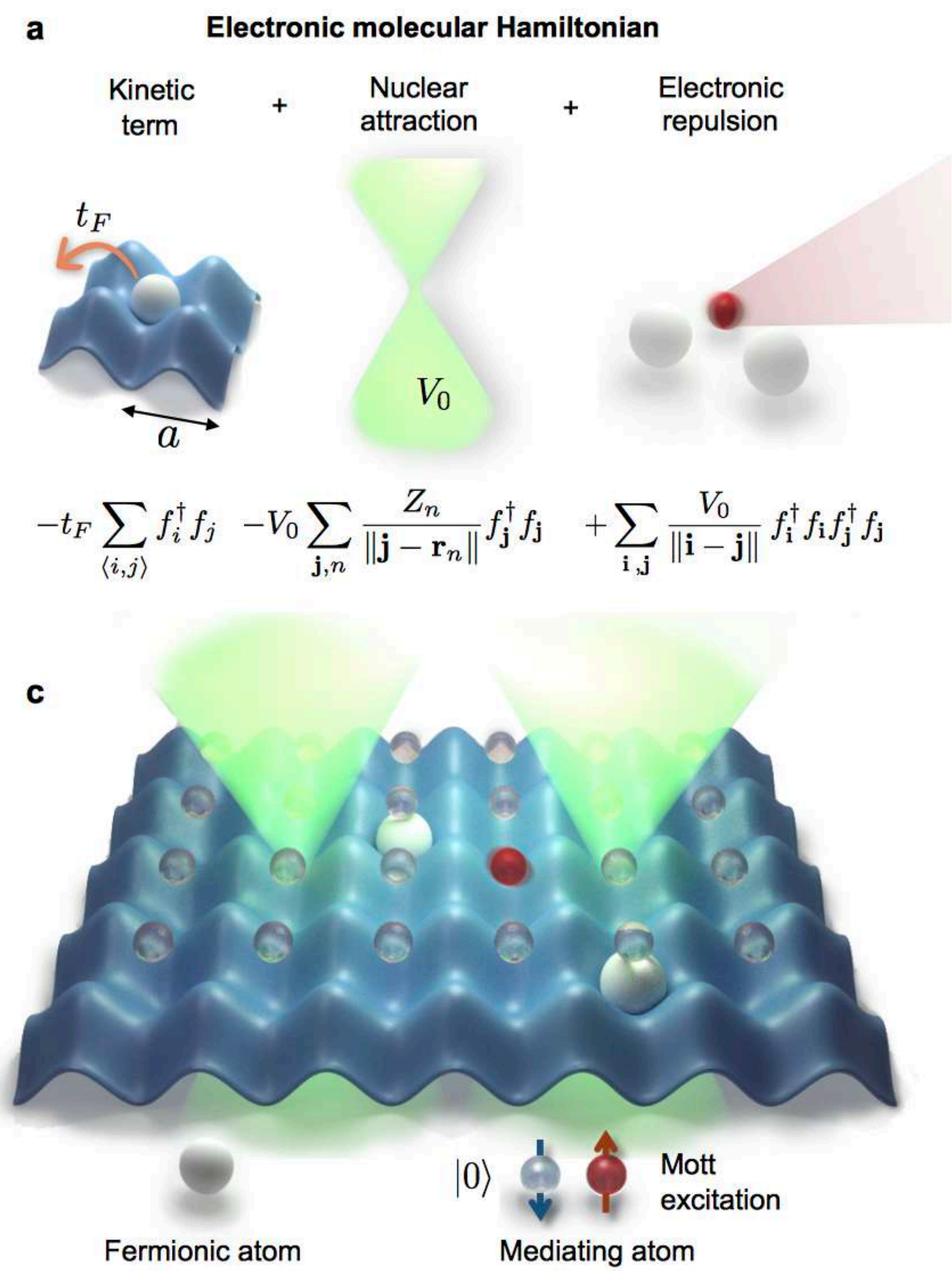


$$m_F(a) + m_F(c) = m_F(b) + m_F(d)$$

…where gauge invariance is inherent in the local angular momentum conservation in scattering processes.

EXAMPLE I: QUANTUM CHEMISTRY VS. NP IN ANALOG SIMULATIONS

Long-range interactions between electrons mediated with Mott insulator spin excitations. Already challenging.

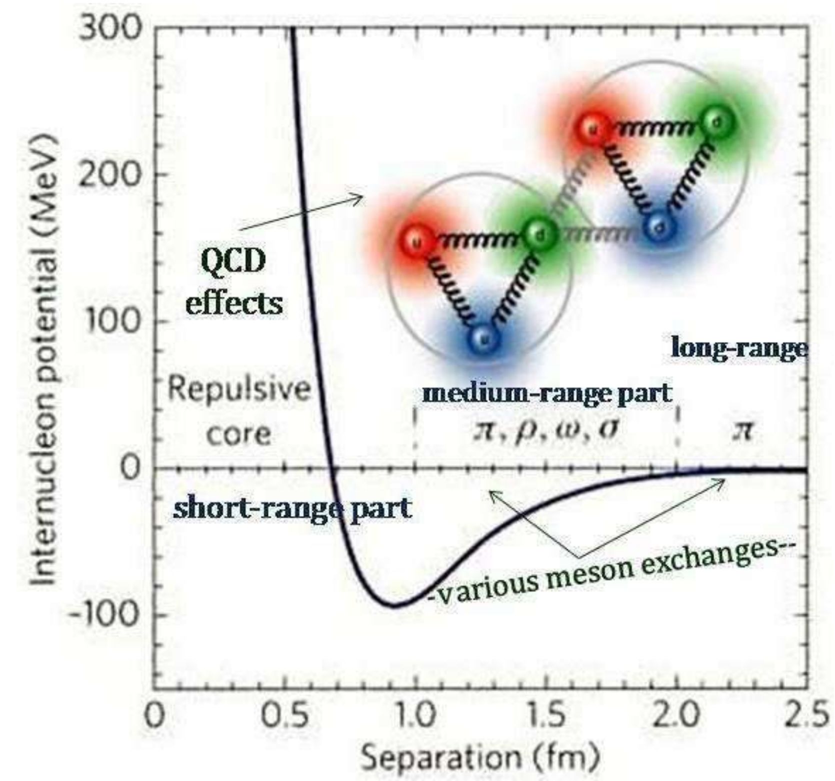


Effective potential $V(r) \approx C + \frac{V_0}{r/a} e^{-r/L}$

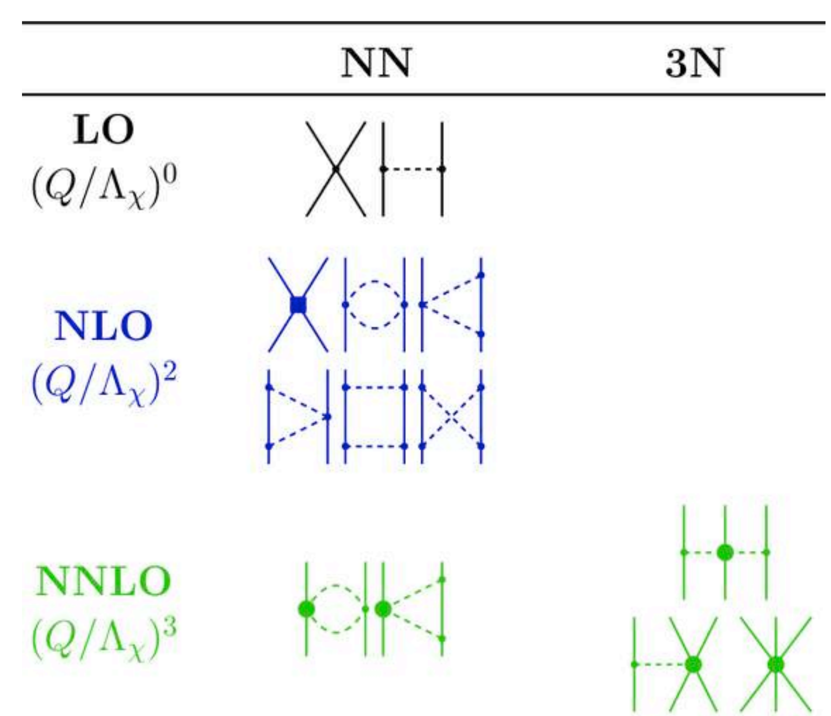
Argüello-Luengo, González-Tudela, Shi, Zoller, Cirac, Nature 574, 215-218 (2019)

? →

How about analog schemes for nuclear Hamiltonian with more complex interactions?



Or in the language of effective field theories:



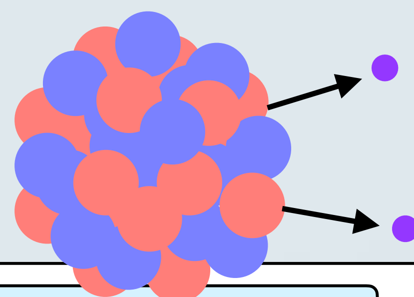
TO SUMMARIZE…

A NUCLEAR PHYSICS ROADMAP FOR LEVERAGING QUANTUM TECHNOLOGIES

www.ibtimes.co.uk

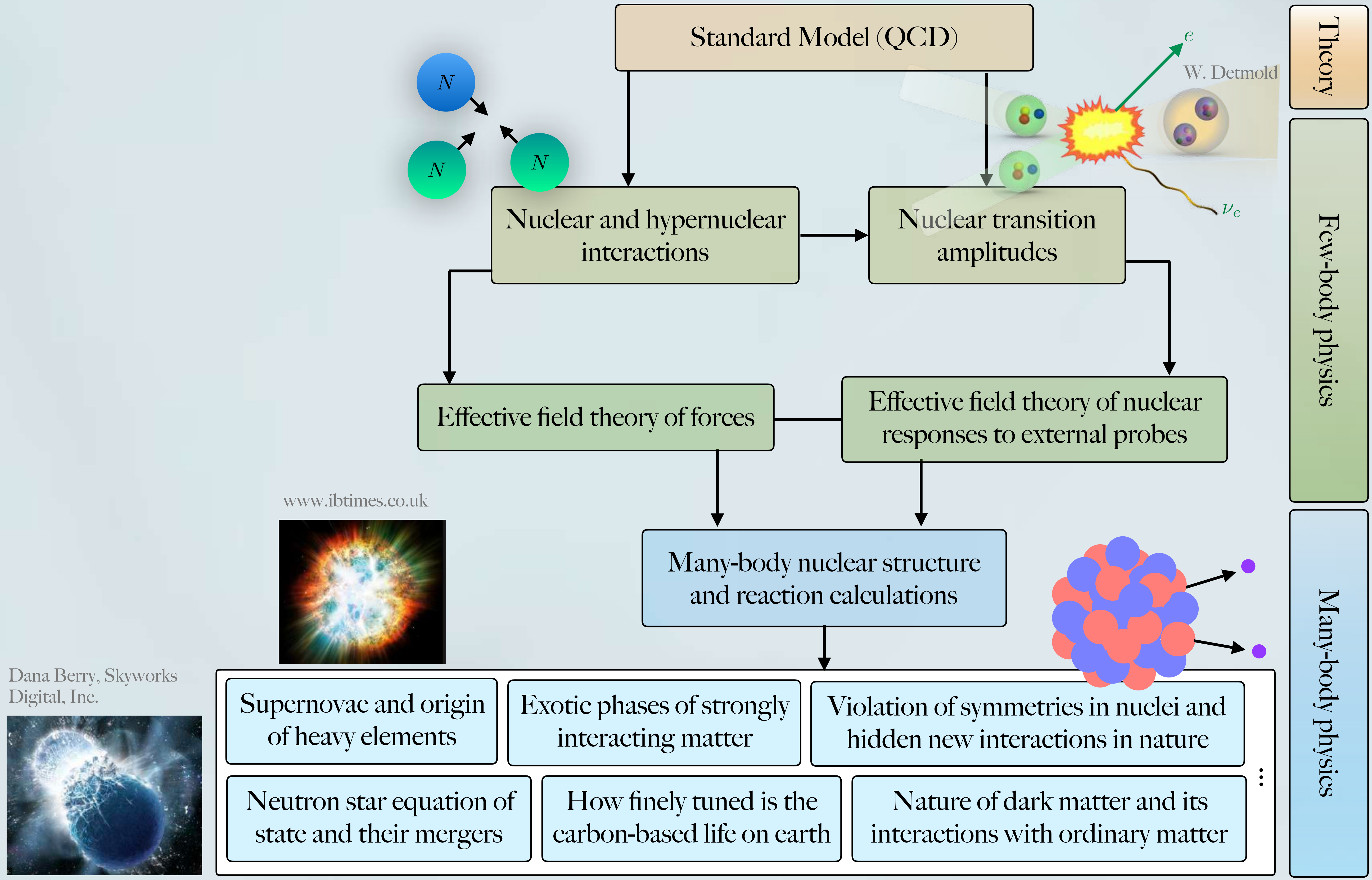
Dana Berry, Skyworks Digital, Inc.

- Supernovae and origin of heavy elements
- Exotic phases of strongly interacting matter
- Violation of symmetries in nuclei and hidden new interactions in nature
- Neutron star equation of state and their mergers
- How finely tuned is the carbon-based life on earth
- Nature of dark matter and its interactions with ordinary matter
- ⋮



Many-body physics

A NUCLEAR PHYSICS ROADMAP FOR LEVERAGING QUANTUM TECHNOLOGIES



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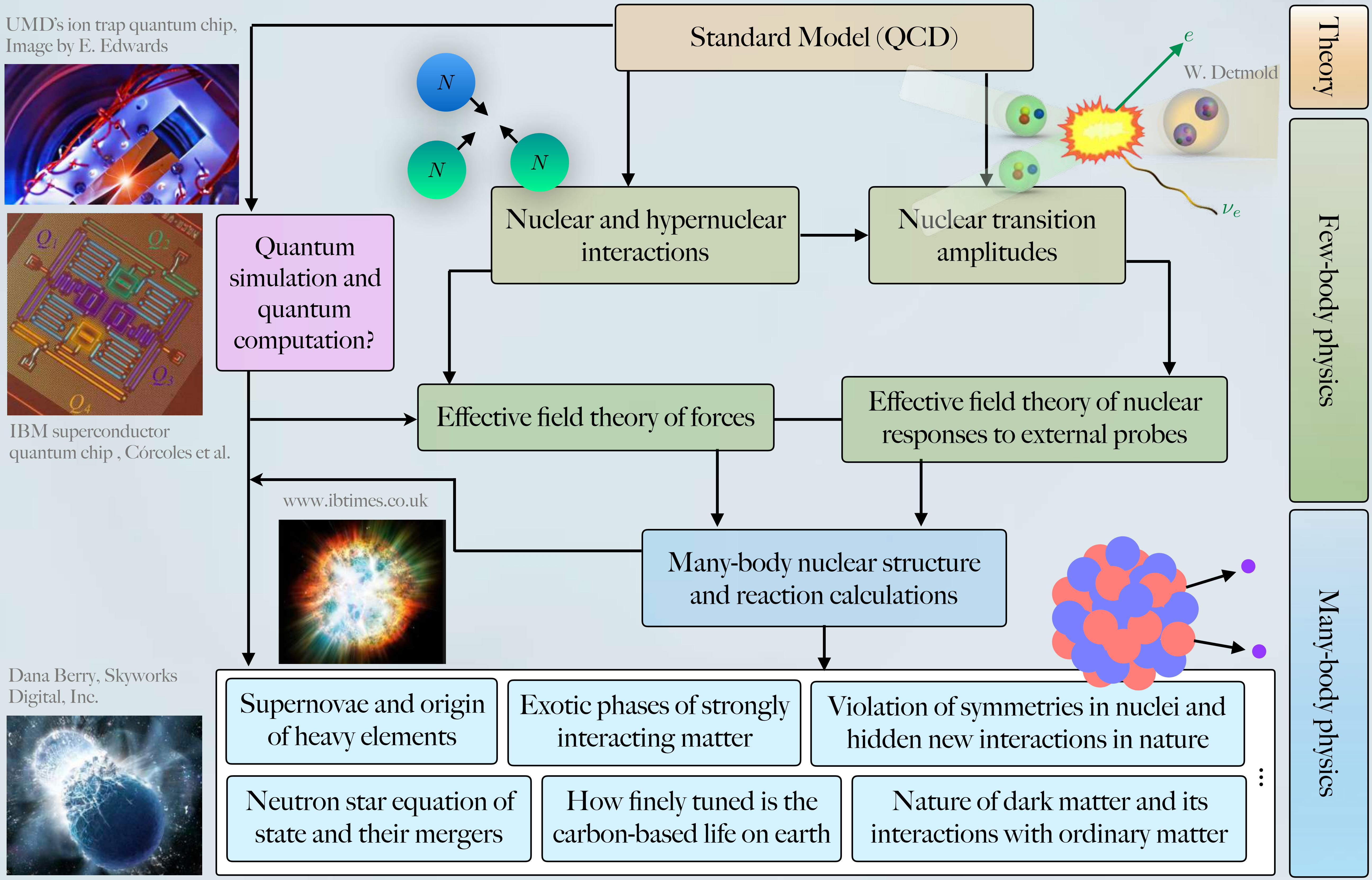

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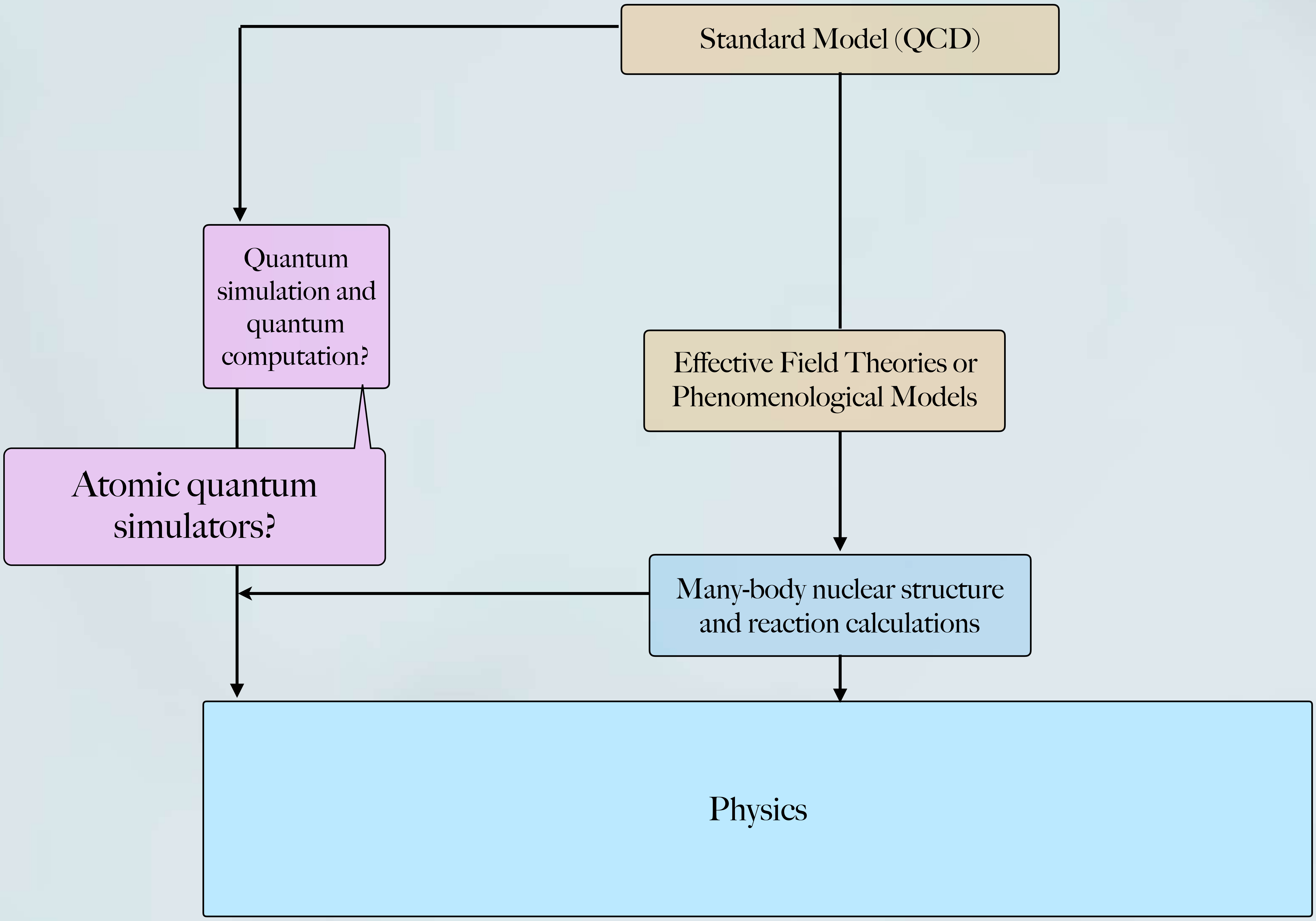

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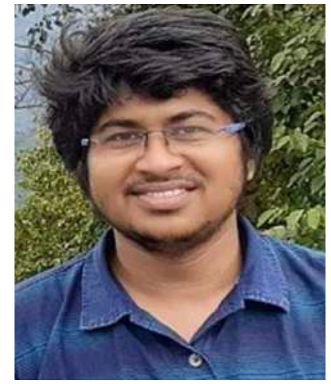

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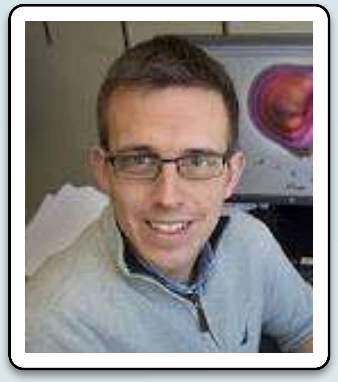

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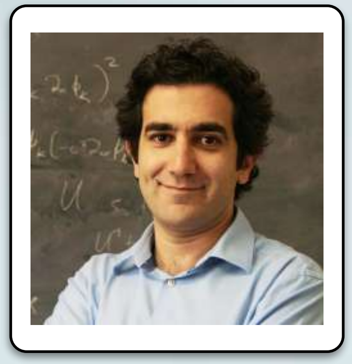

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THANK YOU