Nuclear Physics Entering a Quantum-simulation Era: Lessons from the Past, Vision for the Future

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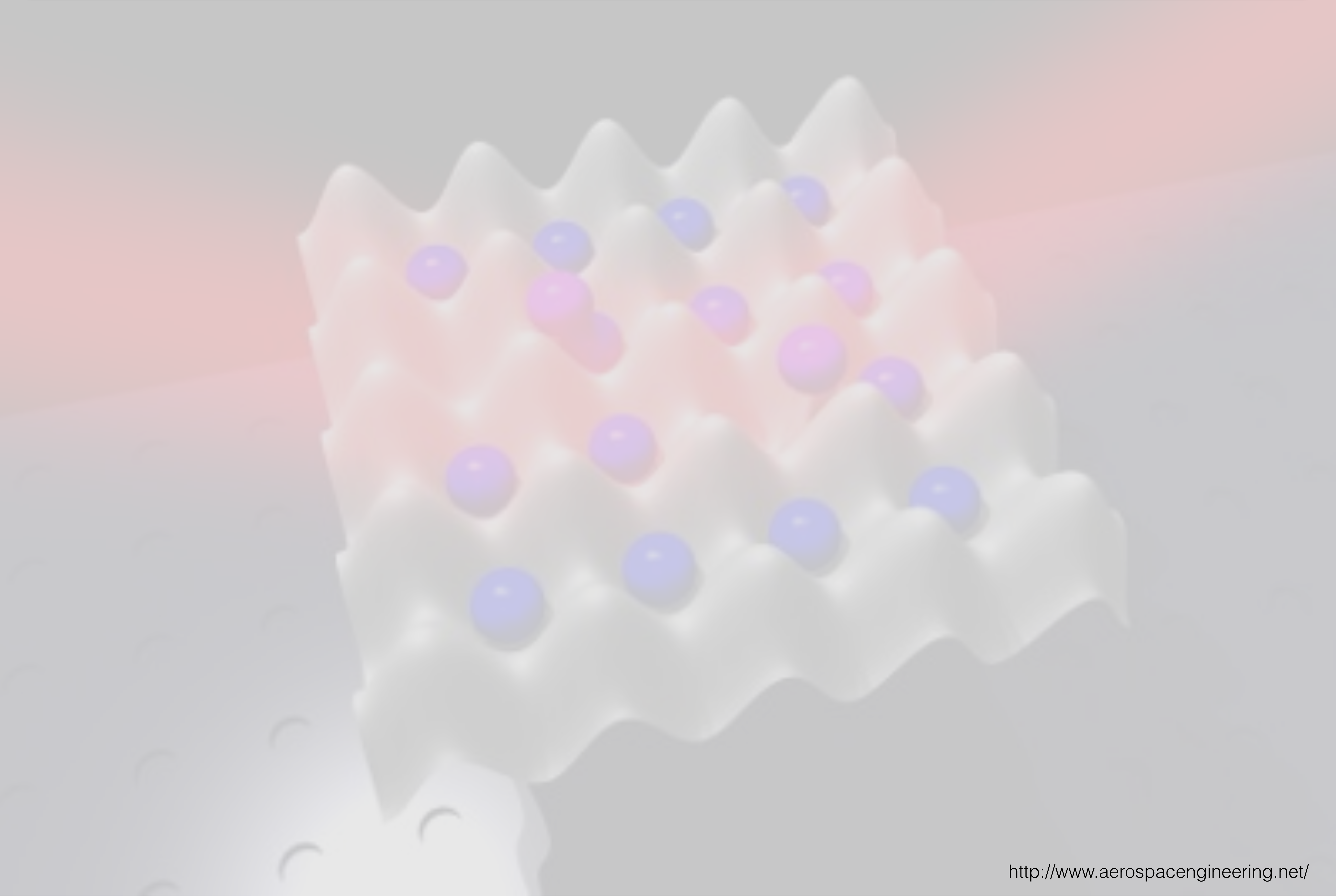
UNIVERSITY OF MARYLAND AND RIKEN FELLOW

Advances in many-body theories: from first principle methods to quantum computing and machine learning
Virtual ECT* workshop, Nov 2-6, 2020

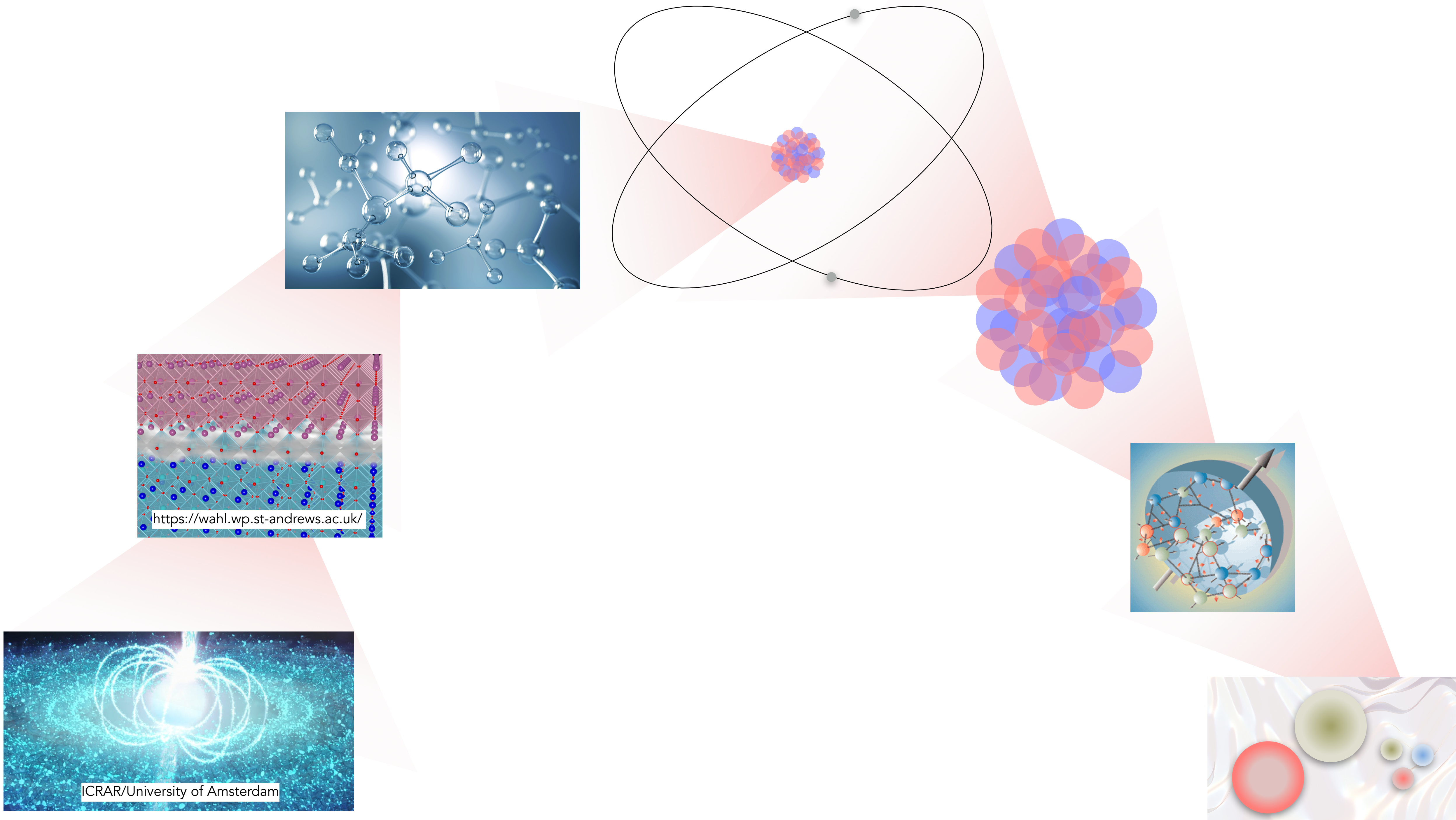
QUANTUM SIMULATION FOR NP: WHAT IT IMPLIES.



http://www.aerospacengineering.net/

QUANTUM SIMULATION FOR NP: WHAT IT IMPLIES.

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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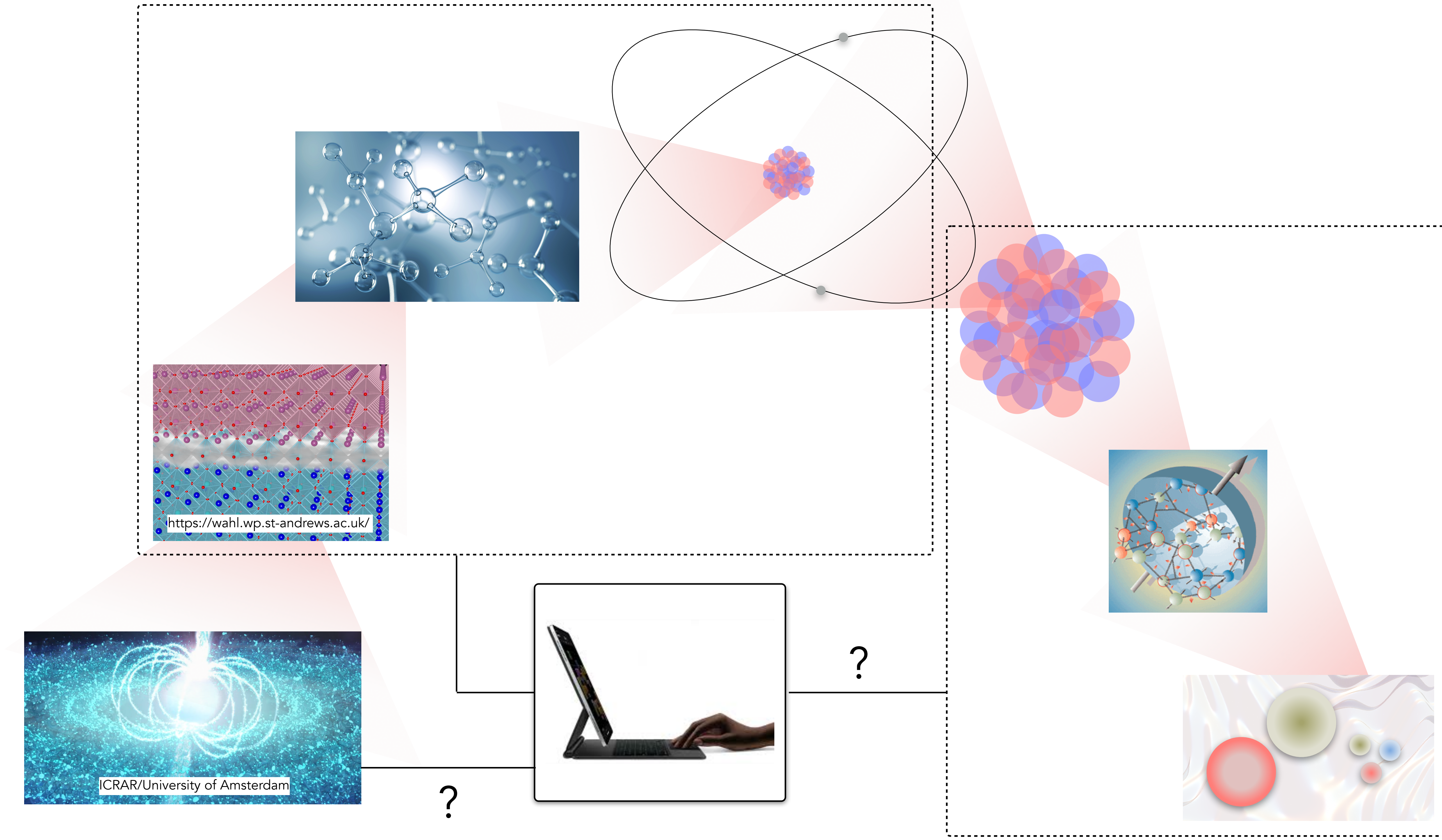

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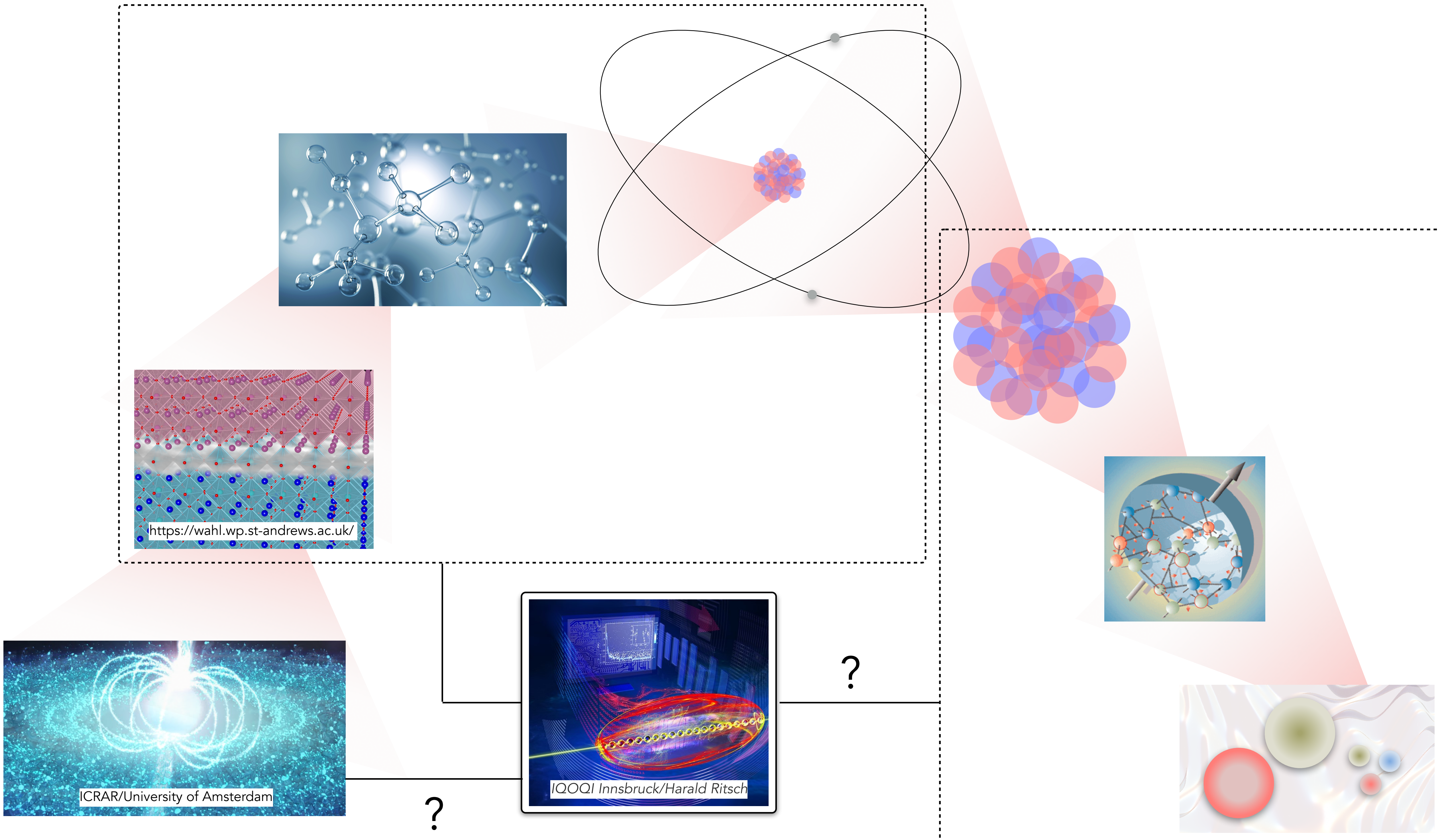
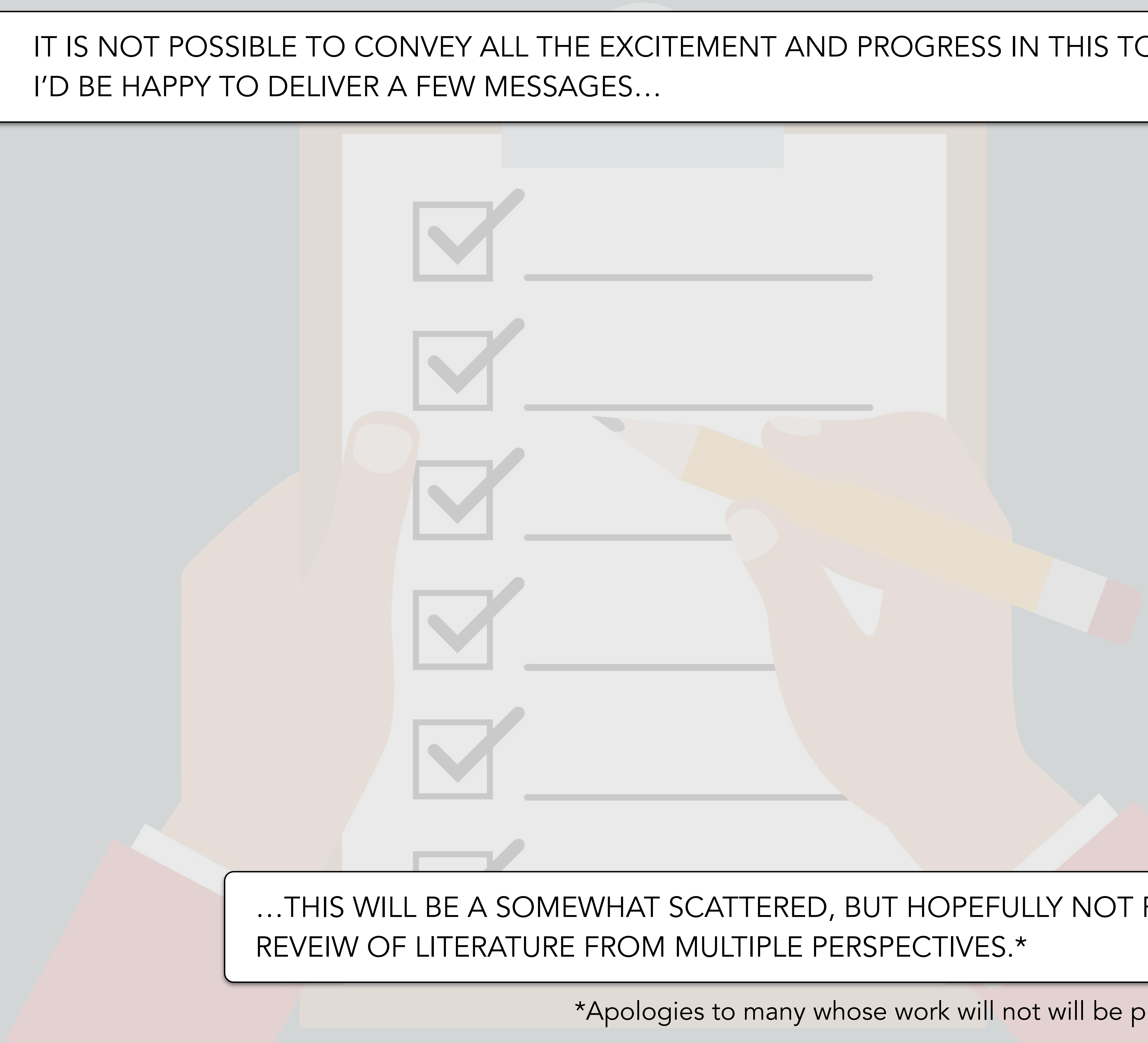


A RANGE OF QUANTUM SIMULATORS WITH VARING CAPACITY AND CAPABILITY IS AVAILABLE!

IT IS NOT POSSIBLE TO CONVEY ALL THE EXCITEMENT AND PROGRESS IN THIS TOPIC IN 30′.
I'D BE HAPPY TO DELIVER A FEW MESSAGES…



…THIS WILL BE A SOMEWHAT SCATTERED, BUT HOPEFULLY NOT RANDOM, REVEIW OF LITERATURE FROM MULTIPLE PERSPECTIVES.*

*Apologies to many whose work will not will be properly covered.

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NP is not short of hard computational problems. Quantum simulation may be the way forward in some. Much need to be done to change the game in comp. NP.

One should leverage both analog and digital simulations. Hybrid analog-digital protocols may reduce time to solution in near term.

Appropriate DOF need to be identified (QCD DOF, nucleonic DOF, macroscopic and hydrodynamical DOF?), along with most efficient mappings to quantum hardware.

Leveraging our classical computing capabilities for hybrid classical-quantum simulations. Quantum means to develop better classical algorithms?

NP problems are different from CM and quantum chemistry problems. A lot can still be learned from progress in those areas, but new strategies and ideas need to be introduced for NP.

Can we discover deeper connections in nuclear phenomenology by quantum-information tools? Can prototypes provide insight?

Theory-experiment co-development is a key to progress. Can NP impact quantum-simulation hardware developments?

Over the next decade, we will witness a new ecosystem, a quantum-skillful NP workforce, and unprecedented interdisciplinary collaborations.

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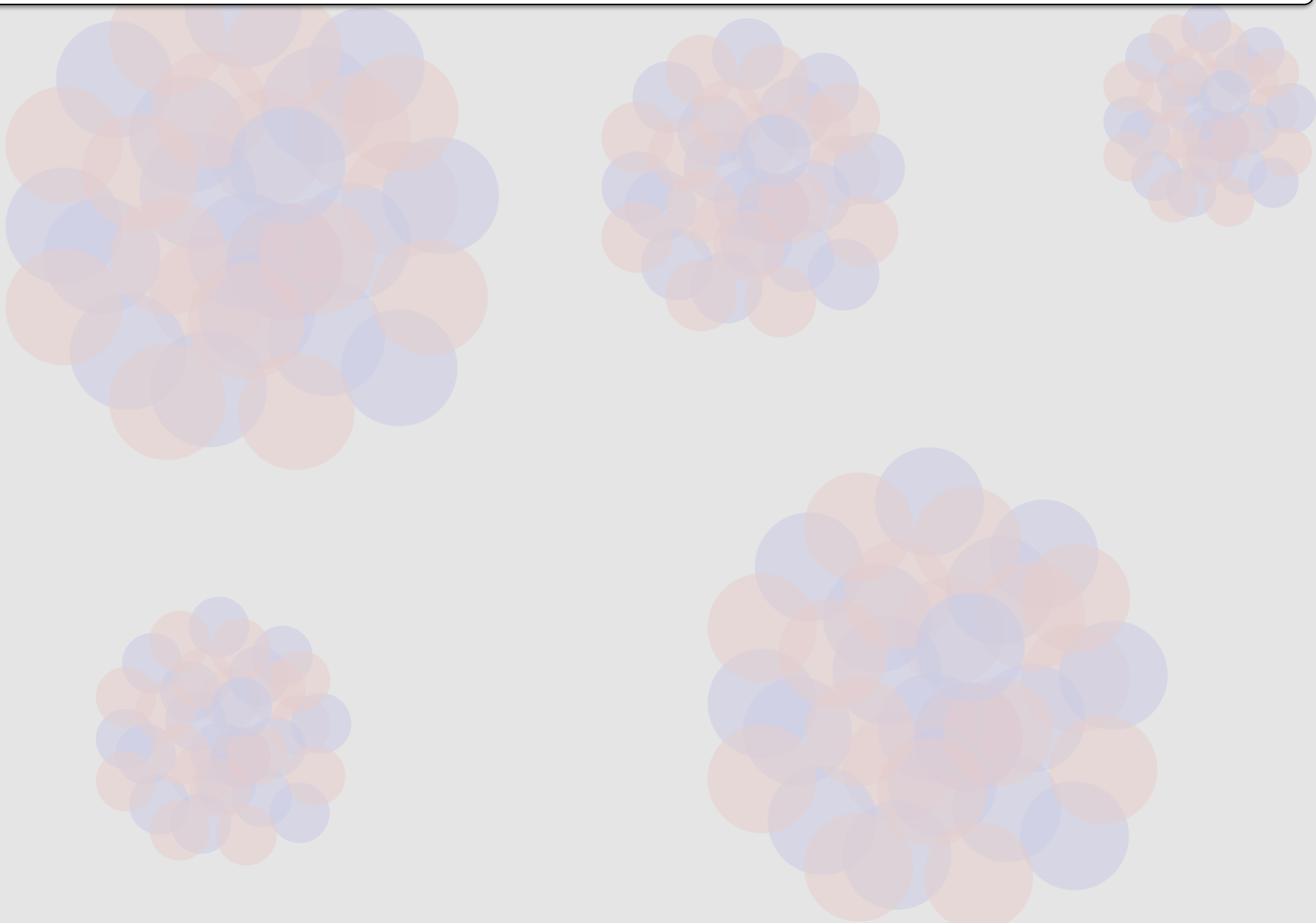
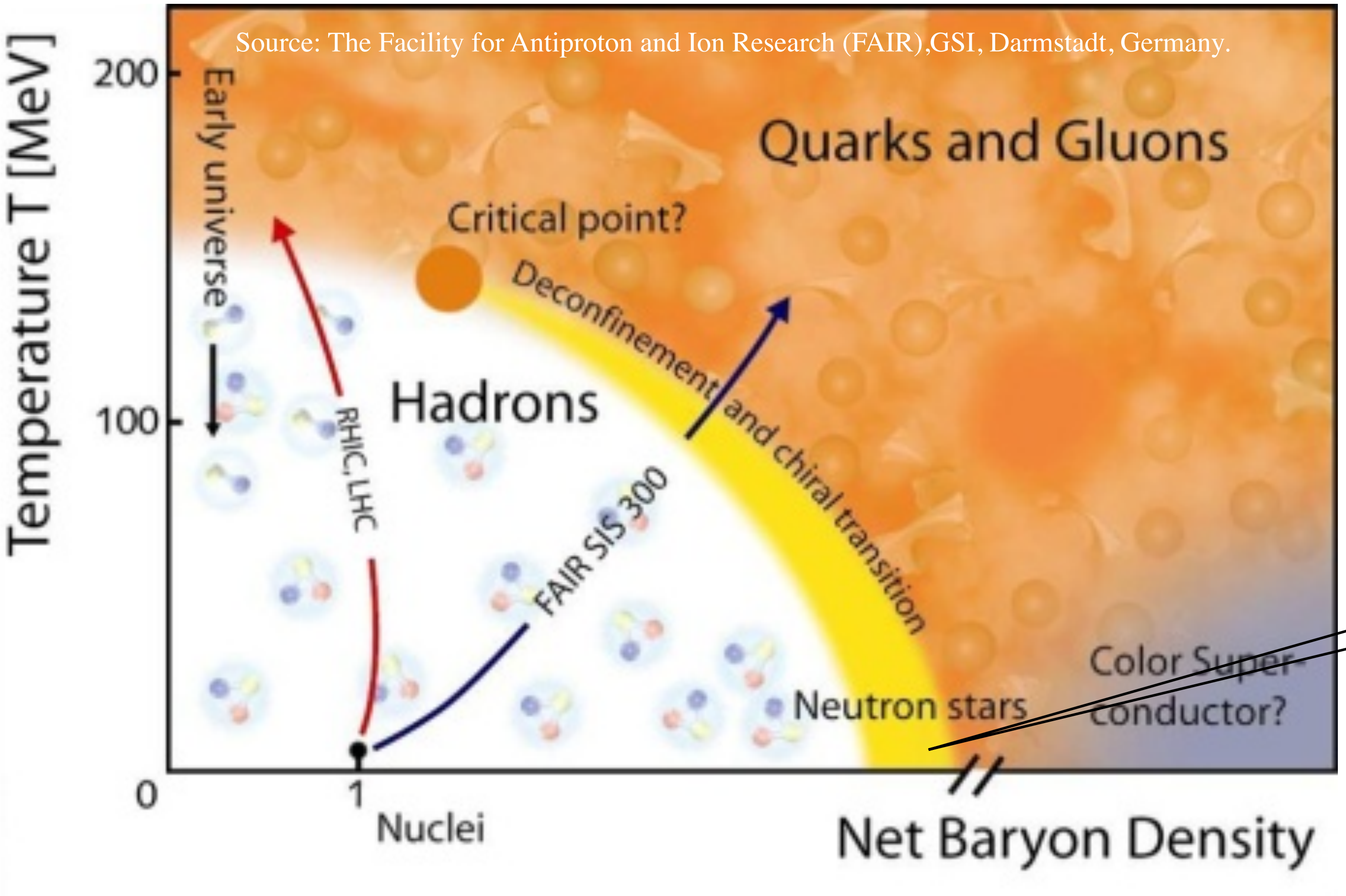
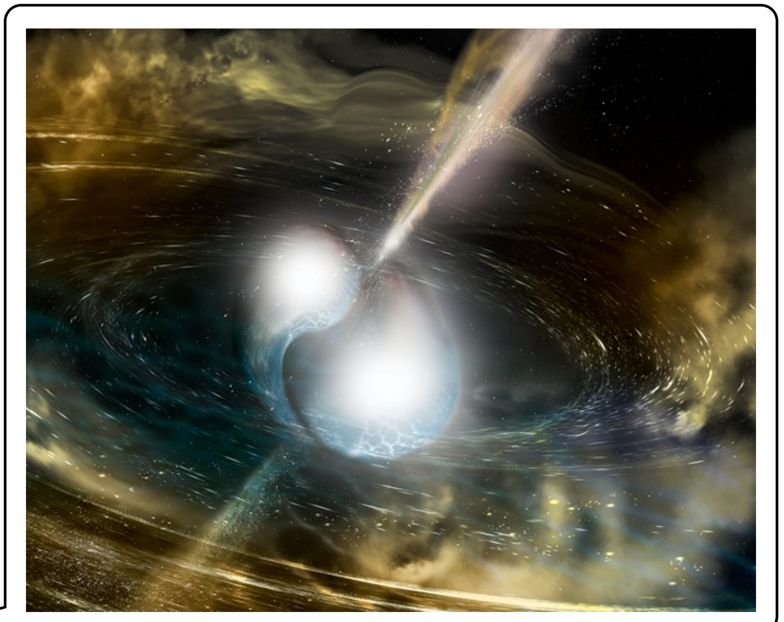
A NUCLEAR PHYSICS MOTIVATION FOR LEVERAGING QUANTUM TECHNOLOGIES



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





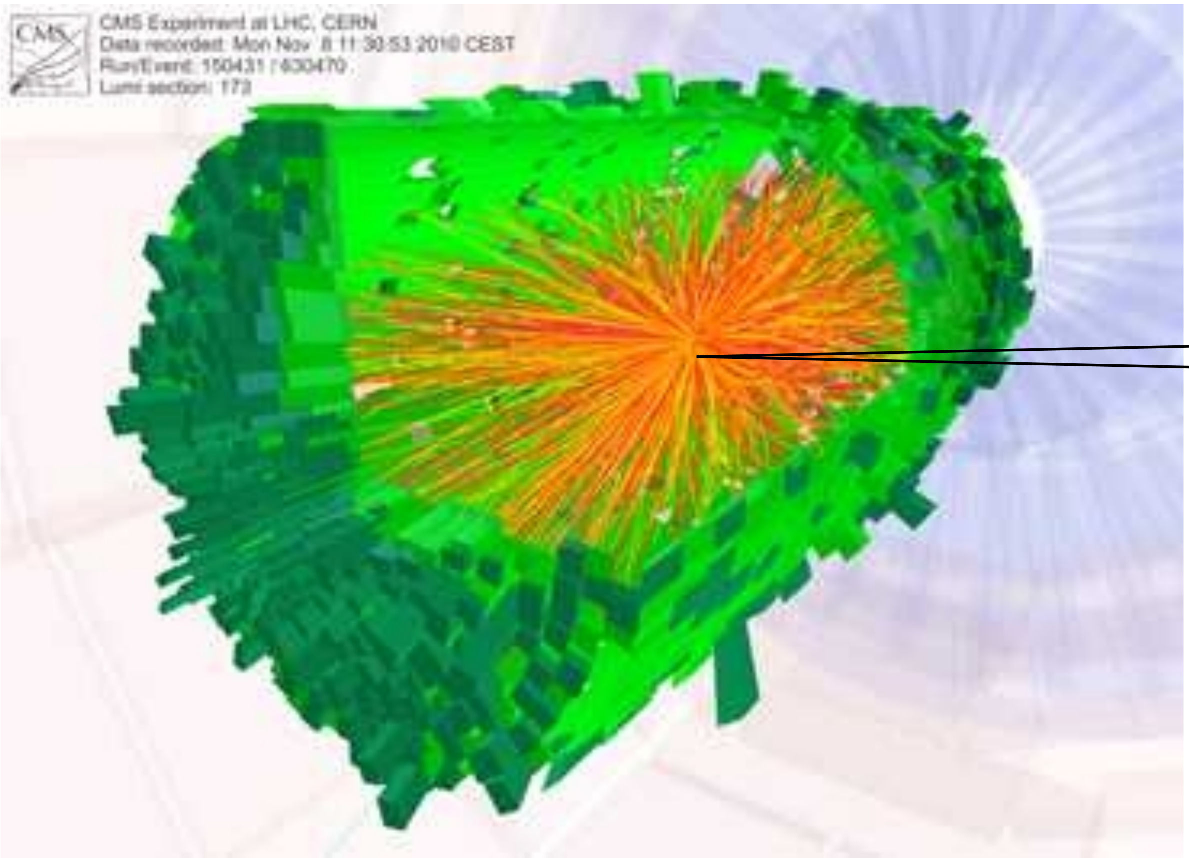
Path integral formulation:

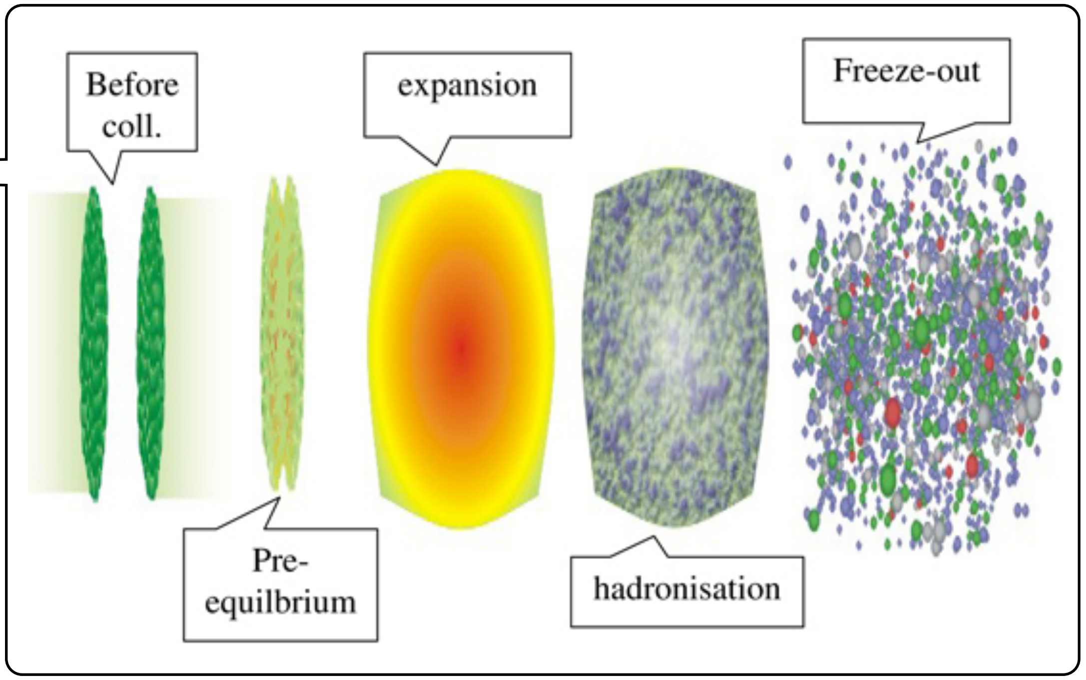
$$e^{-S[U,q,\bar{q}]}$$

with a complex action:

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

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:

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

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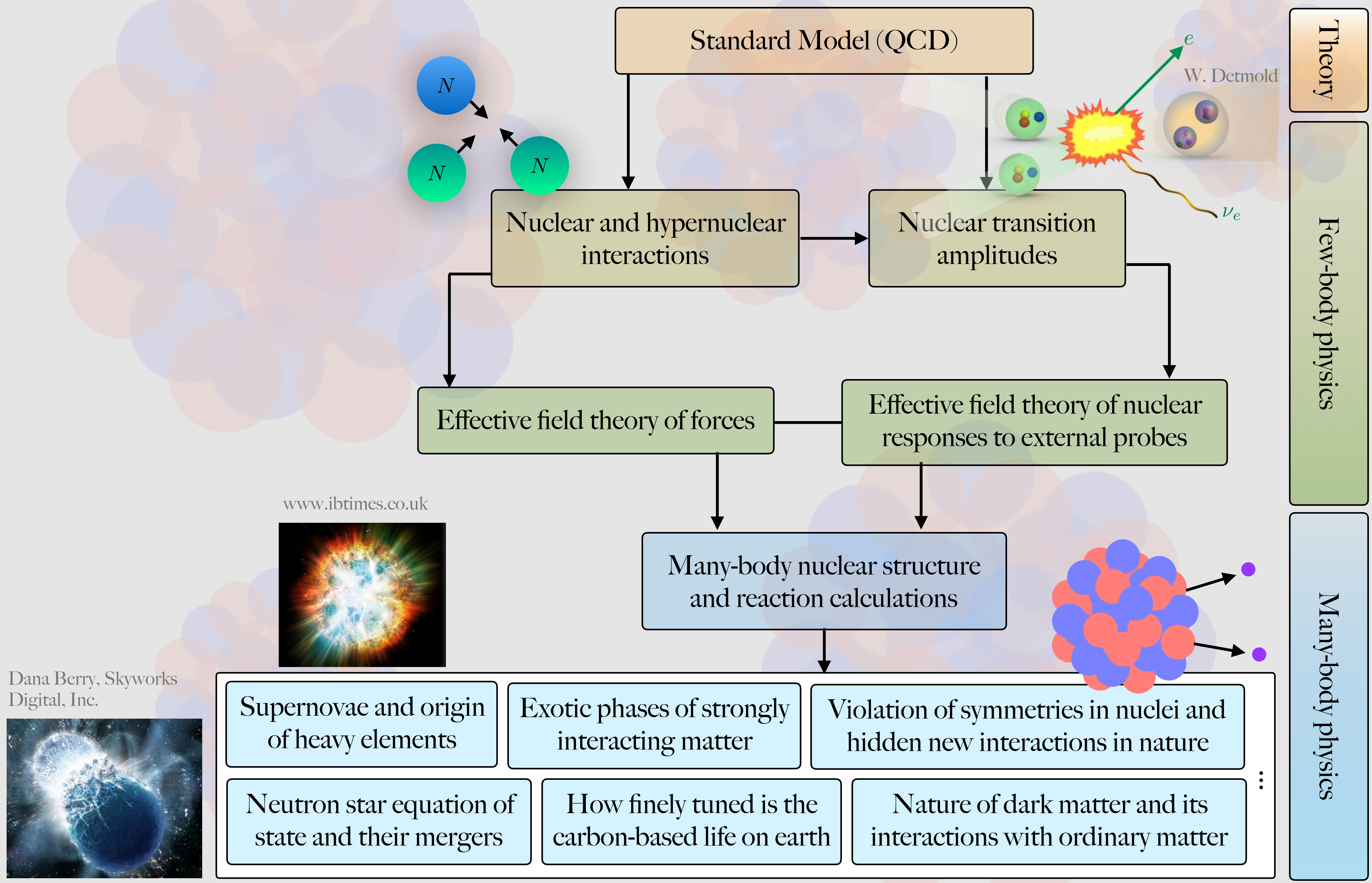

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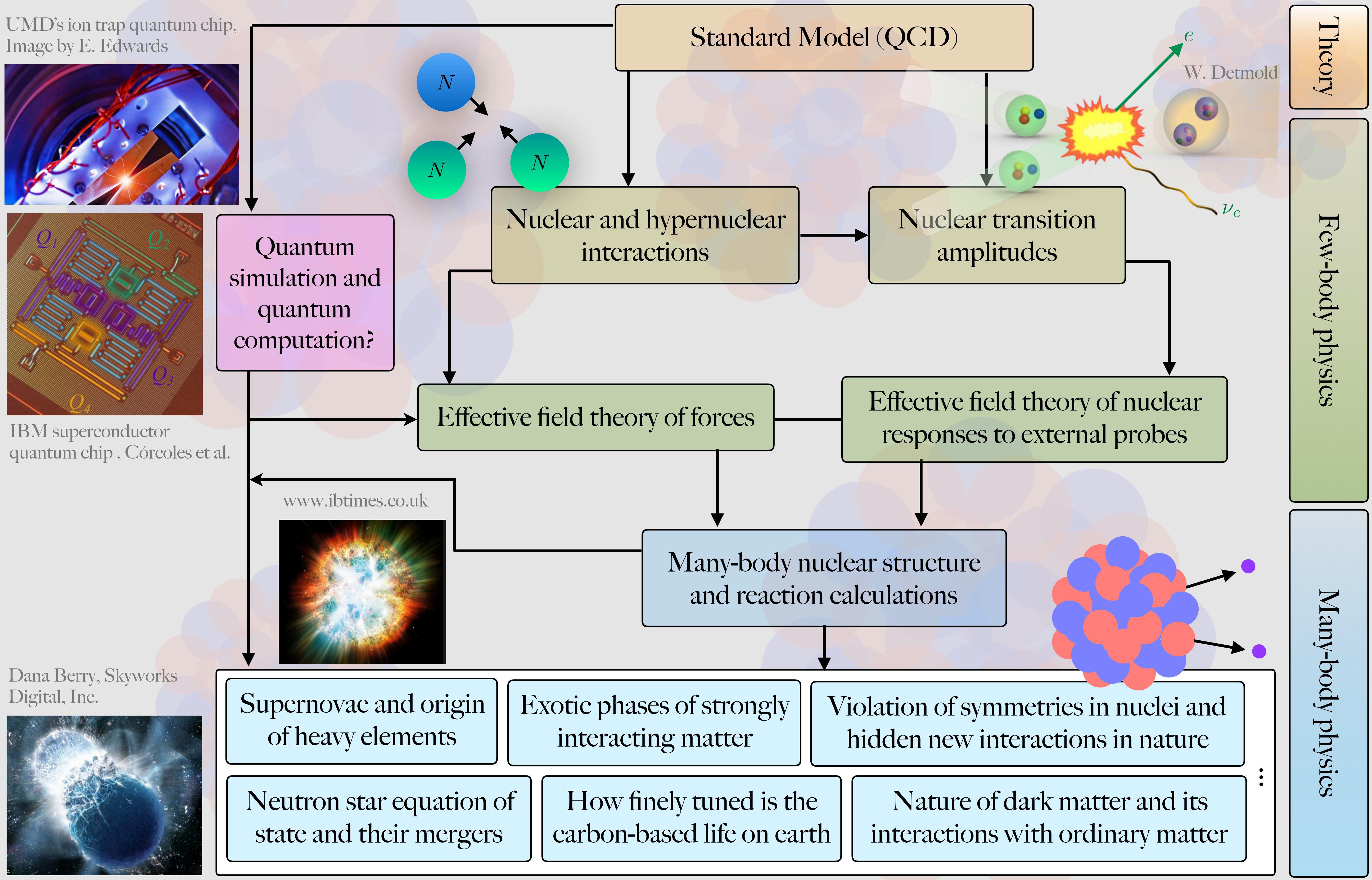

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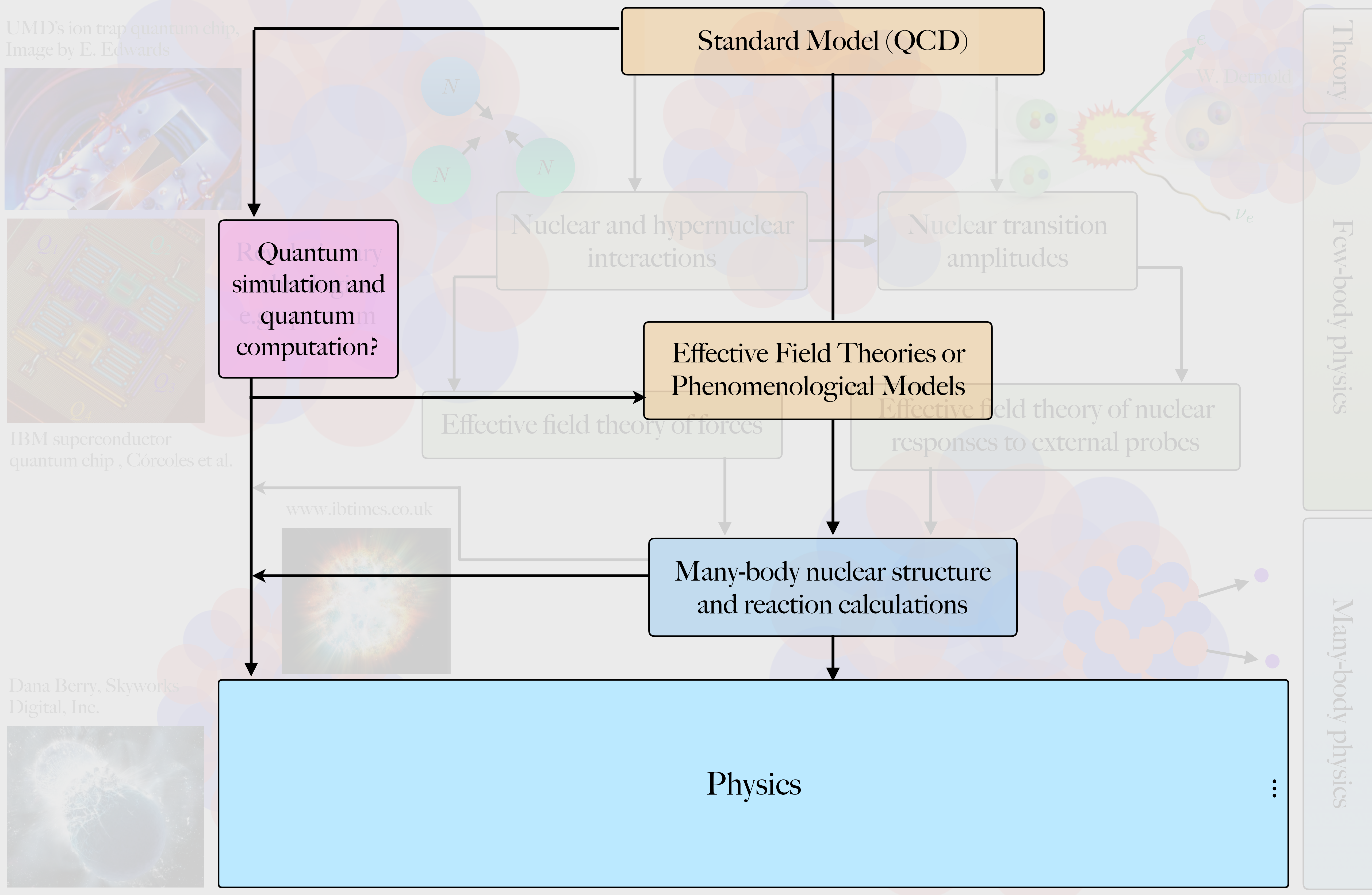
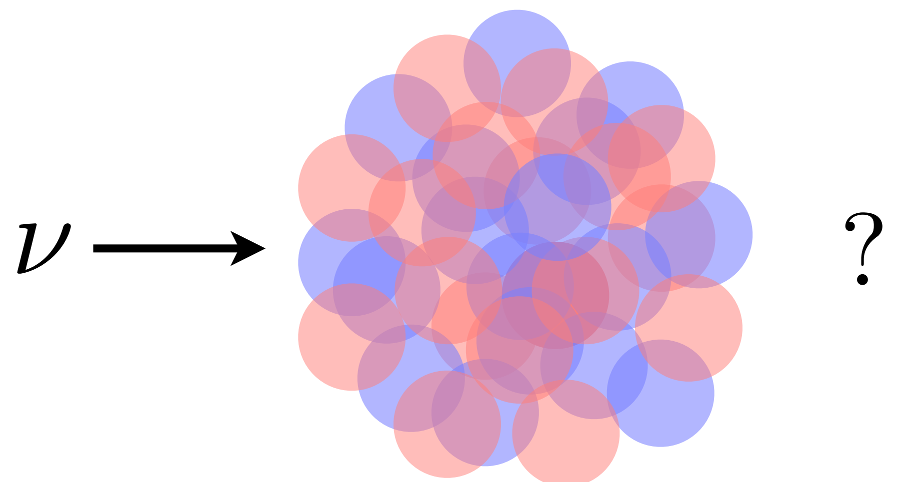
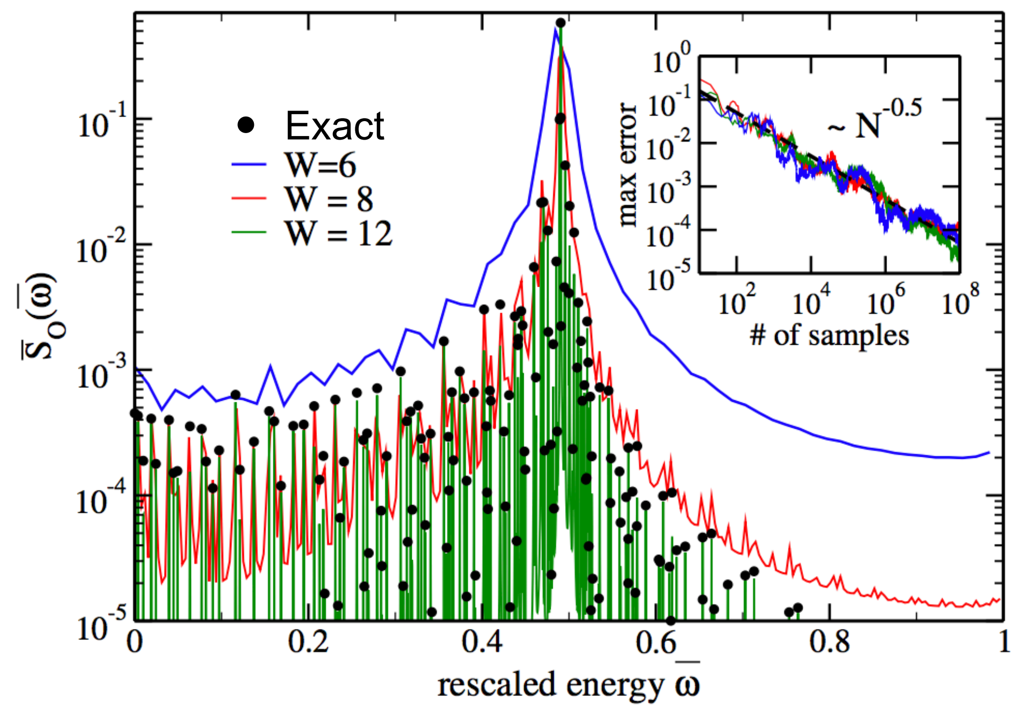


QUANTUM SIMULATION FOR NUCLEAR STRUCTURE AND REACTION: EXAMPLE I

Dynamical response functions needed for ν-nucleus cross sections

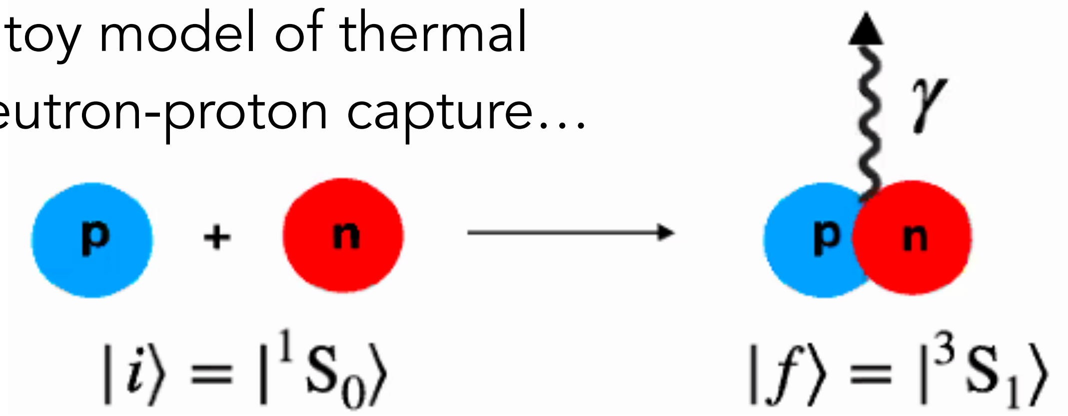


A quantum computation of response function in Fermi-Hubbard model

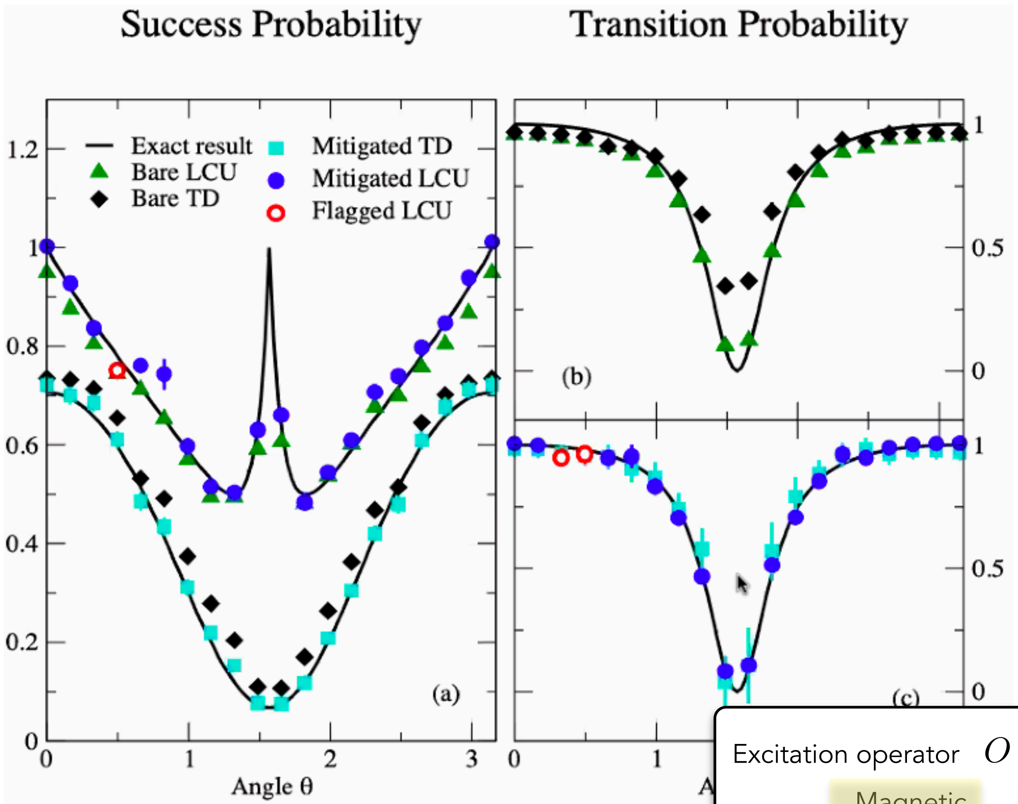


Roggero, Carlson, Phys. Rev. C 100, 034610 (2019)

A toy model of thermal neutron-proton capture…



with quantum algorithms…



Excitation operator $O = \mathbf{m} \cdot \xi$

Magnetic moment

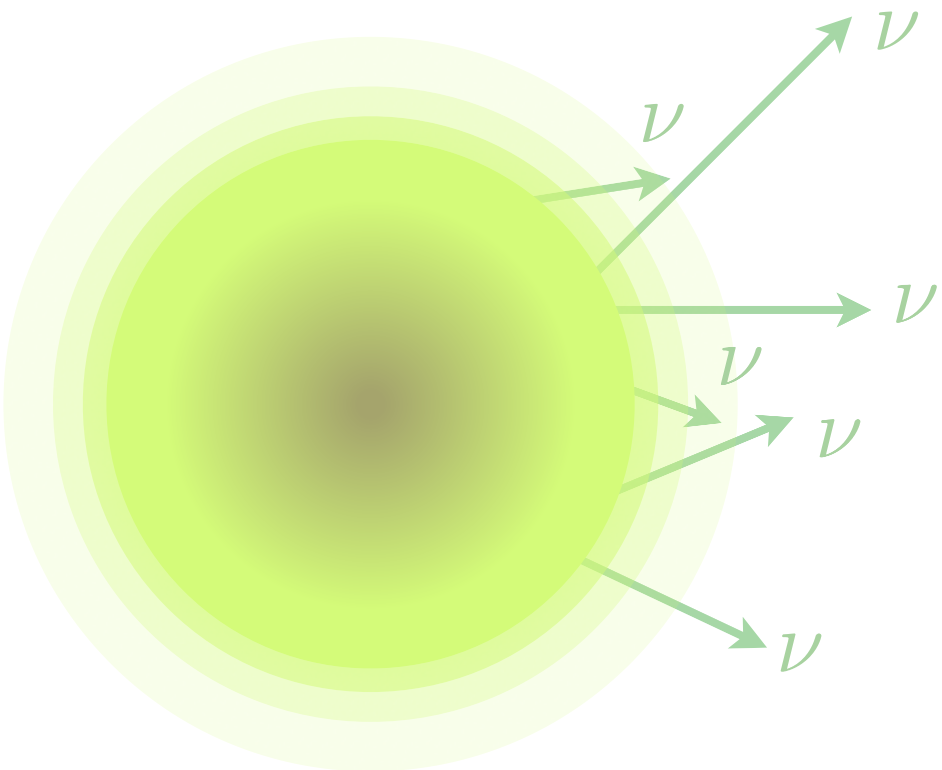
Photon polarization

Roggero, Gu, Baroni, Papenbrock, arXiv:2009.13485 [quant-ph]

See also: Lamm, Lawrence, Yamauchi, Phys. Rev. R 2, 013272 (2020), and Mueller, Tarasov, Venugopalan, Phys. Rev. D 102, 016007 (2020) for computing structure functions in field theories with quantum algorithms.

QUANTUM SIMULATION FOR NUCLEAR ASTROPHYSICS: EXAMPLE II

Collective neutrino oscillations are relevant for core-collapse supernova and neutron-star merger studies…an extremely hard quantum many-body problem to solve.

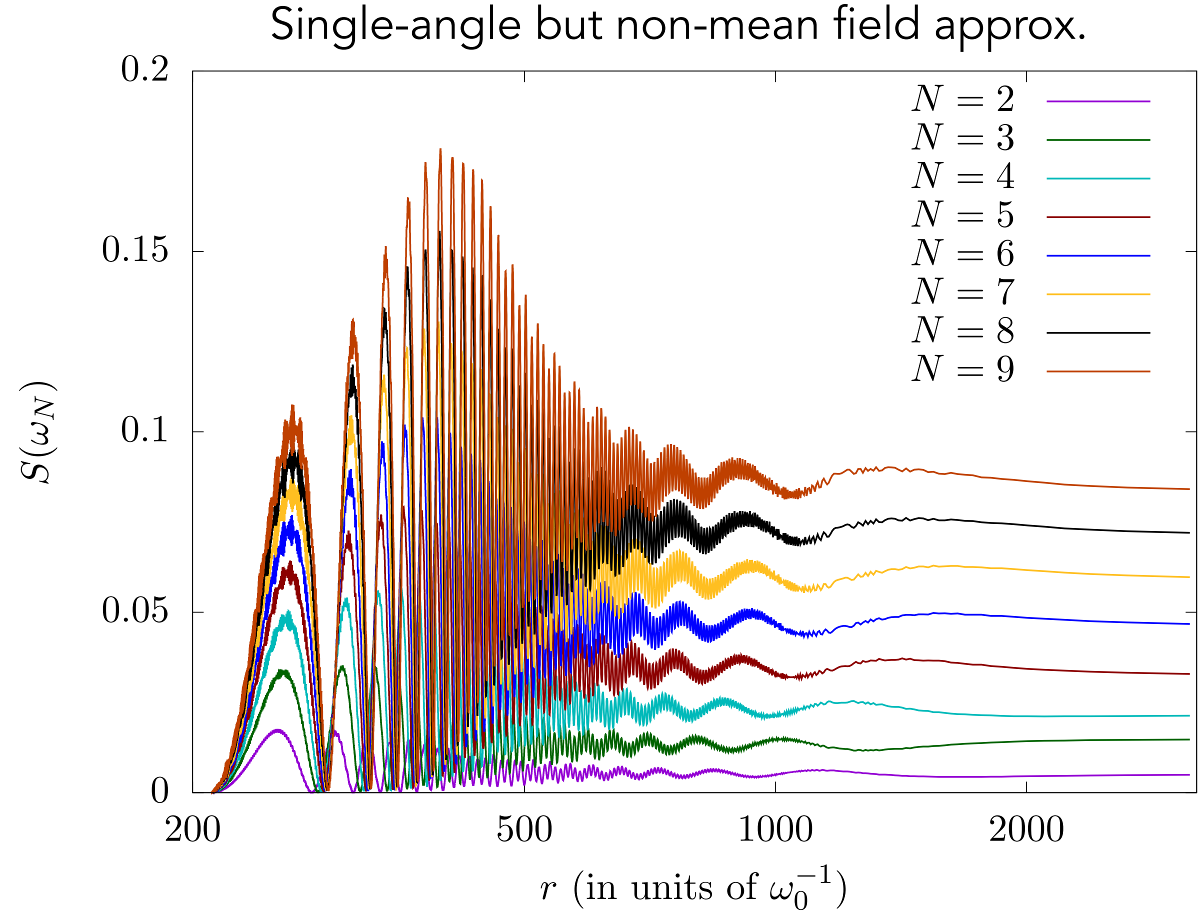


Vacuum and forward νν interaction Hamiltonian:

$$H = \sum_{\mathbf{p}} \omega_{\mathbf{p}} \vec{B} \cdot \vec{J}_{\mathbf{p}} + \sum_{\mathbf{p},\mathbf{q}} \frac{\sqrt{2}G_F}{V}(1 - \cos\theta_{\mathbf{pq}}) \vec{J}_{\mathbf{p}} \cdot \vec{J}_{\mathbf{q}}$$

J. Carlson and many others.

Hilbert space size is reduced from 2^N to 2N in a mean-field approximation. Quantum entanglement measures tell us this might not be a good approximation.

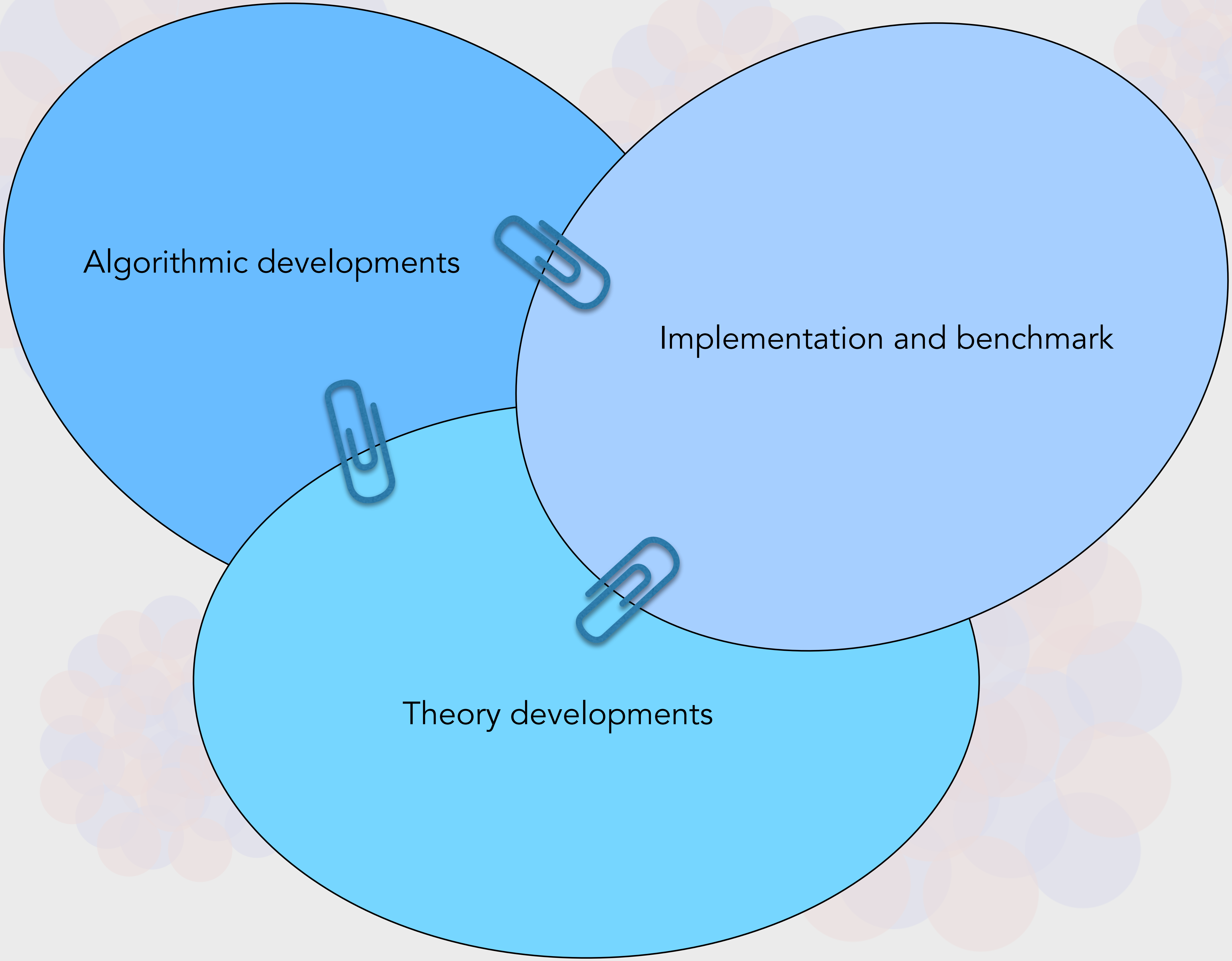


Cervia, Patwardhan, Balantekin, Coppersmith, Johnson, Phys. Rev. D 100, 083001 (2019)

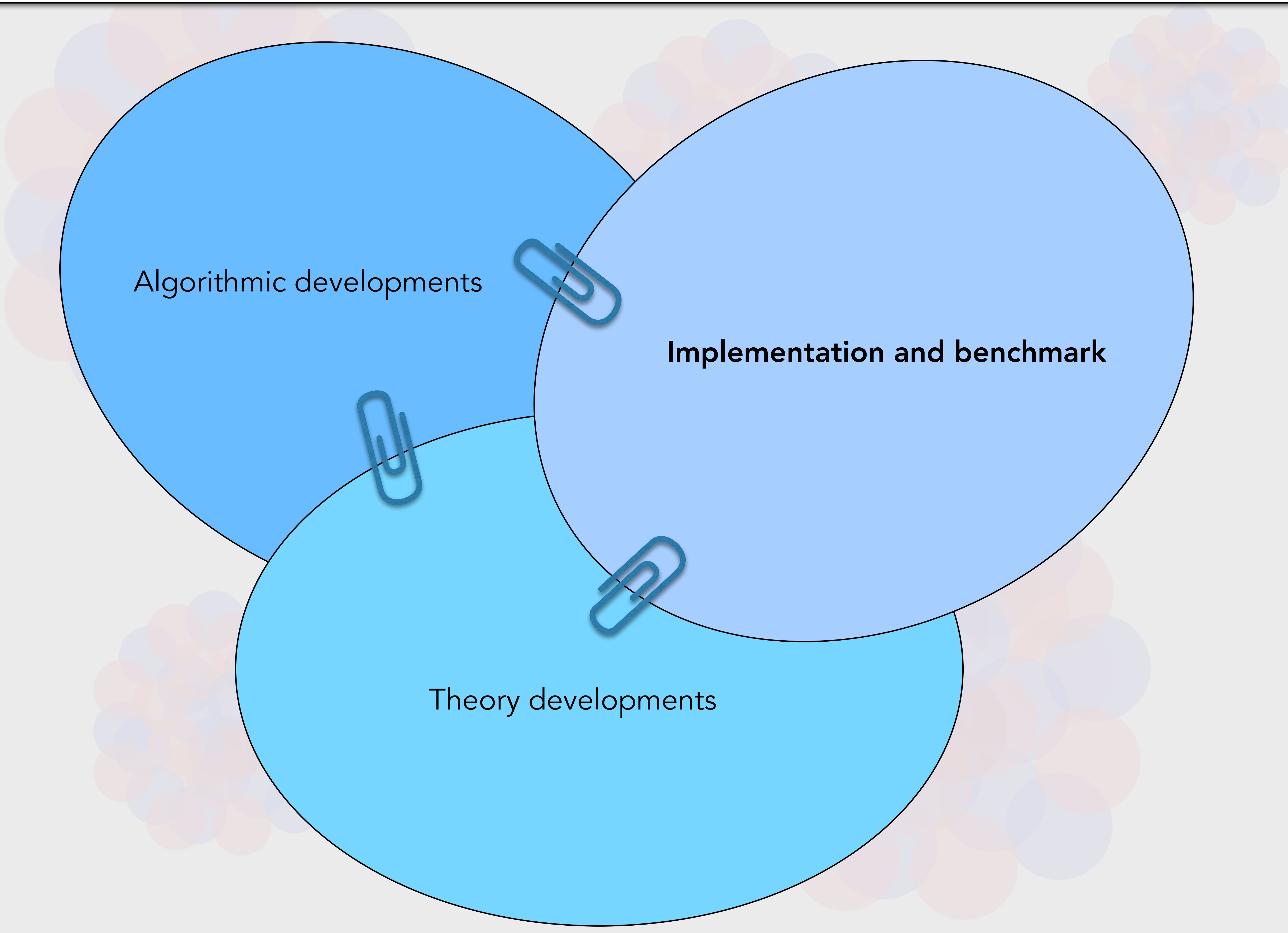
Would need quantum simulation!

Ongoing work by Baroni, Carlson, Hall, Roggero (2020).

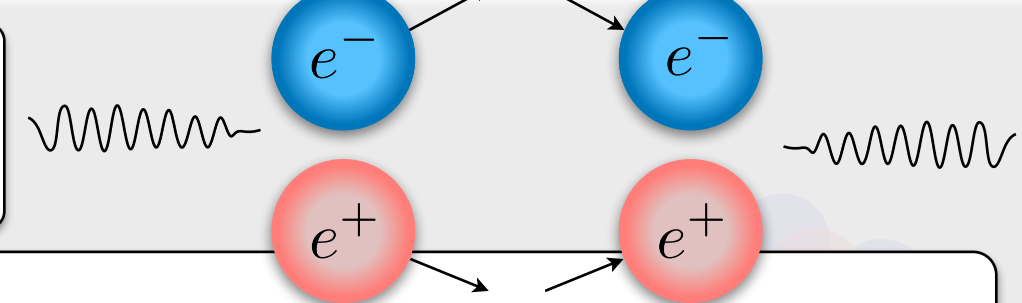
QUANTUM SIMULATION OF QUANTUM FIELD THEORIES: EXAMPLE III

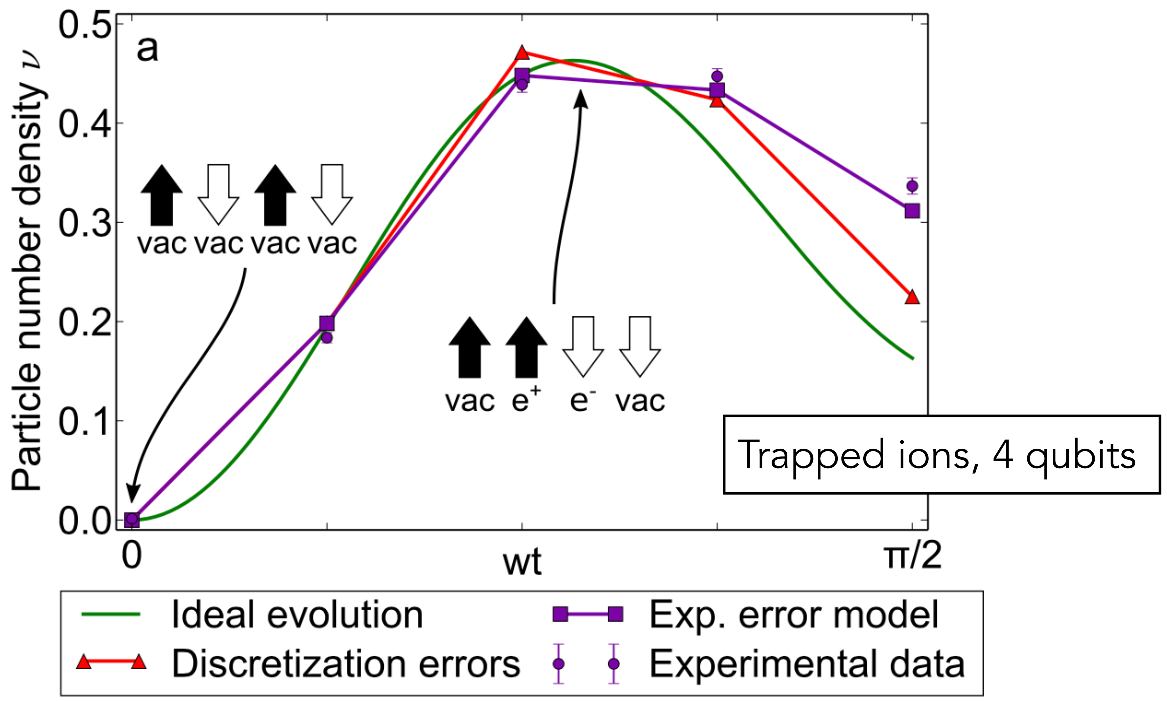


QUANTUM SIMULATION OF QUANTUM FIELD THEORIES: EXAMPLE III

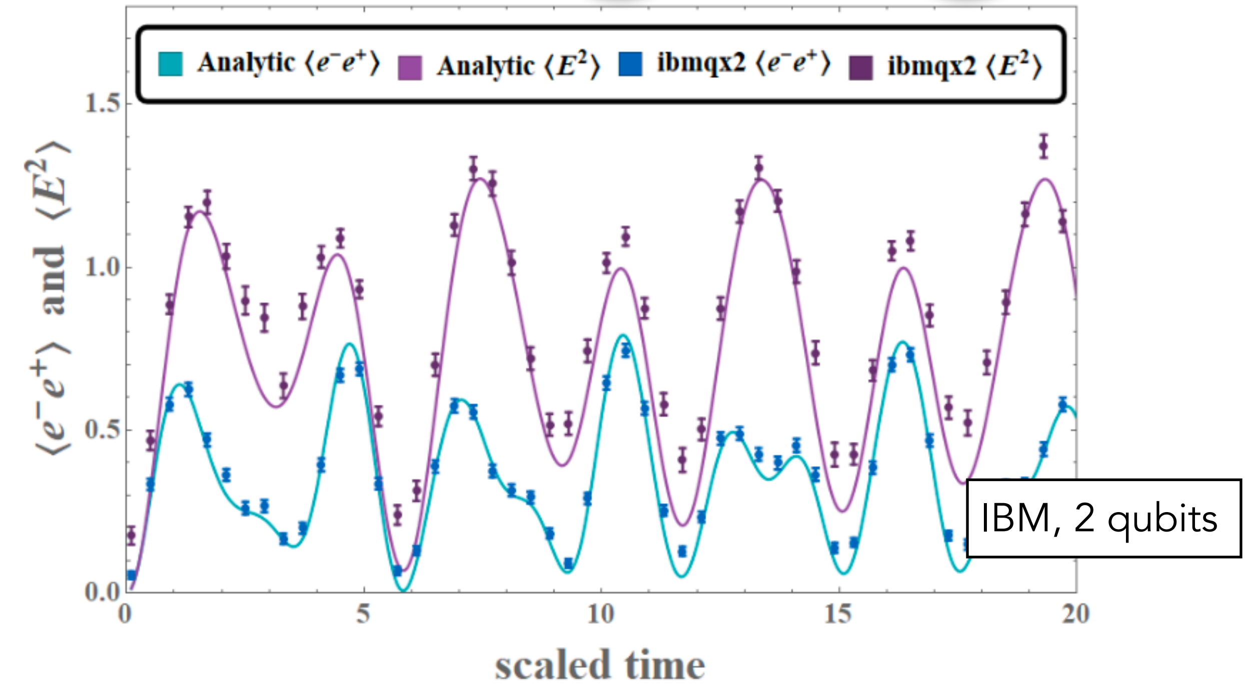


QUANTUM SIMULATION OF QUANTUM FIELD THEORIES: IMPLEMENTATION AND BENCHMARK DIGITAL EXAMPLES

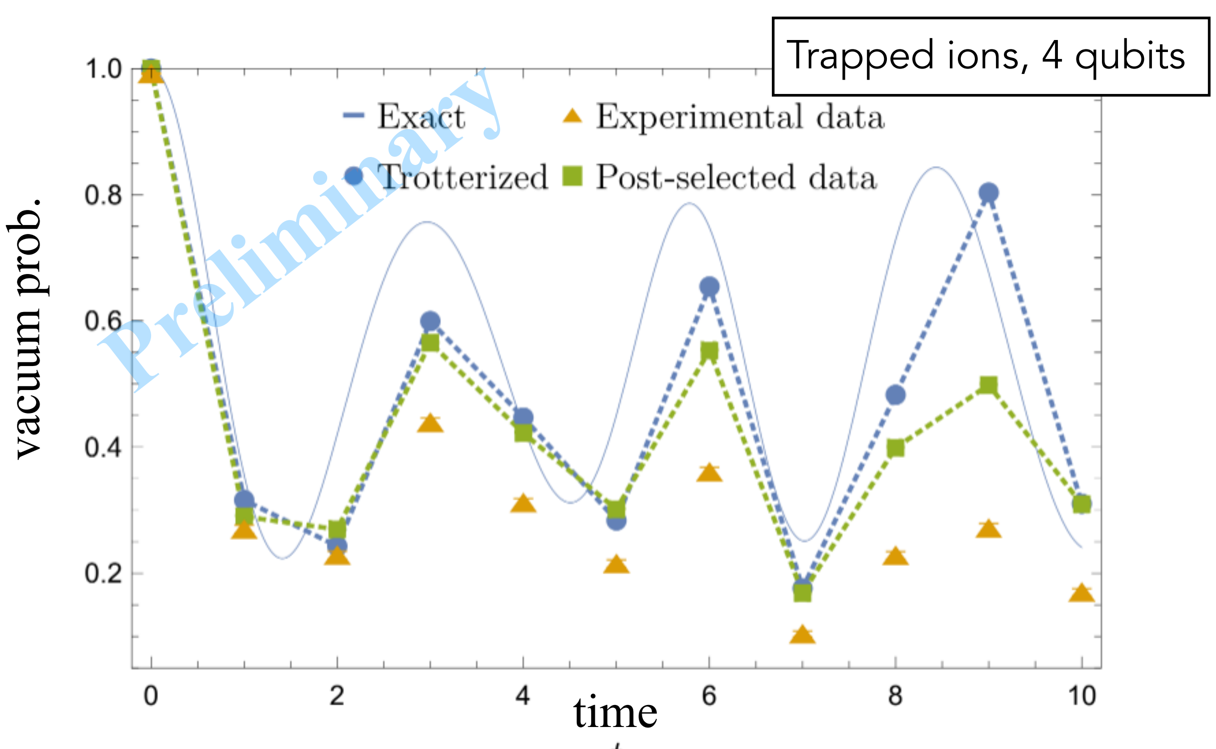


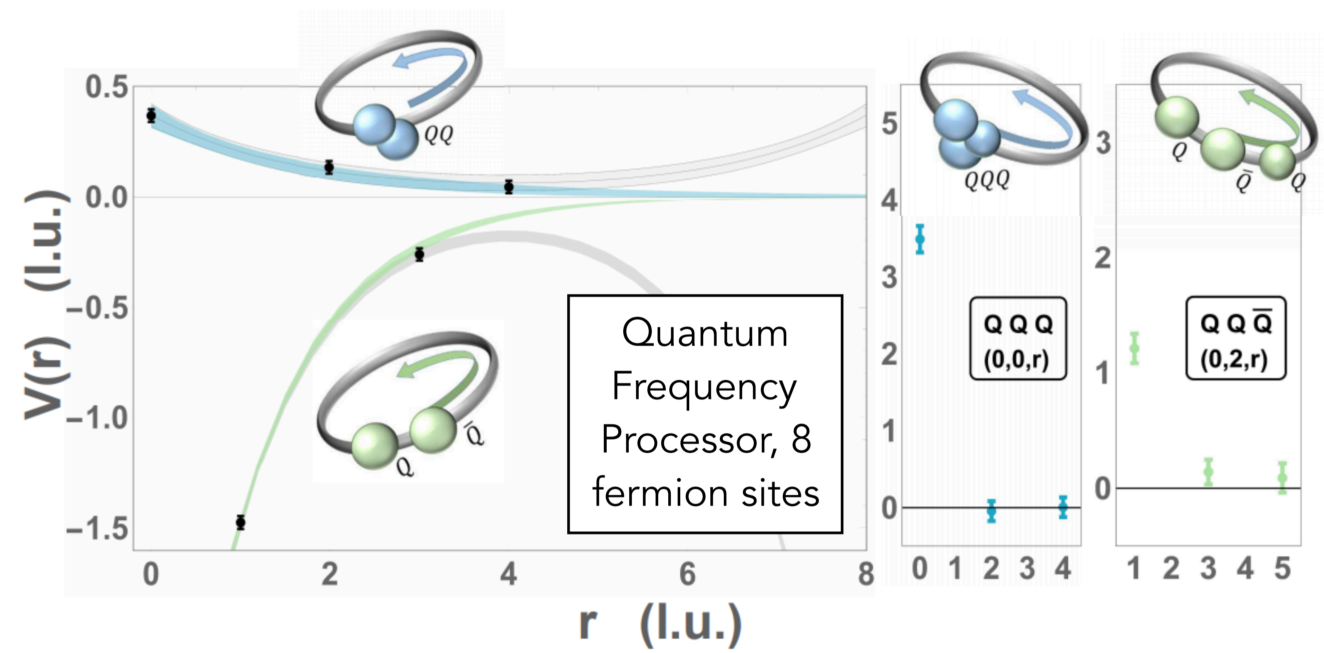


Martinez, Muschik, Schindler, Nigg, Erhard, Heyl, Hauke, Dalmonte, Monz, Zoller, Blatt, Nature 534, 516-519 (2016)



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

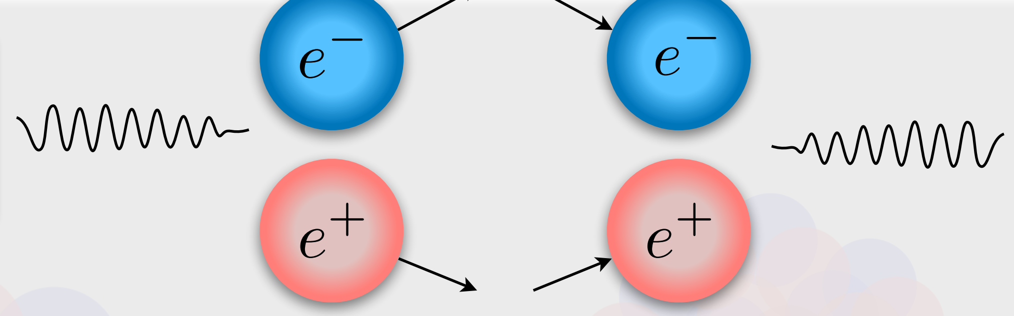




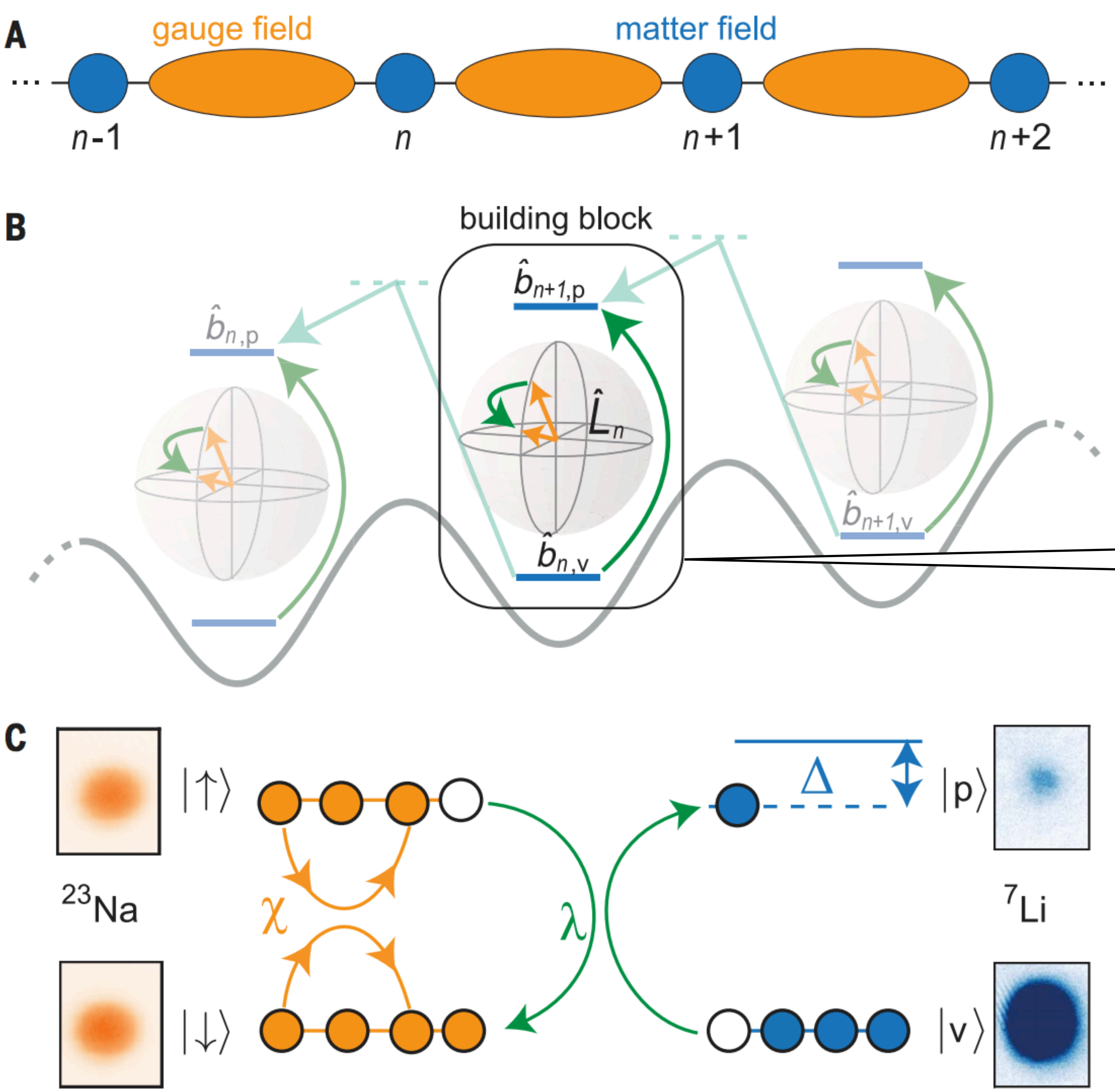
Nguyen, Shaw, Zhu, Huerta Alderete, ZD, Linke (2020)

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

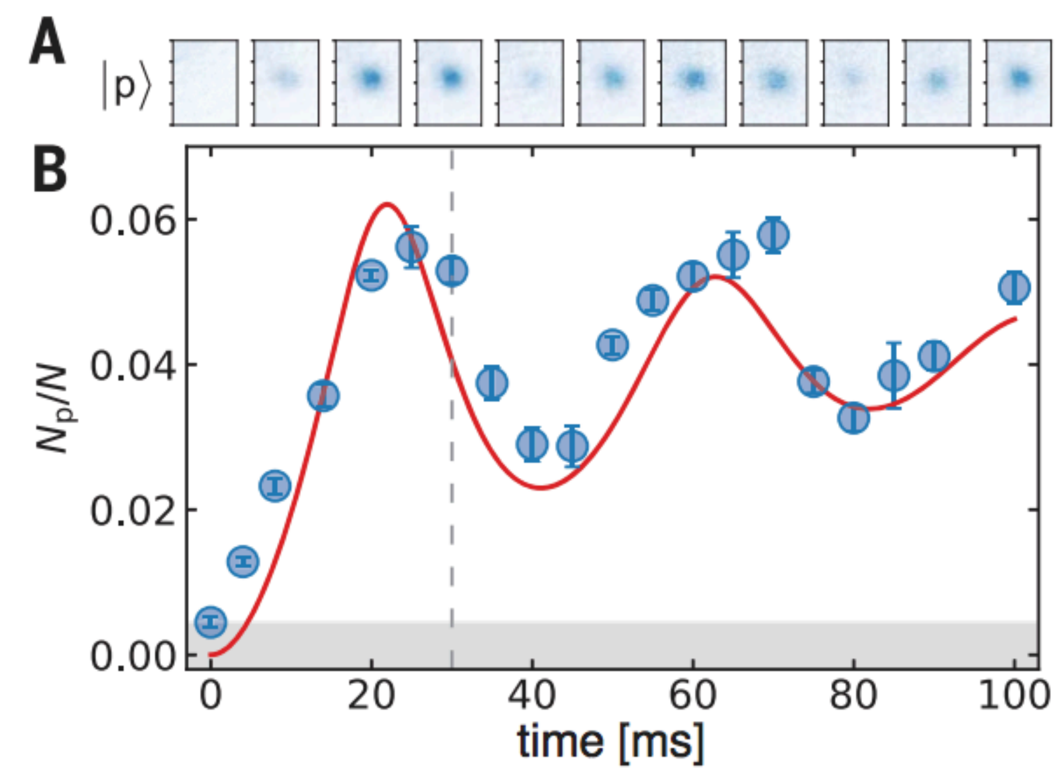
QUANTUM SIMULATION OF QUANTUM FIELD THEORIES: IMPLEMENTATION AND BENCHMARK ANALOG EXAMPLE



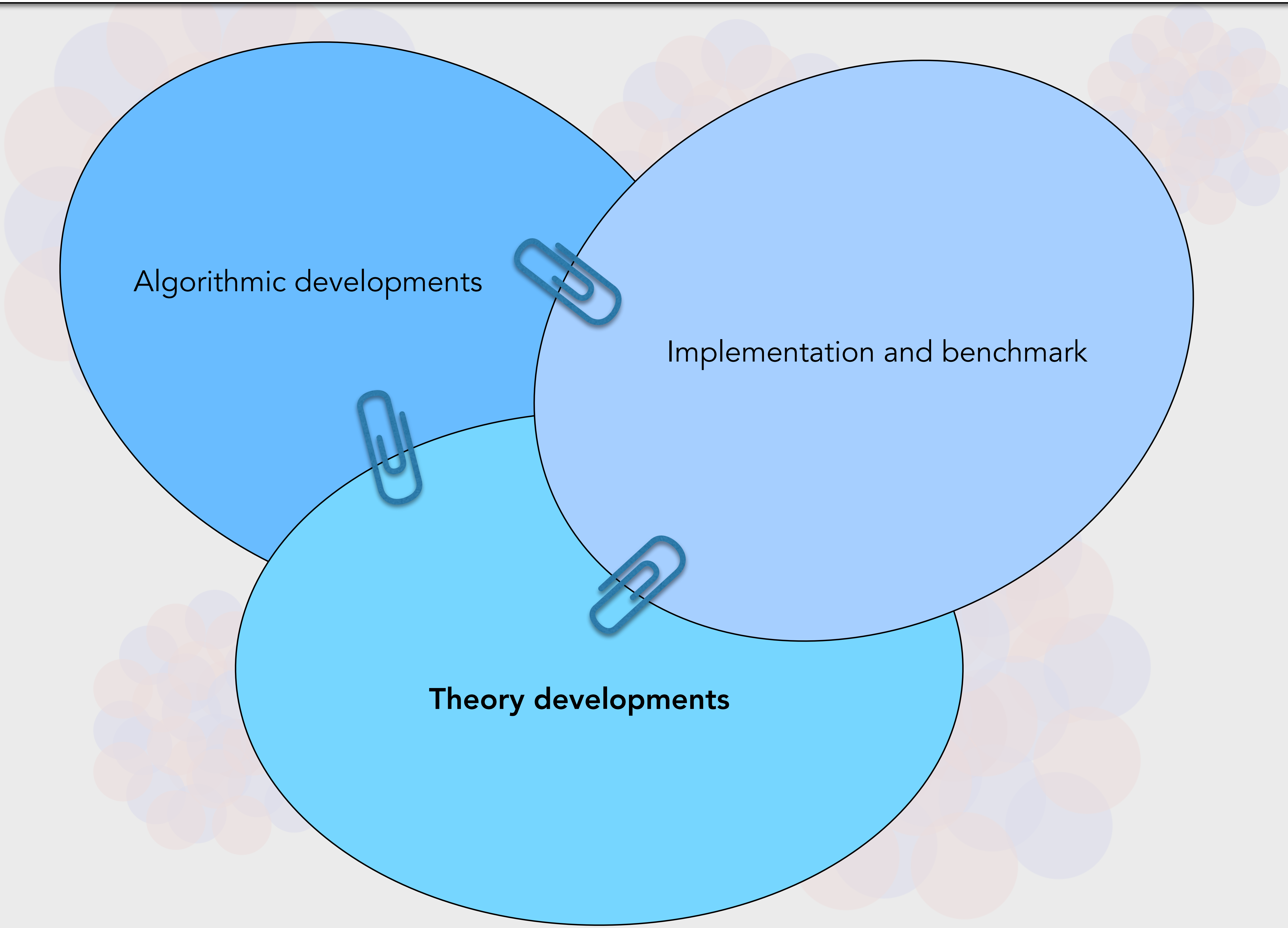
A realization of lattice Schwinger model within QLM with cold atoms in a trapping potential



Mil, Zache, Hegde, Xia, Bhatt, Oberthaler, Hauke, Berges, Jendrzejewski, Science 367, 1128-1130 (2020)



QUANTUM SIMULATION OF QUANTUM FIELD THEORIES: EXAMPLE III

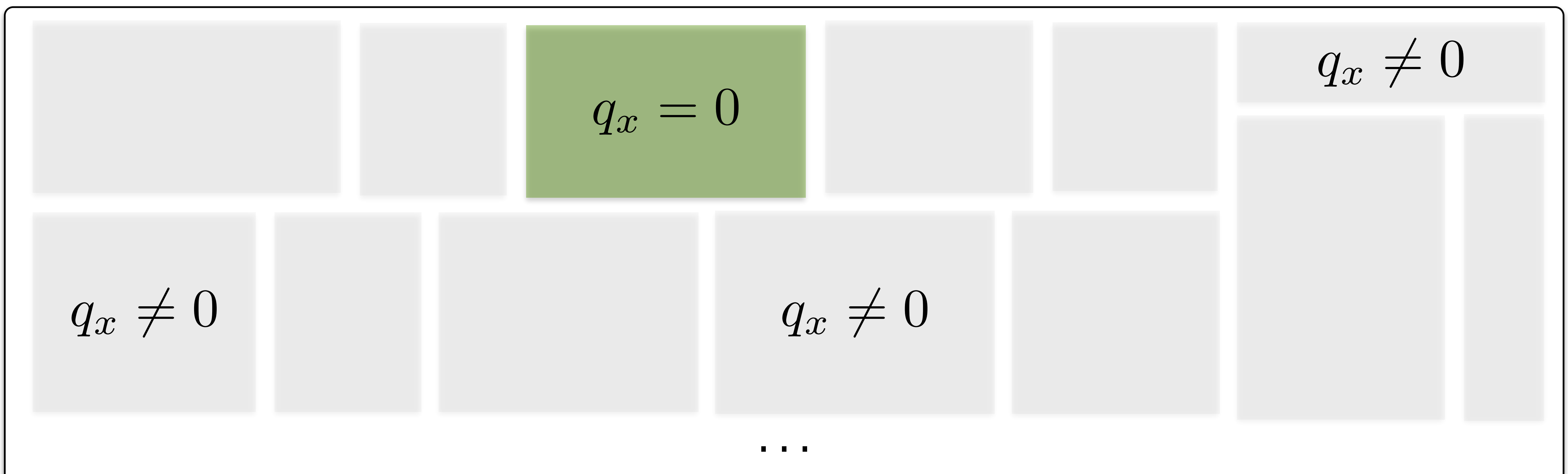


Hamiltonian formalism maybe more natural than the path integral formalism for quantum simulation/computation:

Kogut and Susskind formulation:

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

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



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

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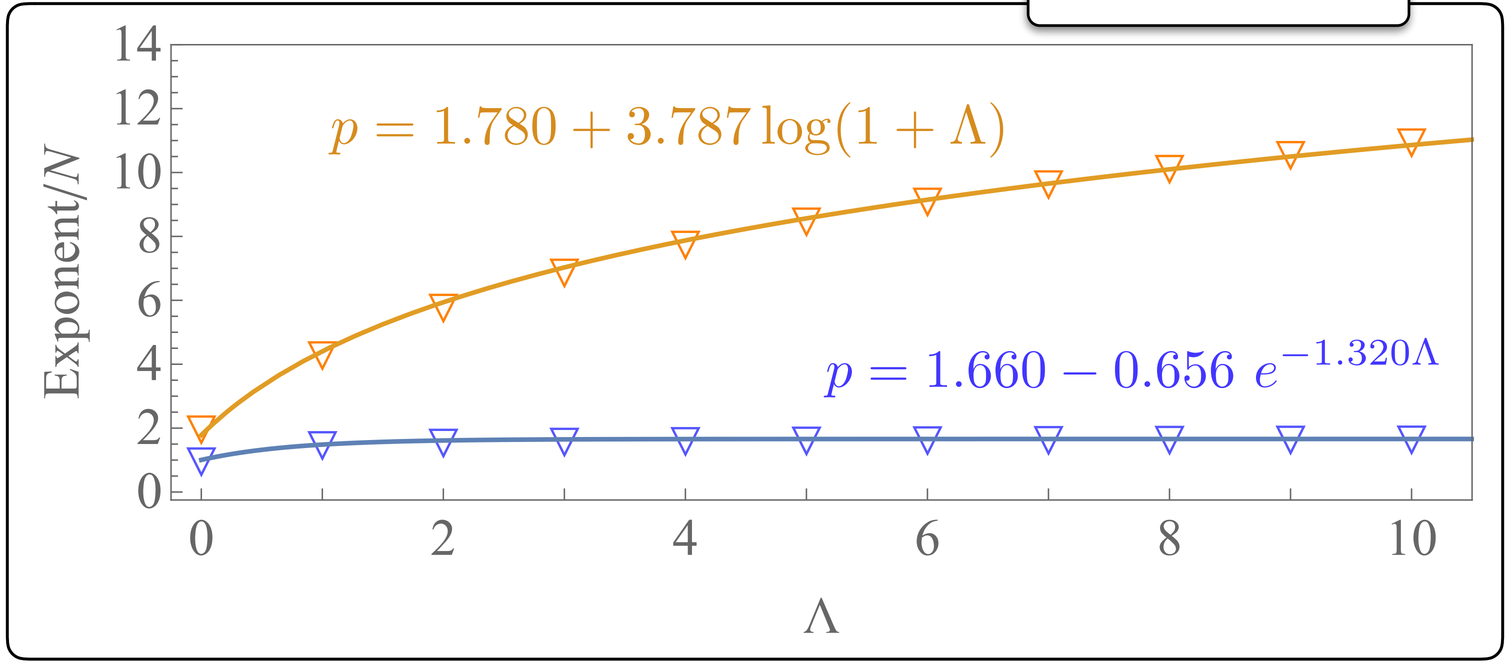
SU(2) gauge theory with matter in 1+1D

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



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

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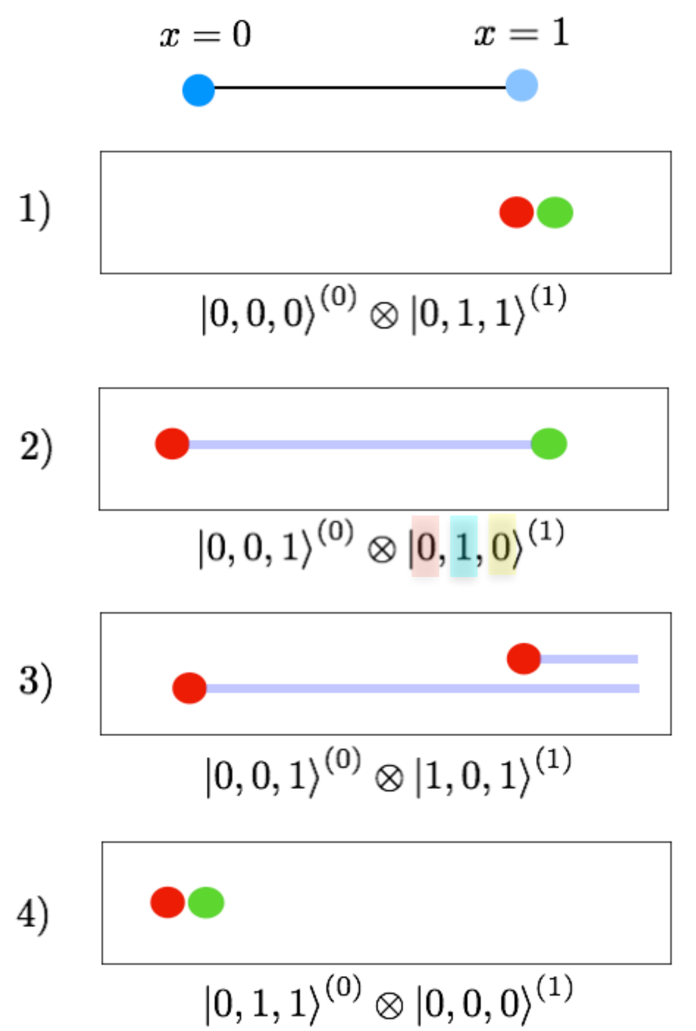
QUANTUM SIMULATION OF GAUGE FIELD THEORIES: THEORY DEVELOPMENTS

Either start from locally gauge-invariant building blocks: Loop String Hadron framework for SU(2) LGT…



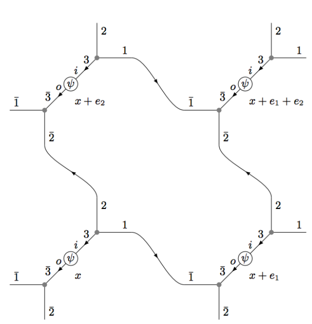
Building the Hilbert space is easy and efficient as non-Abelian Gauss's law is solved.

Incoming strings

Outgoing strings

Loops

A point-splitting procedure allows generalization to all dimensions.

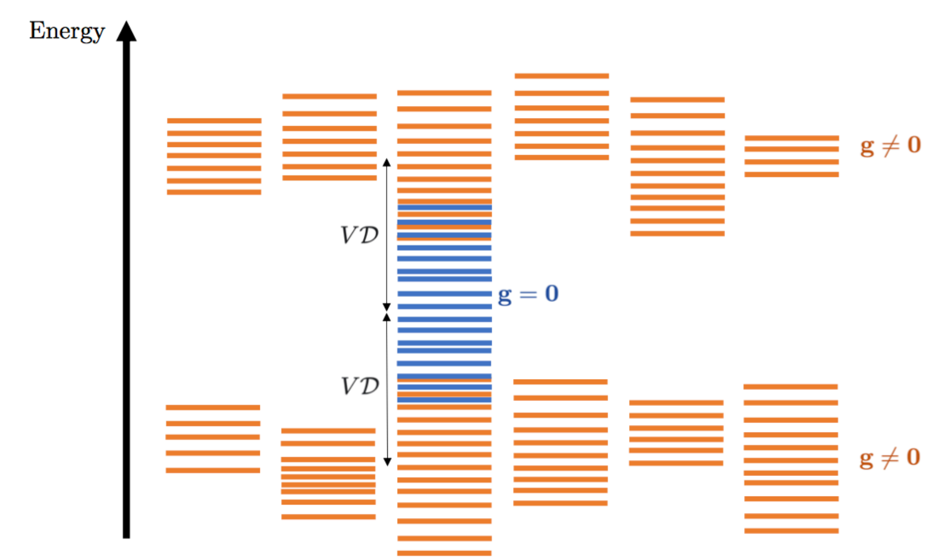


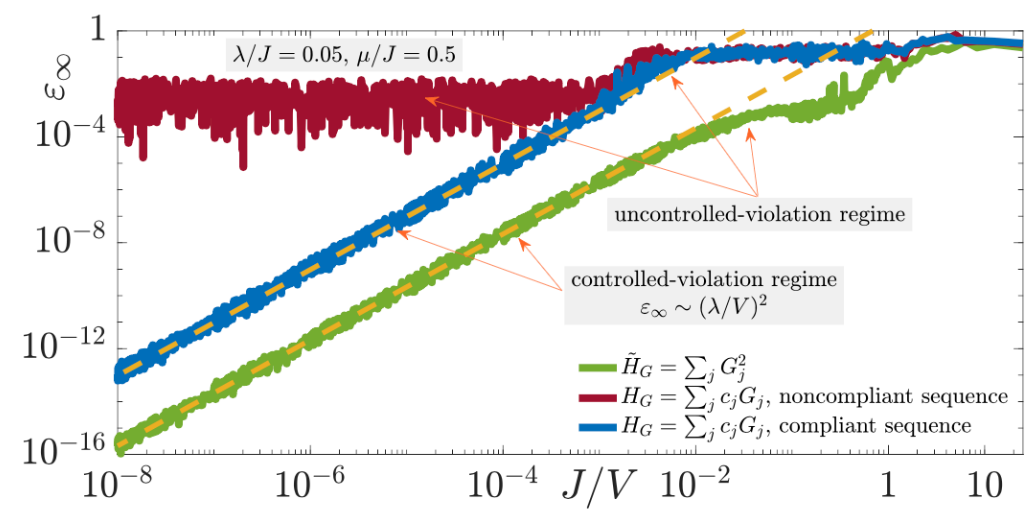
Raychowdhury, Stryker, Phys. Rev. D 101, 114502 (2020).

…or try to suppress gauge-symmetry violation in the implementation.

Gauss's law operator

Add to the Hamiltonian: $VH_G = V\sum c_j G_j$

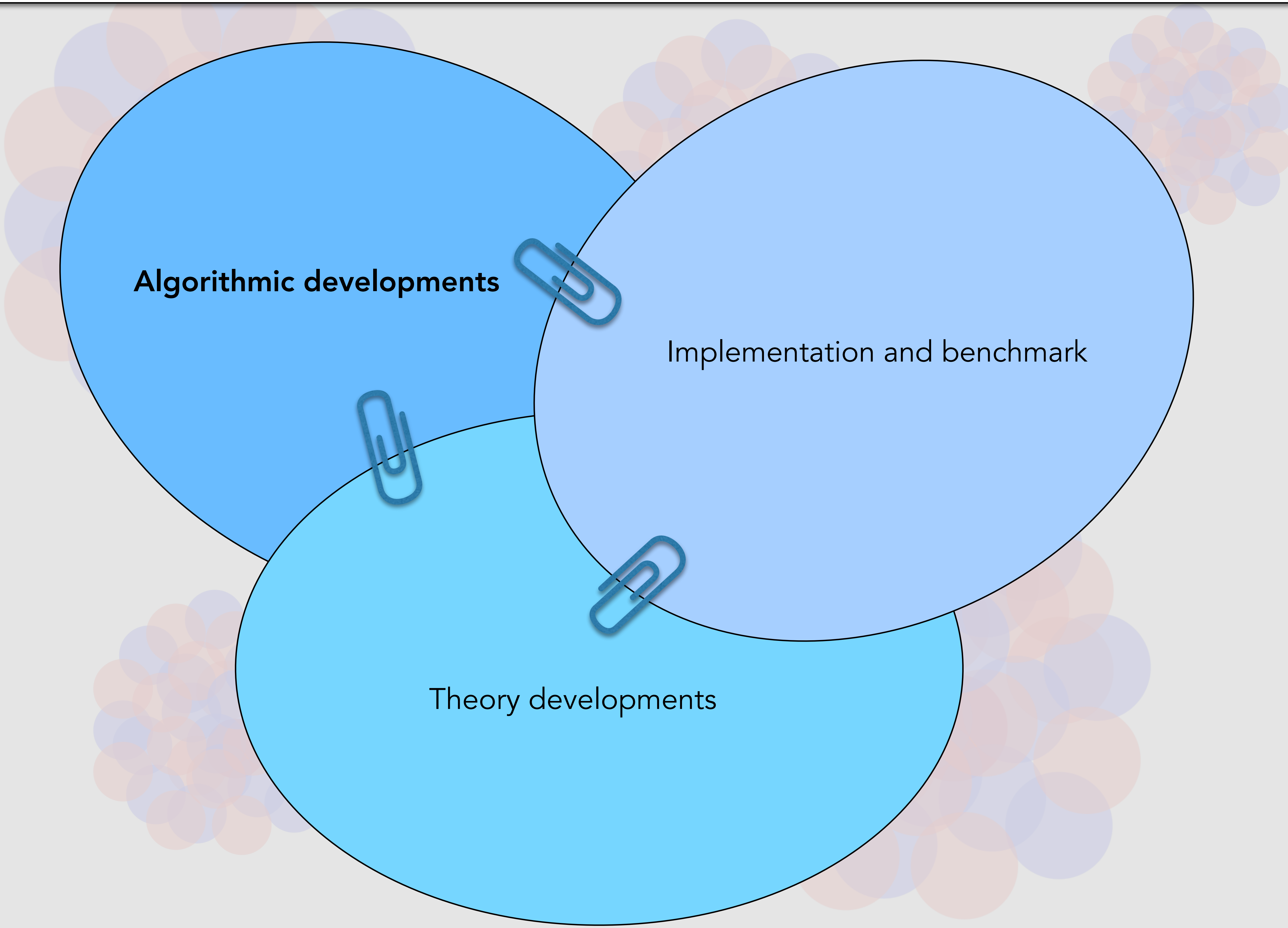




Halimeh, Lang, Mildenberger, Jiang, Hauke, arXiv:2007.00668 [quant-ph]

See also Stannigel, Hauke, Marcos, Hafezi, Diehl, Dalmonte, Zoller, Phys. Rev. Lett. 112, 120406, Tran, Su, Carney, Taylor arXiv:2006.16248 [quant-ph] and Lamm, Lawrence, Yamauchi, arXiv:2005.12688 [quant-ph] for similar symmetry-protection ideas.

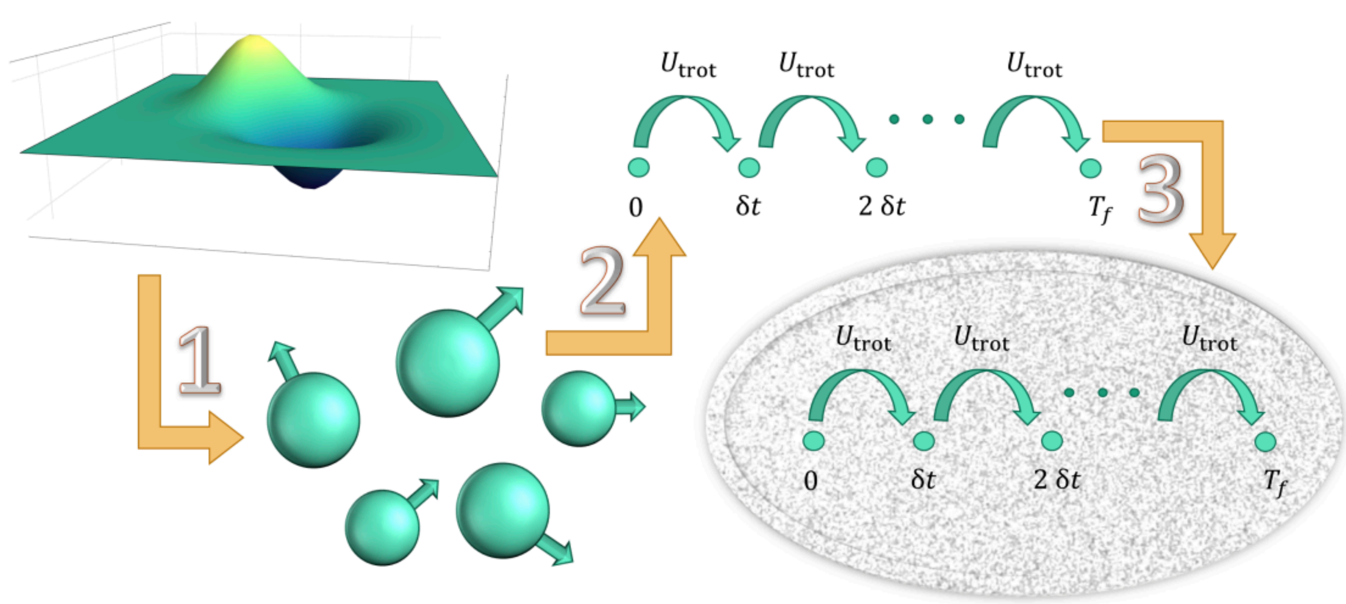
QUANTUM SIMULATION OF QUANTUM FIELD THEORIES: EXAMPLE III

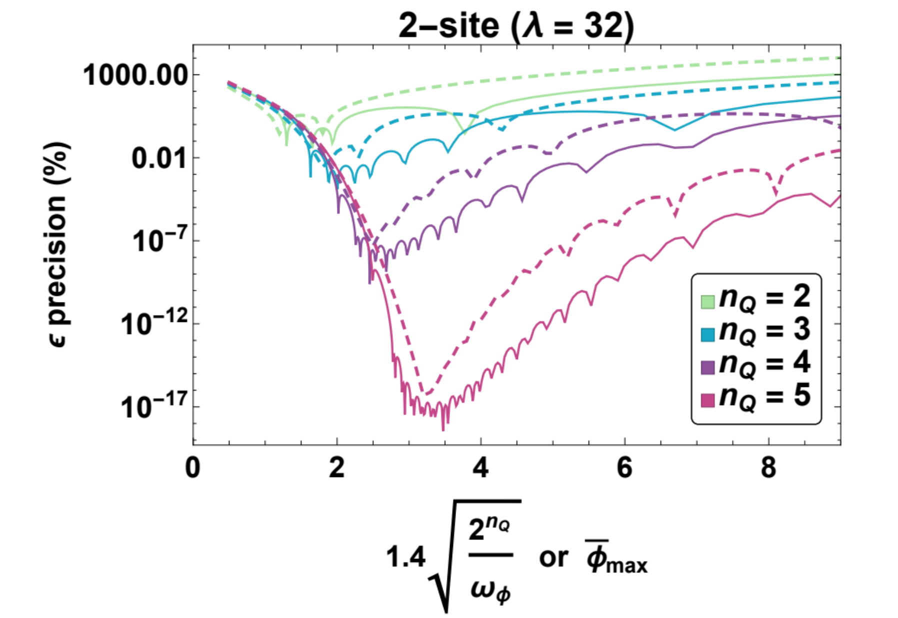


QUANTUM SIMULATION OF GAUGE FIELD THEORIES: ALGORITHMIC DEVELOPMENTS

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

Recourse analysis of scalar field theory digitization





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

See also: Barata , Mueller, Tarasov, Venugopalan (2020) for a single-particle basis

Basis	n_Q	2-body	3-body	4-body	5-body	6-body	7-body	8-body	9-body	10-body	11-body	12-body	CNOT
	2	4											8
	3	9											18
JLP	4	16											32
	5	25											50
	6	36											72
	n_Q	n_Q^2											$2n_Q^2$
	2	1	6	9									80
	3	1	8	30	56	49							1,152
HO	4	1	10	47	140	271	330	225					11,264
	5	1	12	68	244	630	1204	1668	1612	961			89,600
	6	1	14	93	392	1186	2772	5154	7560	8541	7182	3969	626,688

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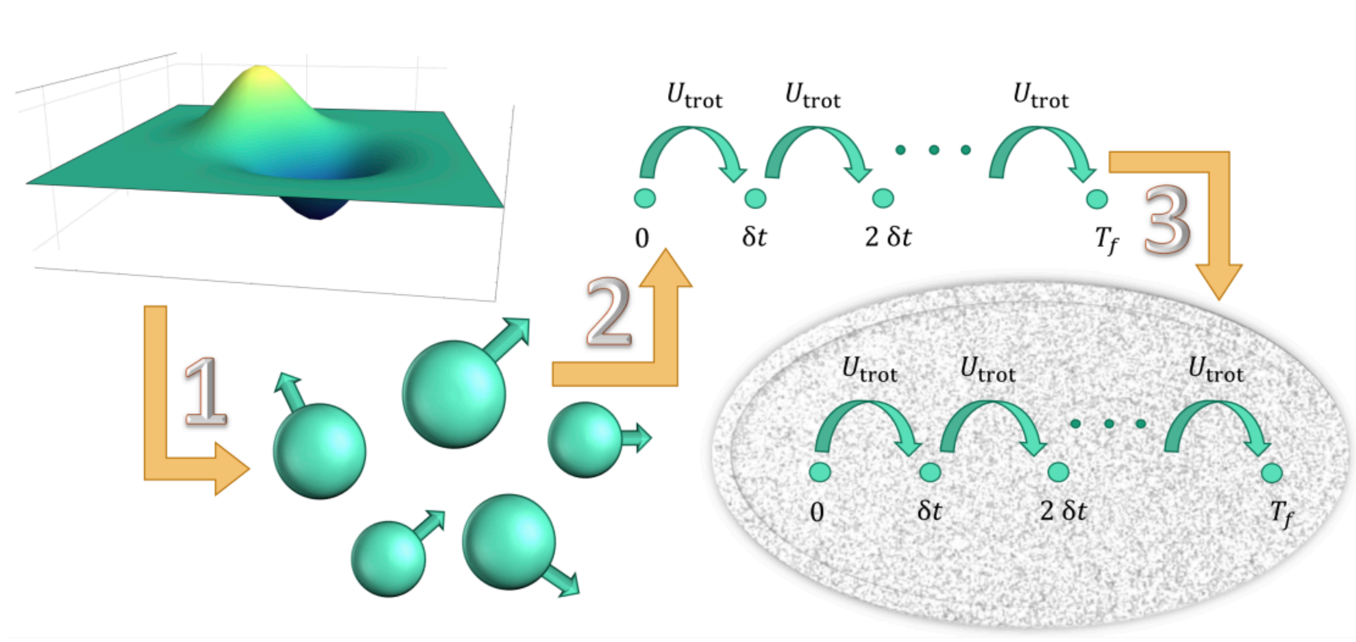
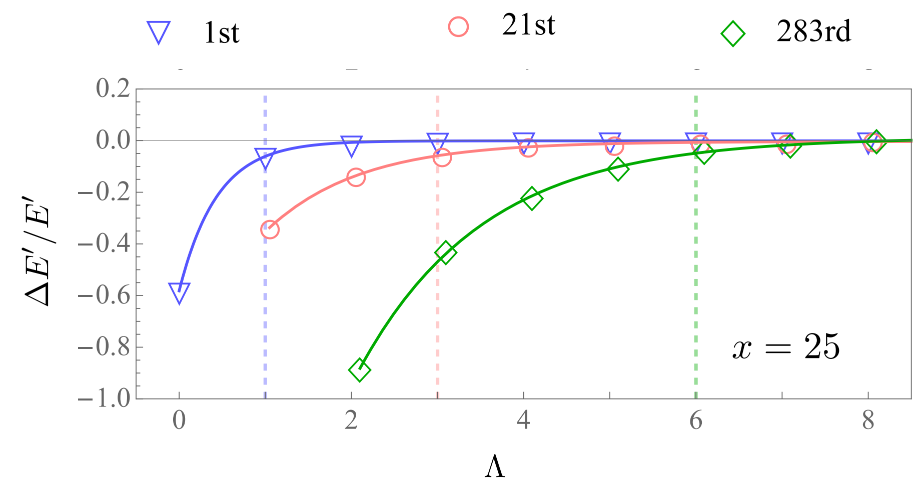
Klco, Savage, Phys. Rev. A 99, 052335 (2019).

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



Similar feature in SU(2) in 1+1D as a function of gauge cutoff

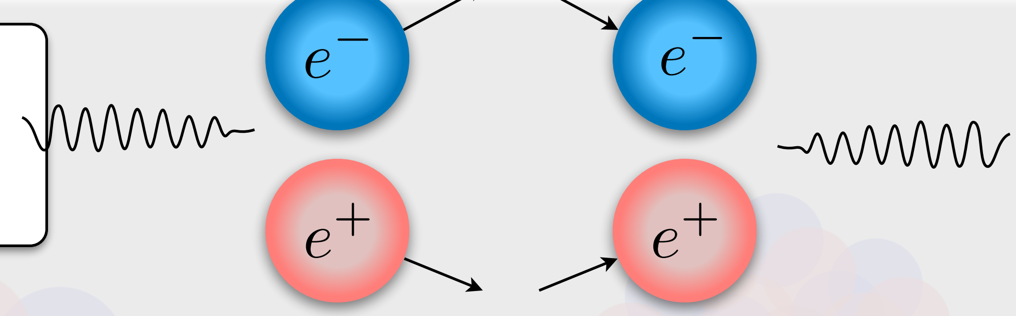


Basis	n_Q	2-body	3-body	4-body	5-body	6-body	7-body	8-body	9-body	10-body	11-body	12-body	CNOT
	2	4											8
	3	9											18
JLP	4	16											32
	5	25											50
	6	36											72
	n_Q	n_Q^2											$2n_Q^2$
	2	1	6	9									80
	3	1	8	30	56	49							1,152
HO	4	1	10	47	140	271	330	225					11,264
	5	1	12	68	244	630	1204	1668	1612	961			89,600
	6	1	14	93	392	1186	2772	5154	7560	8541	7182	3969	626,688

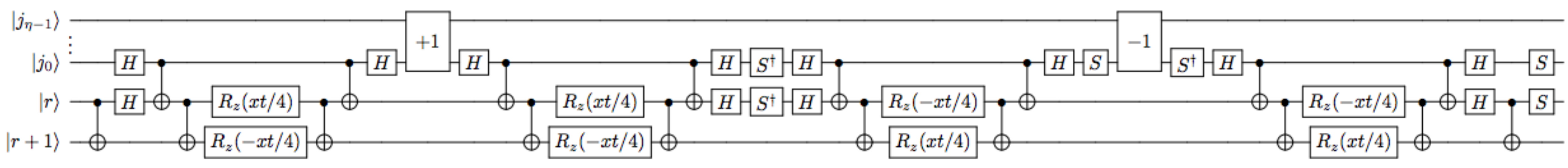
JLP: Jordan, Lee, and Preskill, Quant. Inf. Comput.14,1014(2014)

See also: Barata , Mueller, Tarasov, Venugopalan (2020) for a single-particle basis

QUANTUM SIMULATION OF GAUGE FIELD THEORIES: ALGORITHMIC DEVELOPMENTS



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 ($x = 10$)	$9.6 \cdot 10^{7}$	$3.2 \cdot 10^{11}$	$1.2 \cdot 10^{11}$	$4.2 \cdot 10^{14}$

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SOME SIMILARITIES BUT MAJOR DIFFERENCES

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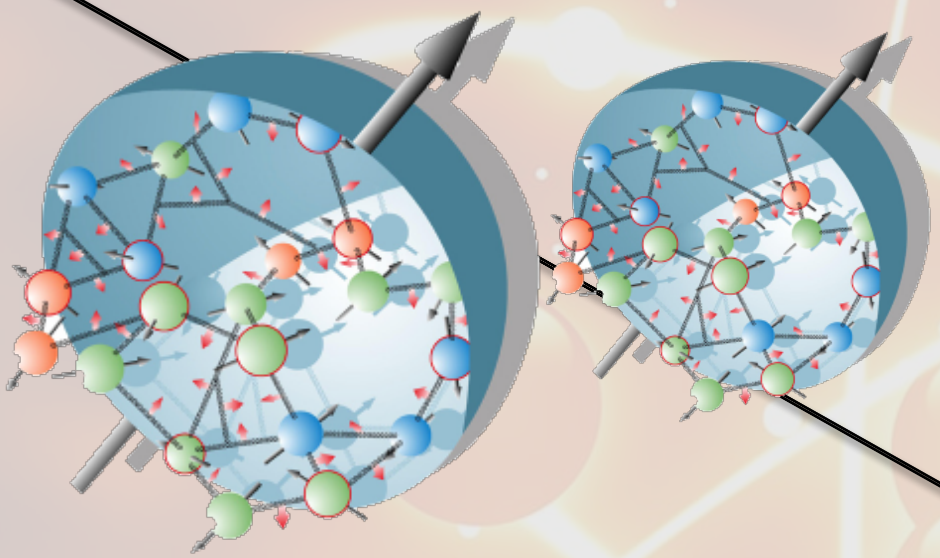

Starting from the nucelar Hamiltonian

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.

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.

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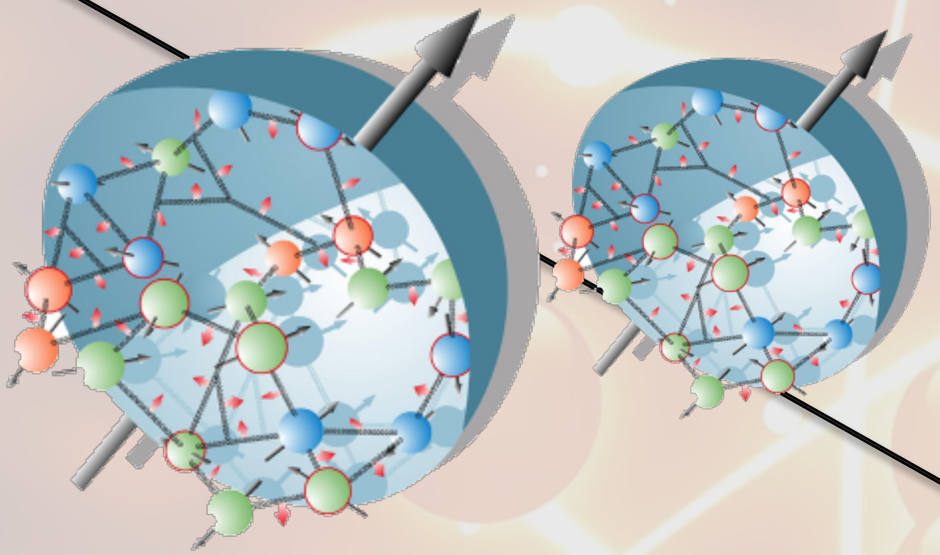

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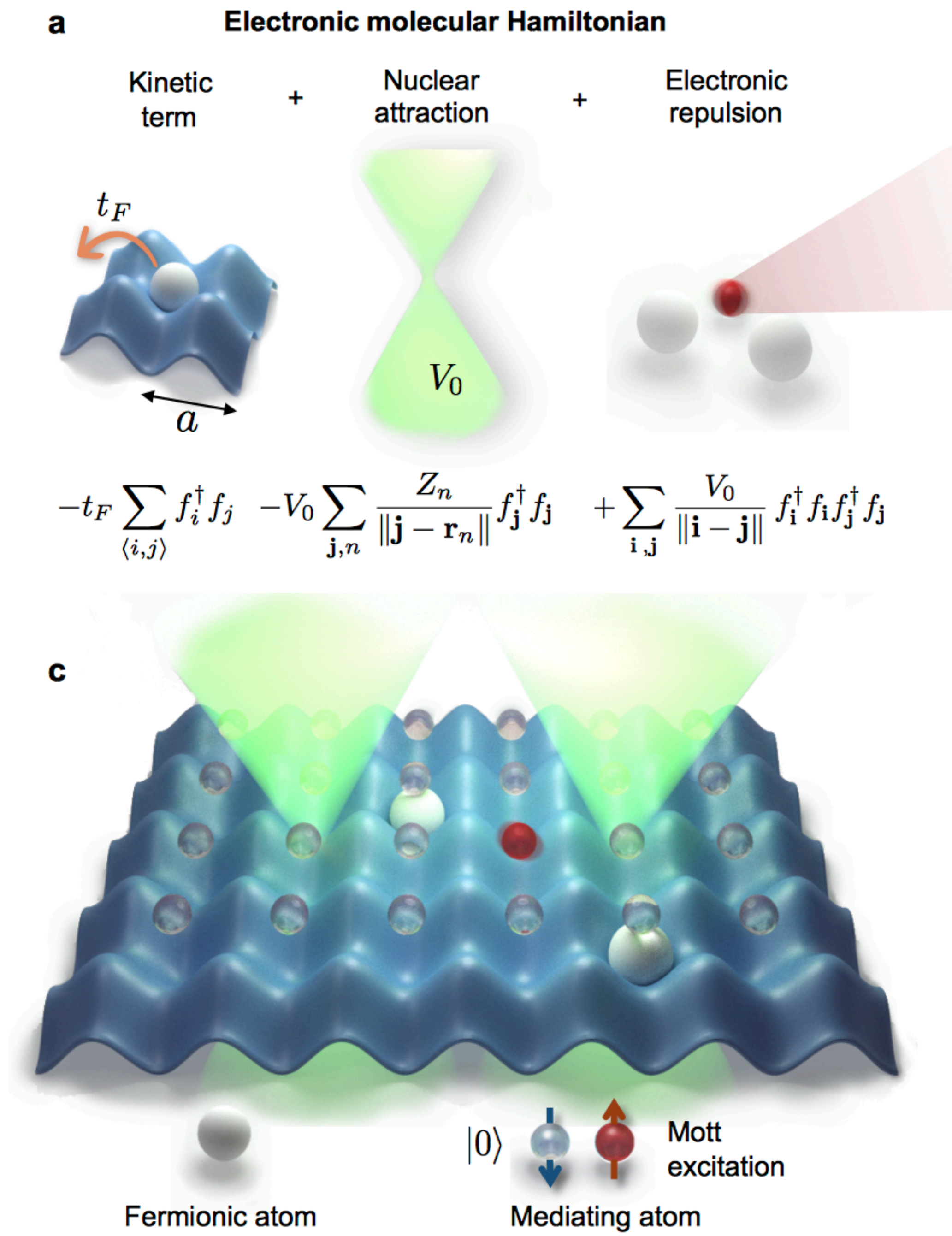
Attempts to cast QFT problems in a language closer to quantum chemistry and NR simulations:
Kreshchuk, Kirby, Goldstein, Beauchemin, Love, arXiv:2002.04016 [quant-ph]
Liu, Xin, arXiv:2004.13234 [hep-th]
Barata , Mueller, Tarasov, Venugopalan (2020)

EXAMPLE I: QUANTUM CHEMISTRY VS. NP IN ANALOG SIMULATIONS

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

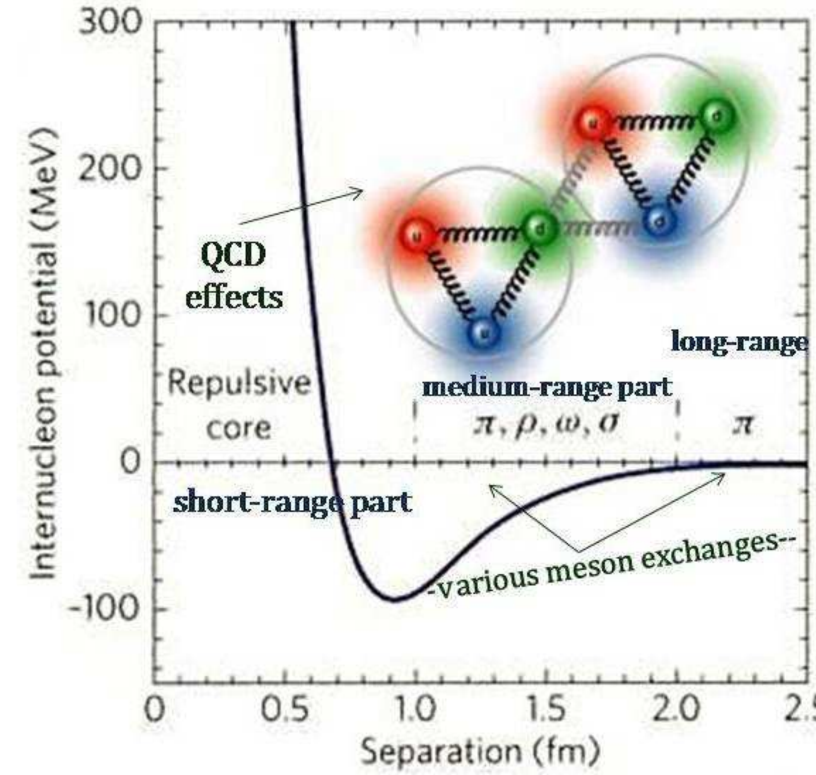


Effective potential $V(r) \approx C + \frac{V_0}{r/a} e^{-r/L}$

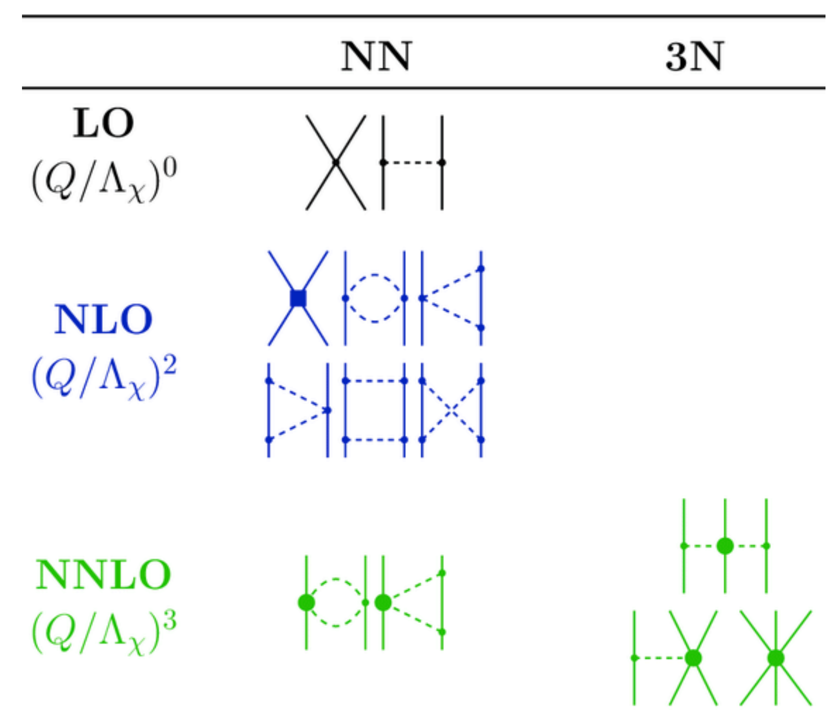
Argüello-Luengo, González-Tudela, Shi, Zoller, Cirac, Nature 574, 215-218 (2019)

? →

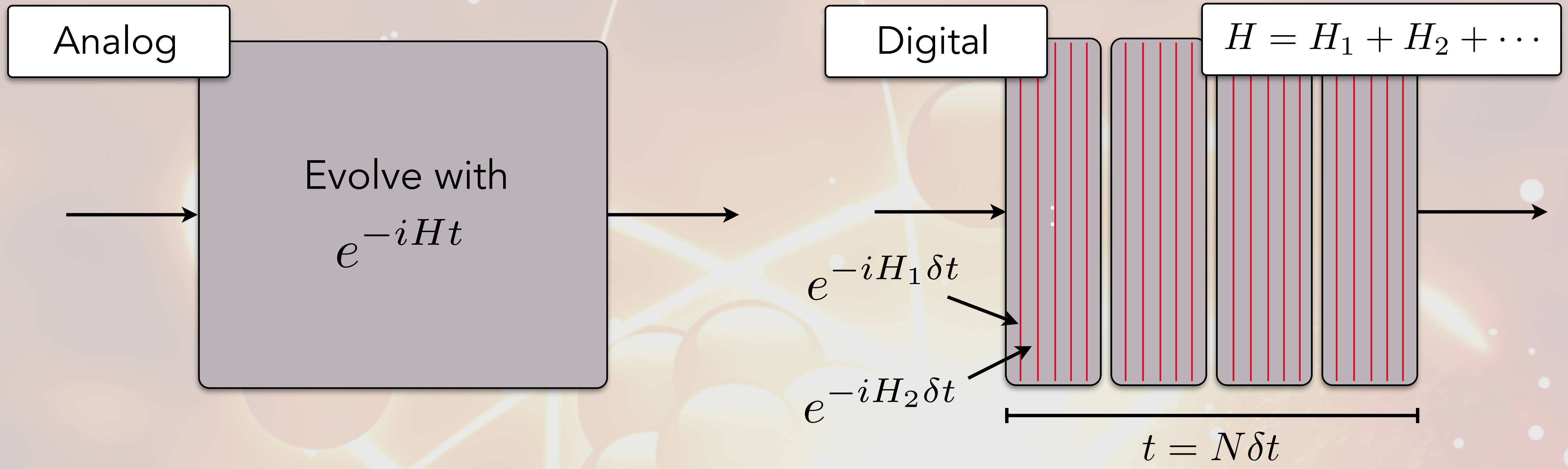
How about analog schemes for nuclear Hamiltonian with more complex interactions?



Or in the language of effective field theories:



EXAMPLE II: QUANTUM CHEMISTRY/CM VS. NP IN DIGITAL SIMULATIONS



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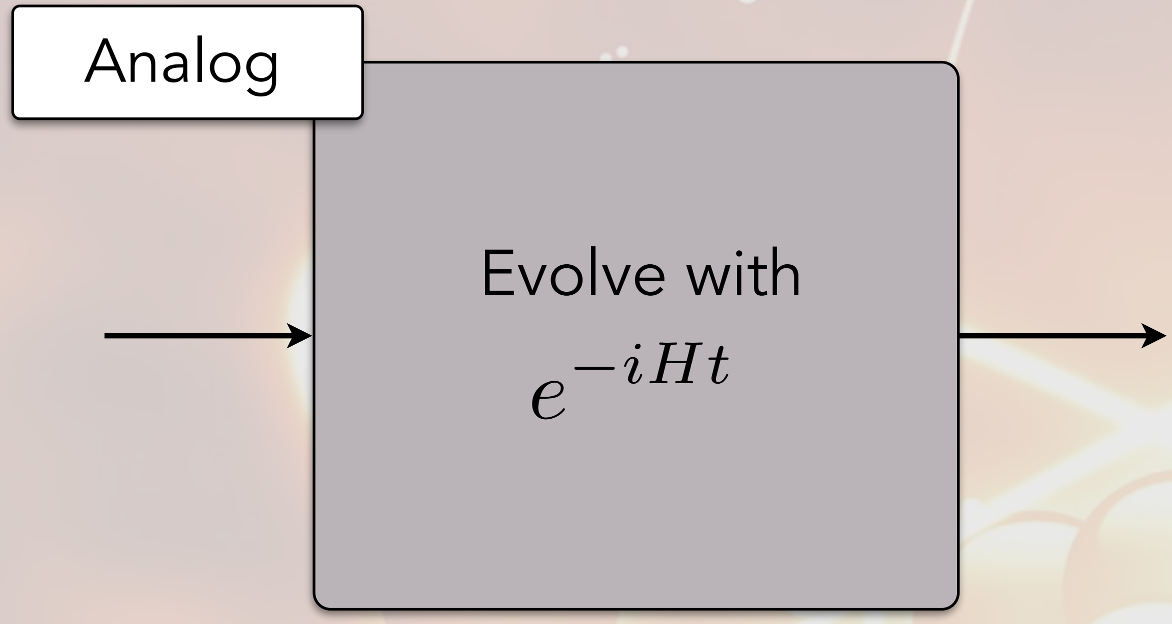
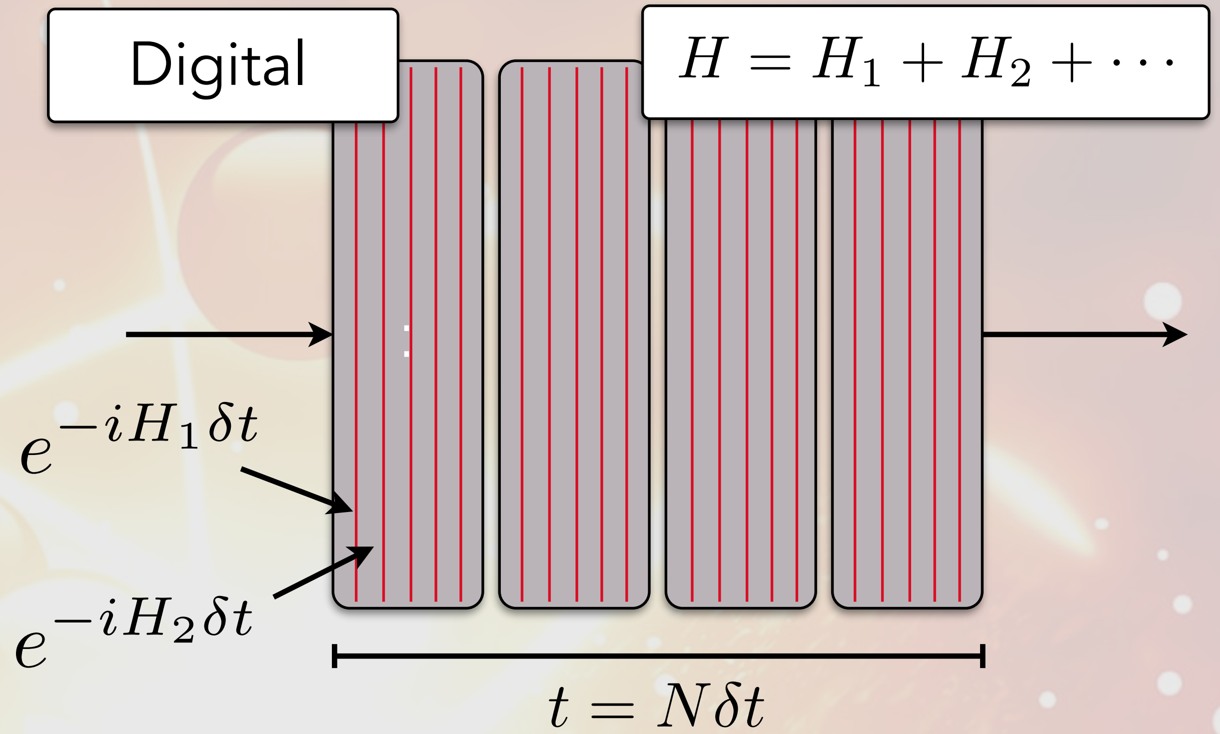
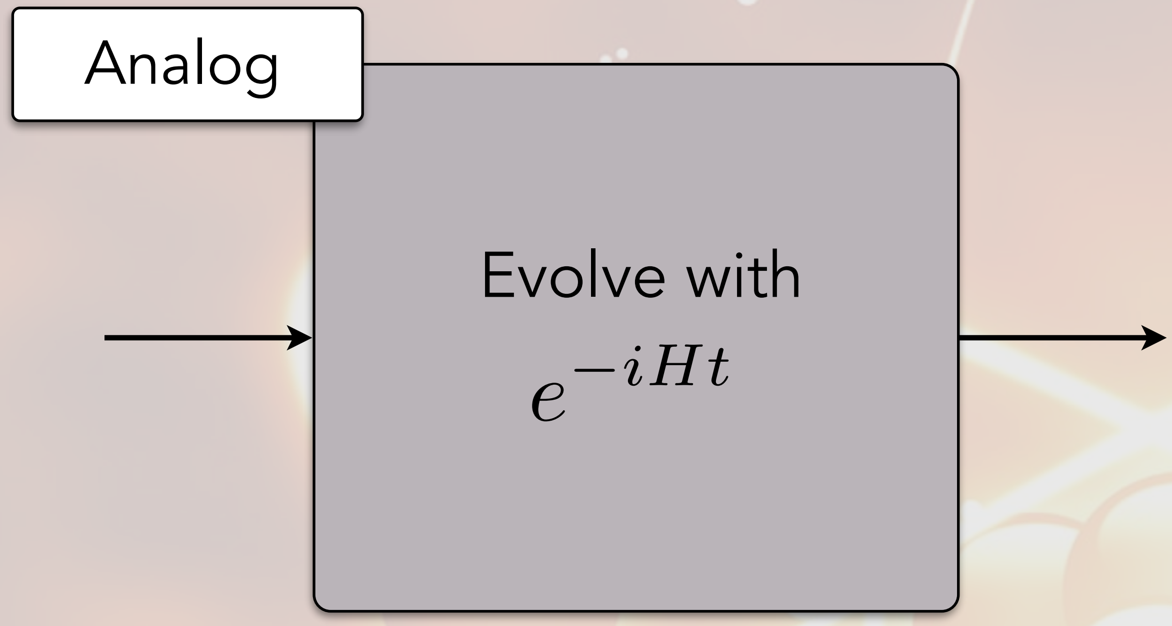


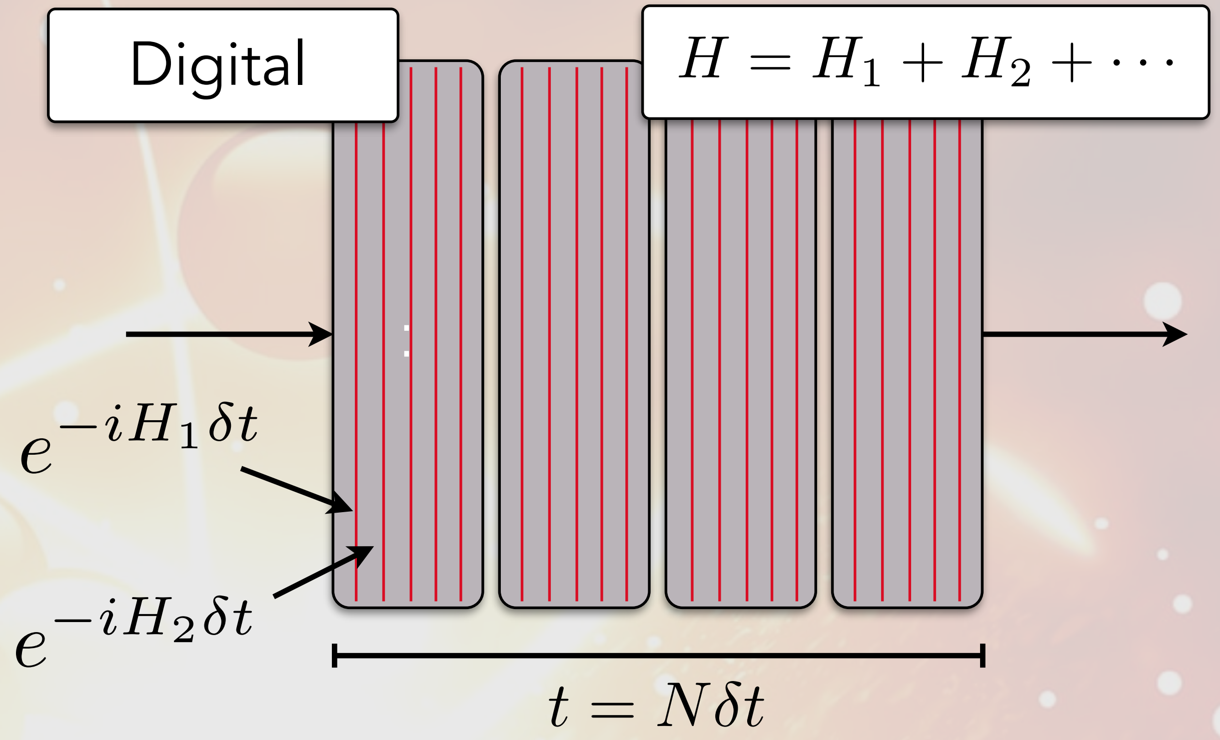


Childs, Su, Tran, Wiebe, Zhu, arXiv:1912.08854 [quant-ph]

Application	System	Best previous result	New result
Simulating quantum dynamics	Electronic structure	$\widetilde{\mathcal{O}}(n^2 t)$ (Interaction picture)	$n^{2+o(1)} t^{1+o(1)}$
	k-local Hamiltonians	$\widetilde{\mathcal{O}}(n^k \|H\|_1 t)$ (Qubitization)	$n^k \|\|\|H\|\|\|_1 \|H\|_1^{o(1)} t^{1+o(1)}$
	$1/x^\alpha$ $(\alpha < d)$	$\widetilde{\mathcal{O}}(n^{4-\alpha/d} t)$ (Qubitization)	$n^{3-\alpha/d+o(1)} t^{1+o(1)}$
	$1/x^\alpha$ $(d \le \alpha \le 2d)$	$\widetilde{\mathcal{O}}(n^3 t)$ (Qubitization)	$n^{2+o(1)} t^{1+o(1)}$
	$1/x^\alpha$ $(\alpha > 2d)$	$\widetilde{\mathcal{O}}\left((nt)^{1+2d/(\alpha-d)}\right)$ (Lieb-Robinson bound)	$(nt)^{1+d/(\alpha-d)+o(1)}$
	Clustered Hamiltonians	$2^{\mathcal{O}\left(h_B^2 t^2 \,\mathrm{cc}(g)/\epsilon\right)}$	$2^{\mathcal{O}\left(h_B^{o(1)} t^{1+o(1)} \,\mathrm{cc}(g)/\epsilon^{o(1)}\right)}$
Simulating local observables	$1/x^\alpha (\alpha > 2d)$	—	$t^{\left(1+d\frac{\alpha-d}{\alpha-2d}\right)\left(1+\frac{d}{\alpha-d}\right)+o(1)}$
Monte Carlo simulation	Transverse field Ising model	$\widetilde{\mathcal{O}}(n^{59} j^{21} \epsilon^{-9})$	$\widetilde{\mathcal{O}}(n^{45} j^{14} \epsilon^{-2} + n^{38} j^{21} \epsilon^{-9})$
	Quantum ferromagnets	$\widetilde{\mathcal{O}}(n^{115}(1+\beta^{46})/\epsilon^{25})$	$\widetilde{\mathcal{O}}(n^{92}(1+\beta^{46})/\epsilon^{25})$

EXAMPLE II: QUANTUM CHEMISTRY/CM VS. NP IN DIGITAL SIMULATIONS





No such scaling studies performed for NP Hamiltonian. Limited studies started for quantum field theories.

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

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

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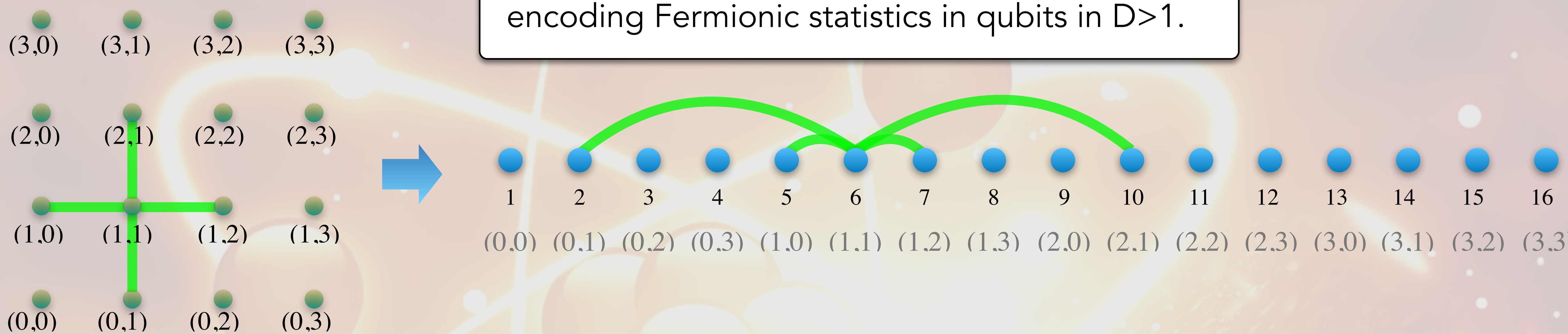
Jordan-Wigner transformation is not efficient for encoding Fermionic statistics in qubits in D>1.



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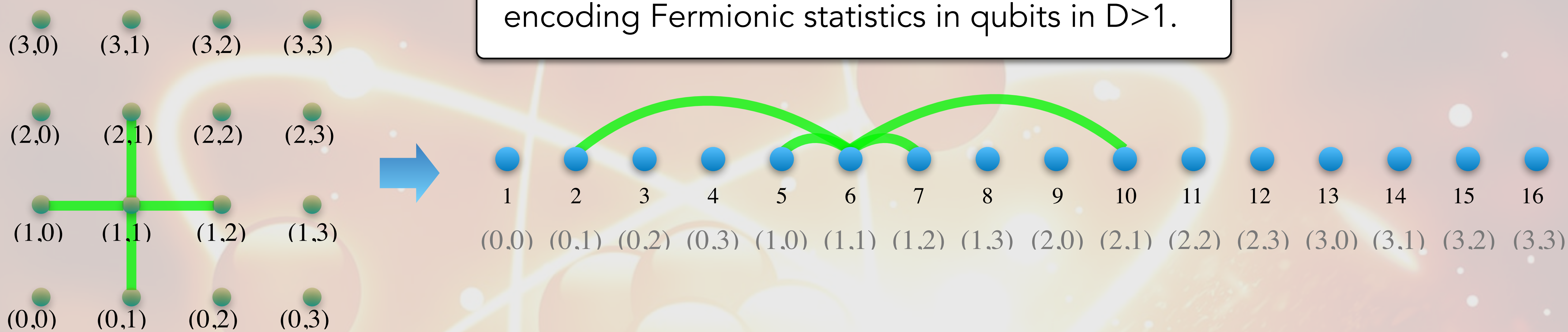
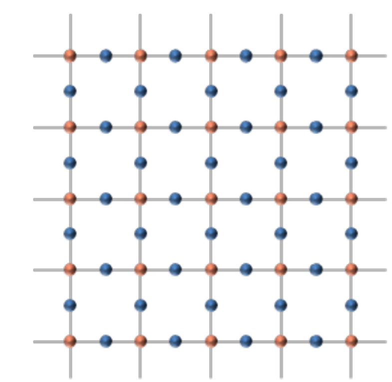


`Derby, Klassen, arXiv:2003.06939 [quant-ph]`

Reference	[BK02]	[VC05; WHT16]	[Jia+18]	[SW19][1]	[Set+19]
Qubit Number	$4L(L-1)$	$4L^2$	$4L(L-1)$	$4L^2-2L$	$6L^2$
Qubit to Mode Ratio	$2-\frac{2}{L}$	2	$2-\frac{2}{L}$	$2-\frac{1}{L}$	3
Max Weight Hopping	6	4	4	5	4
Max Weight Coulomb	8	2	6	6	6
Encoded Fermionic Space	Even	Full	Even	Full	Even
Graph Types	General	General	Square Lattice	Square Lattice	General
Corrects Single Qubit Errors?	No	No	Yes	No	Yes



`Chen, Phys. Rev. Research 2, 033527 (2020).`
`Zohar, Cirac, Phys. Rev. B 98, 075119 (2018)`

Local mappings using auxiliary gauge groups exist. Can leverage our gauge theory algorithms here?

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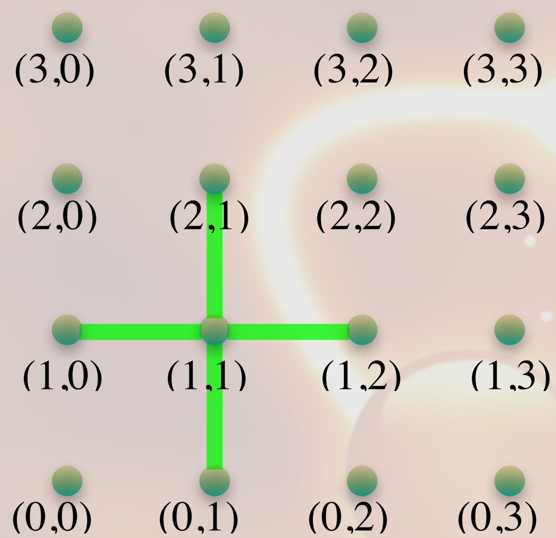

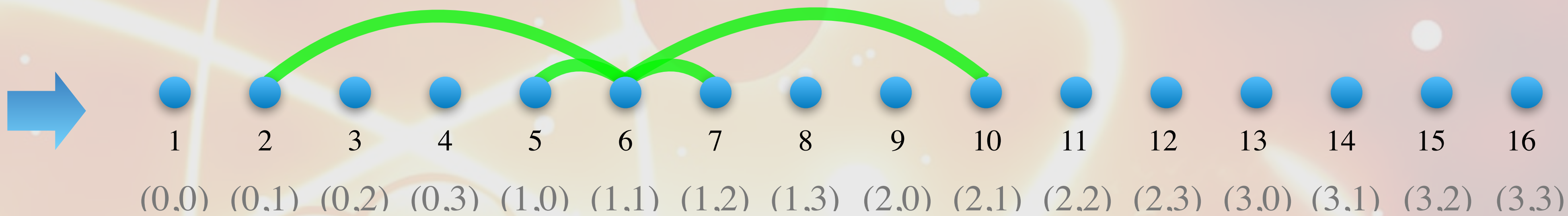

Again a complete study of the most efficient fermionic mapping given the structure of nuclear Hamiltonian is needed. First steps are taken.

Roggero, Li, Carlson, Gupta, Perdue, Phys. Rev. D 101, 074038 (2020)

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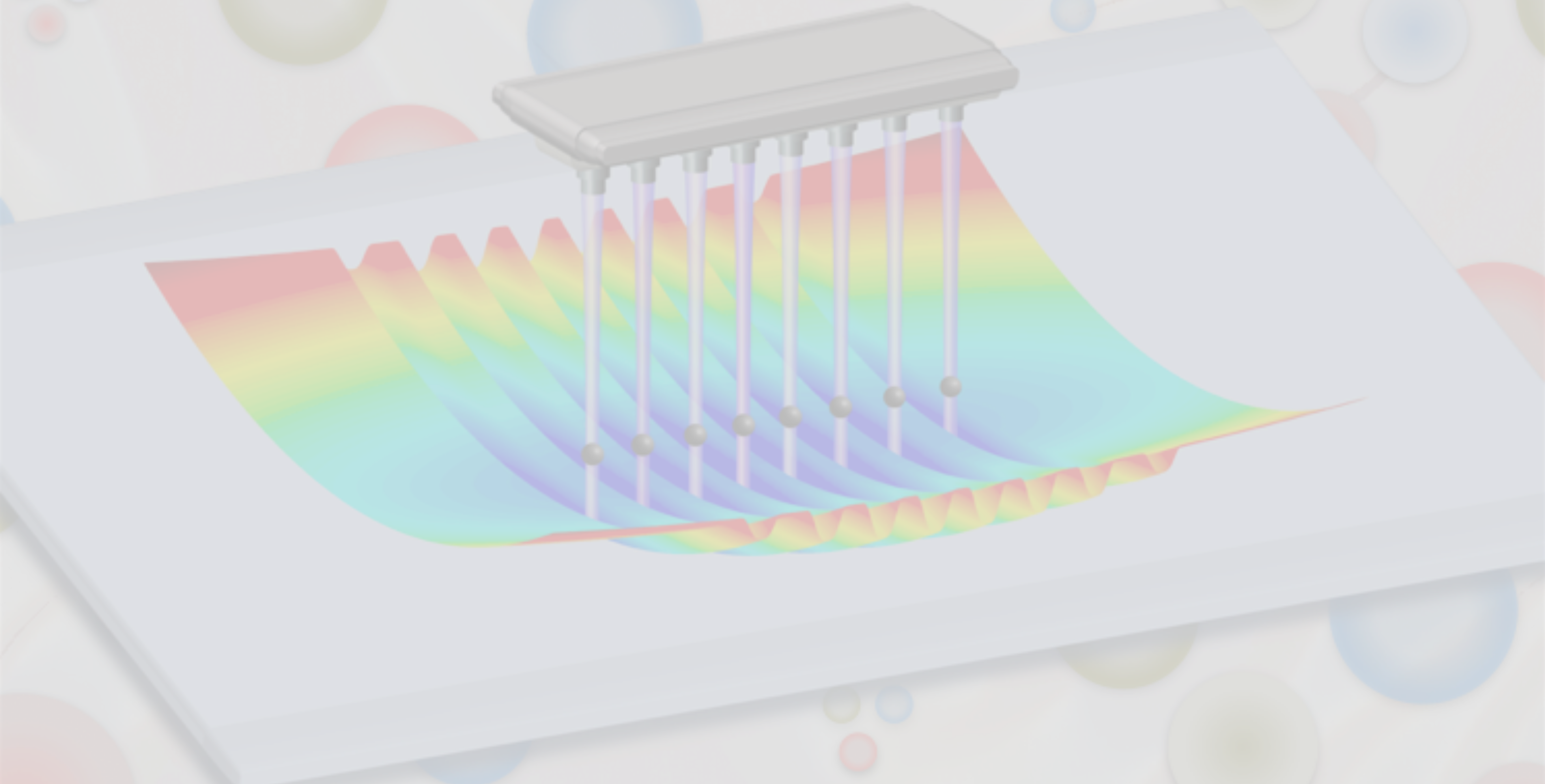
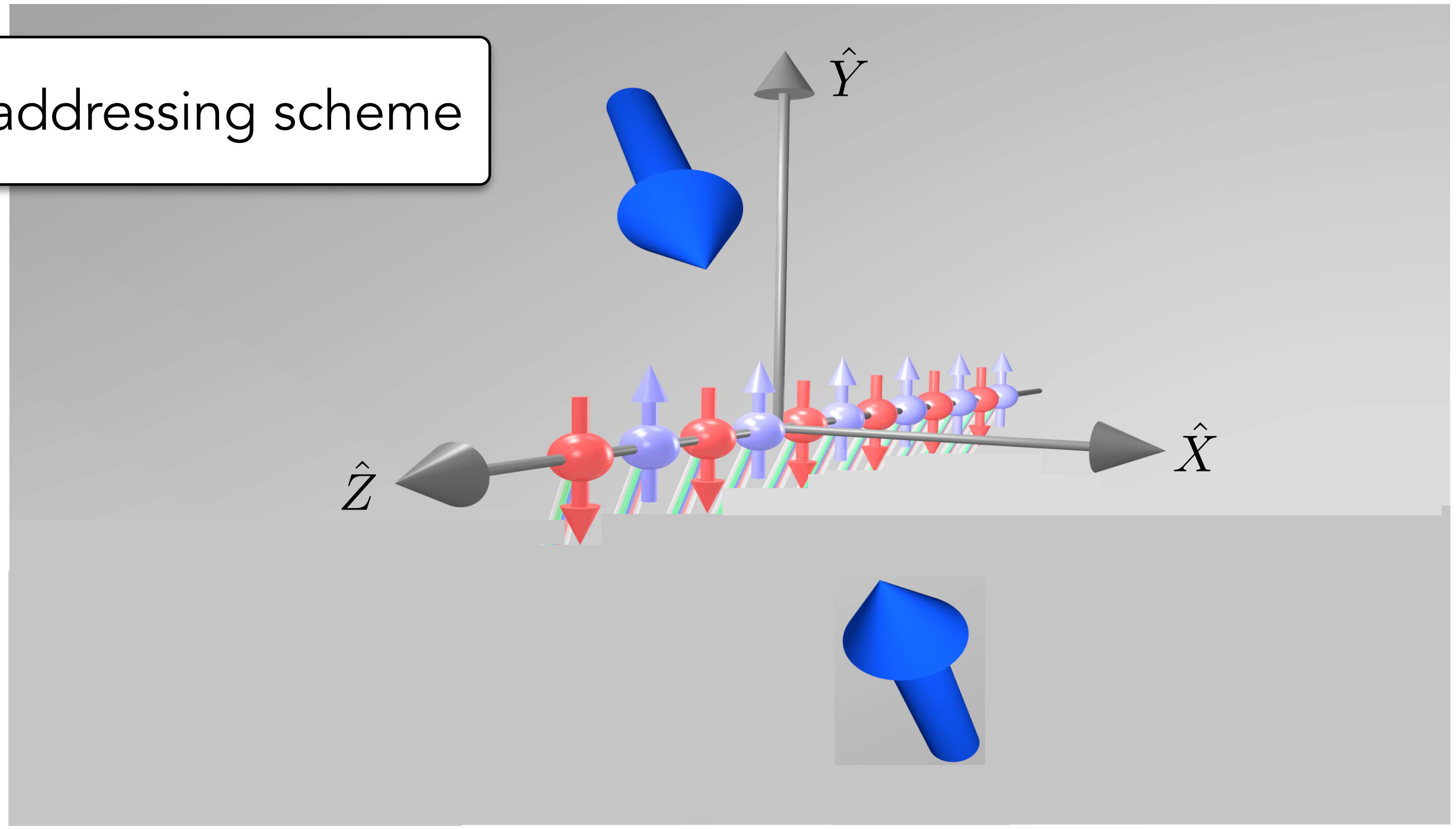
AN EXAMPLE FROM THE WORLD OF ANALOG SIMULATIONS



Credit: Shaw/Davoudi, UMD

EXAMPLE: A TRAPPED-ION ANALOG SIMULATOR

A global addressing scheme

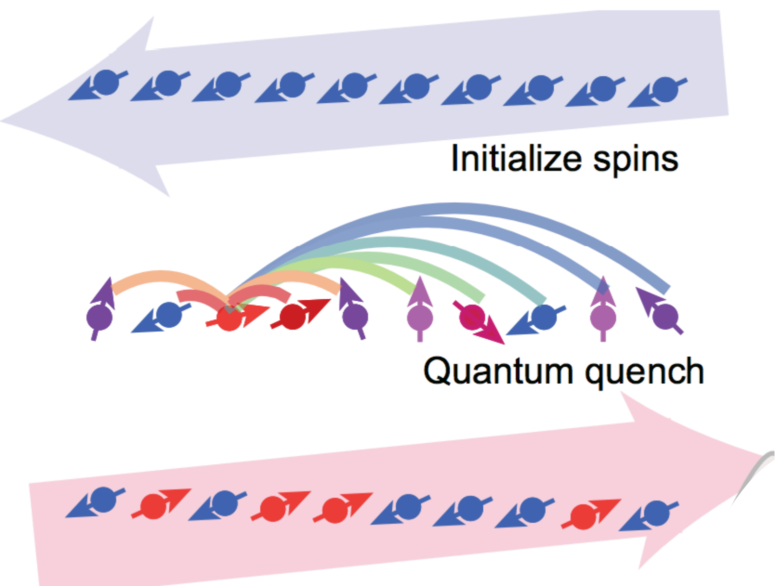


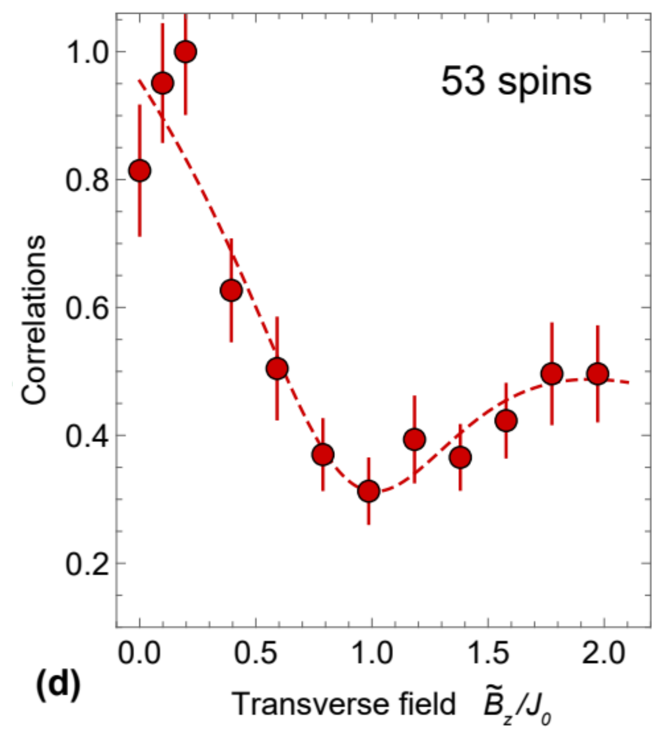
Effective Hamiltonian

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

with coupling:

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

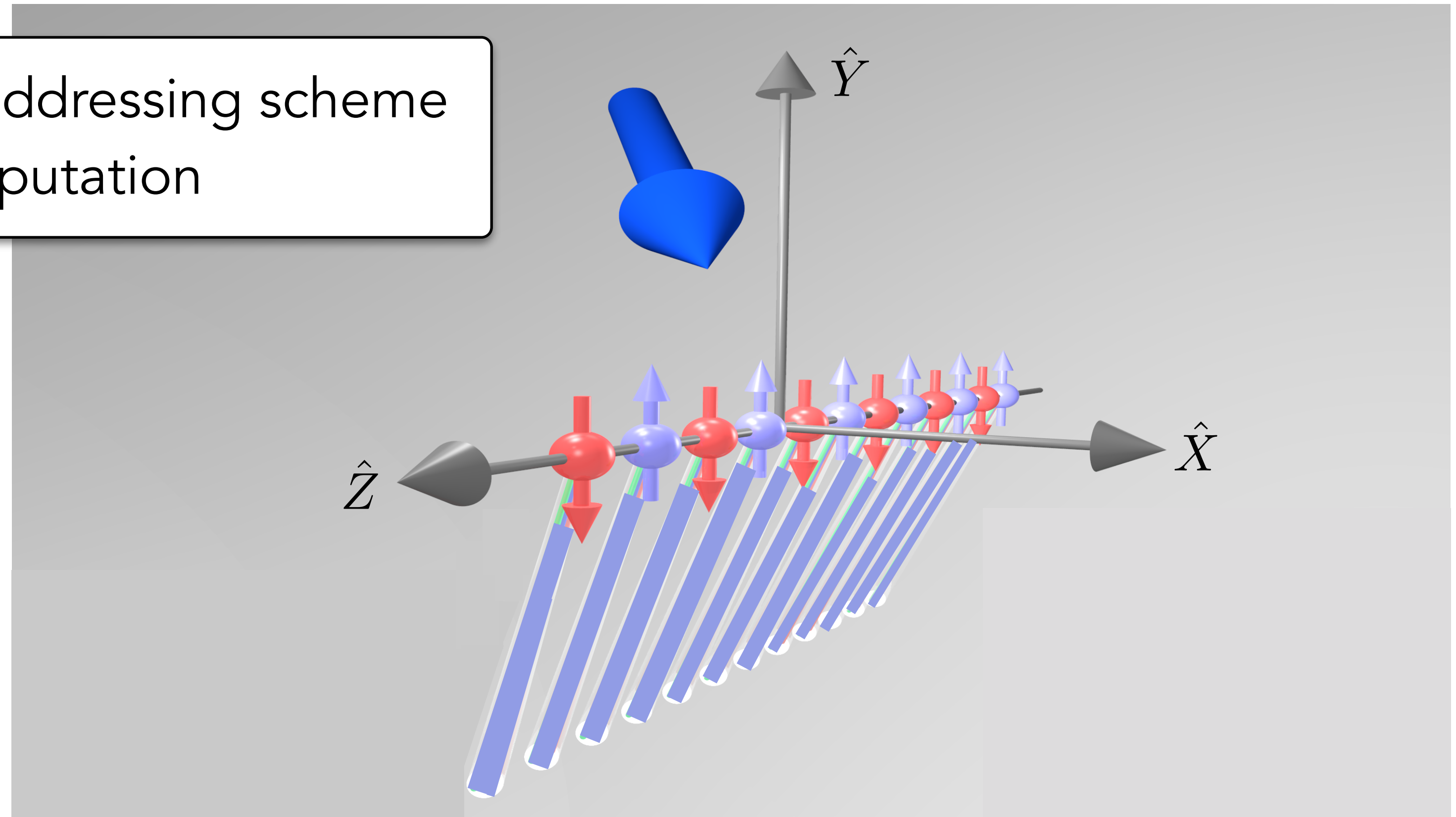




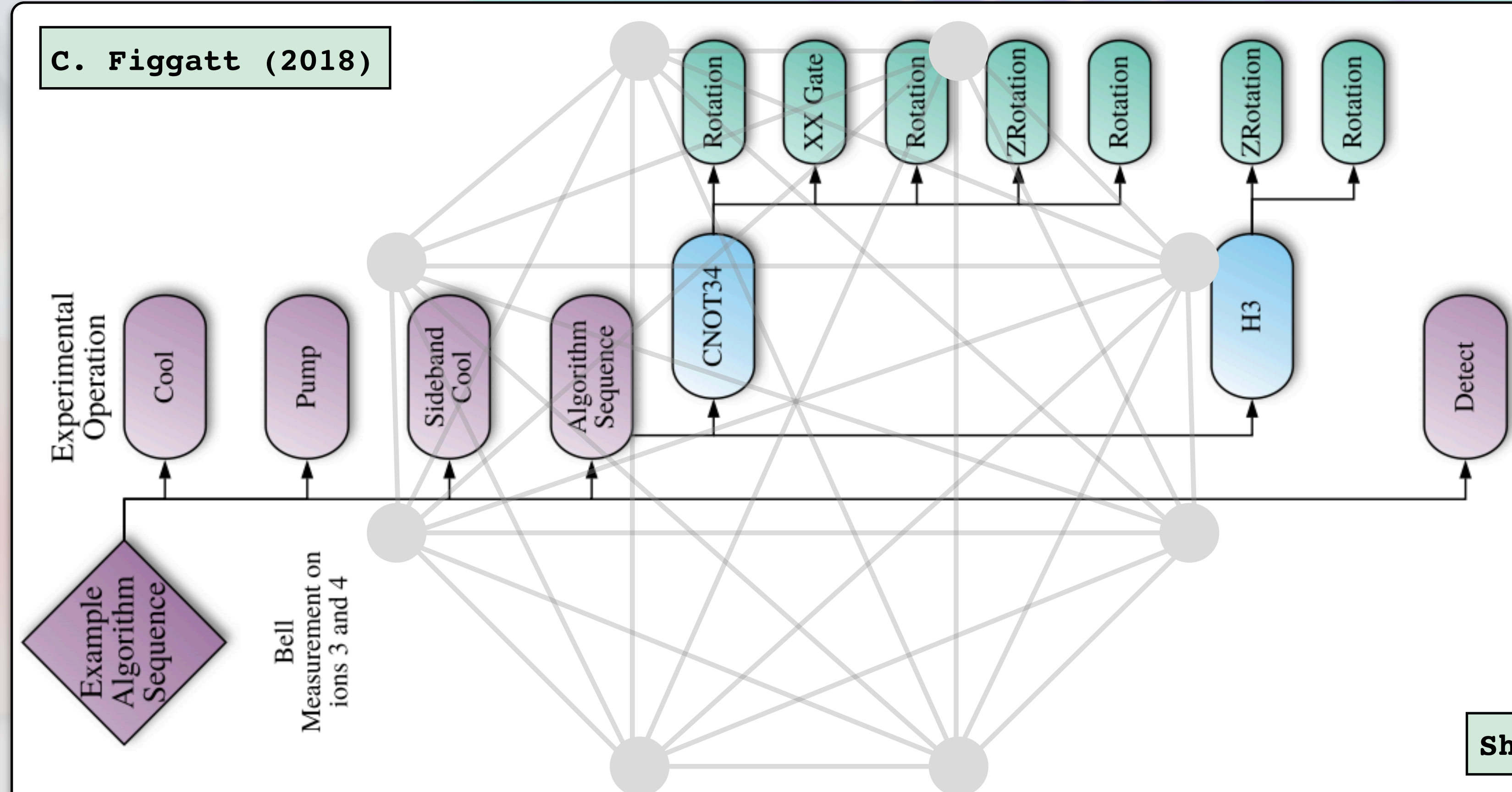
Zhang et al, Nature 551, 601–604 (2017).

EXAMPLE: A TRAPPED-ION DIGITAL SIMULATOR

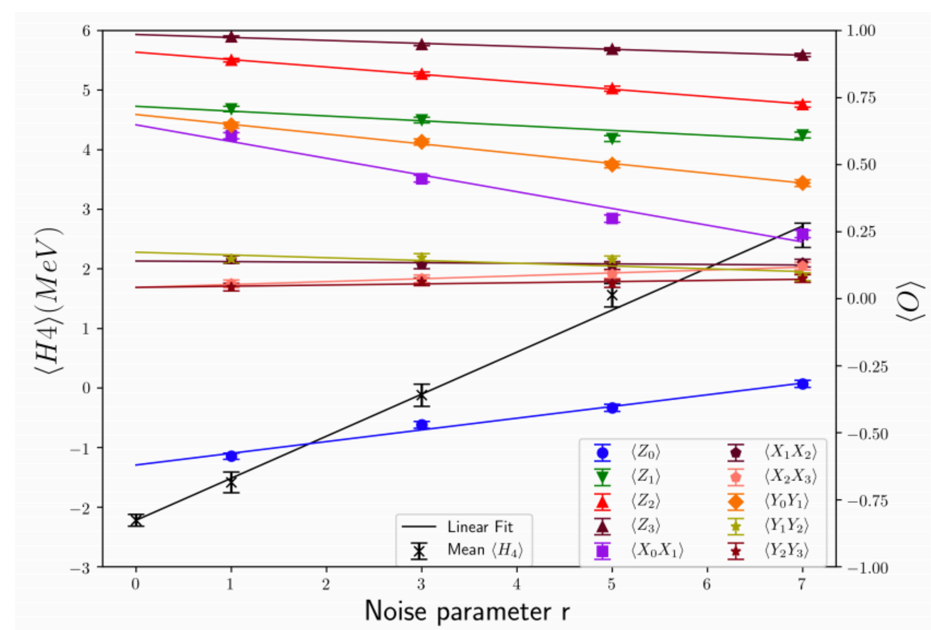
An individual addressing scheme for digital computation



C. Figgatt (2018)



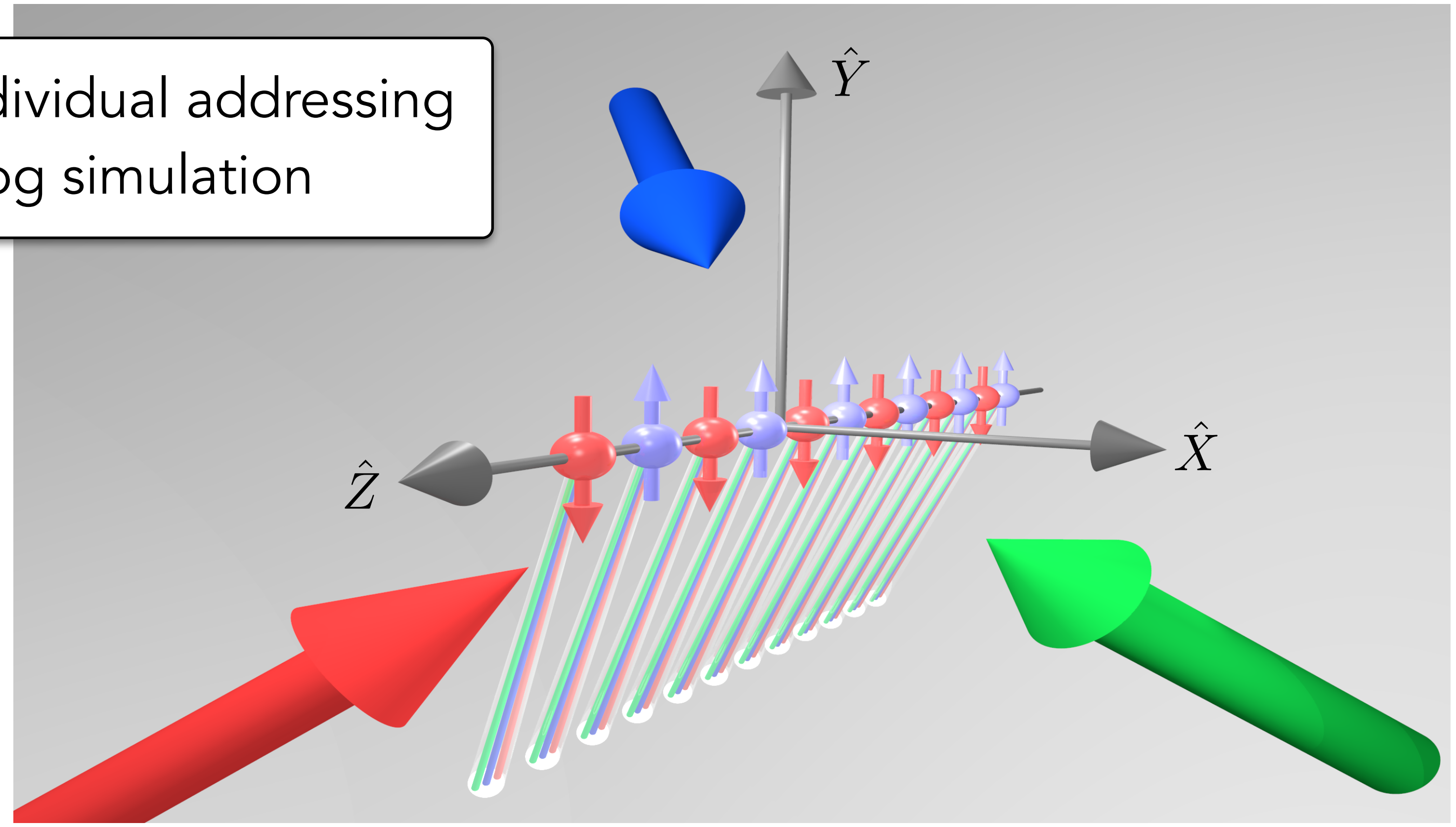
VQE for finding deuteron's binding



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

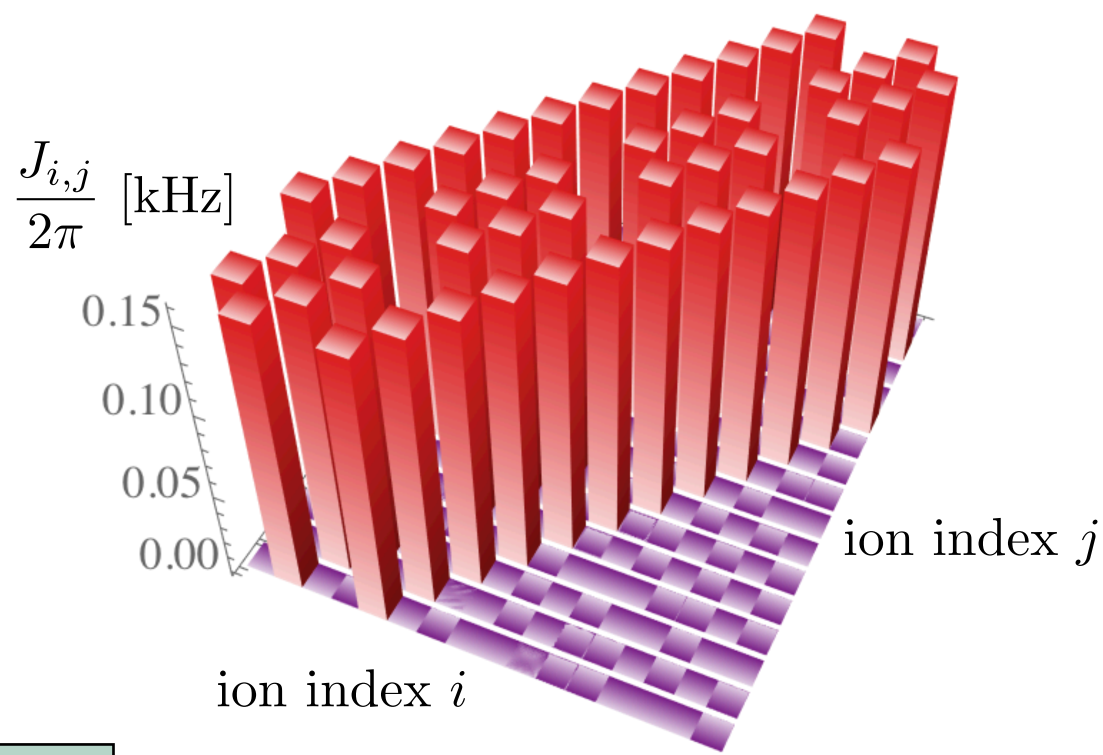
EXAMPLE: A TRAPPED-ION ANALOG SIMULATOR

An enhanced individual addressing scheme for analog simulation



Engineering a Heisenberg model Hamiltonian

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



For Schwinger model, Z_2 gauge theory in 2+1D, Chern-Simons theory in 2+1D.

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

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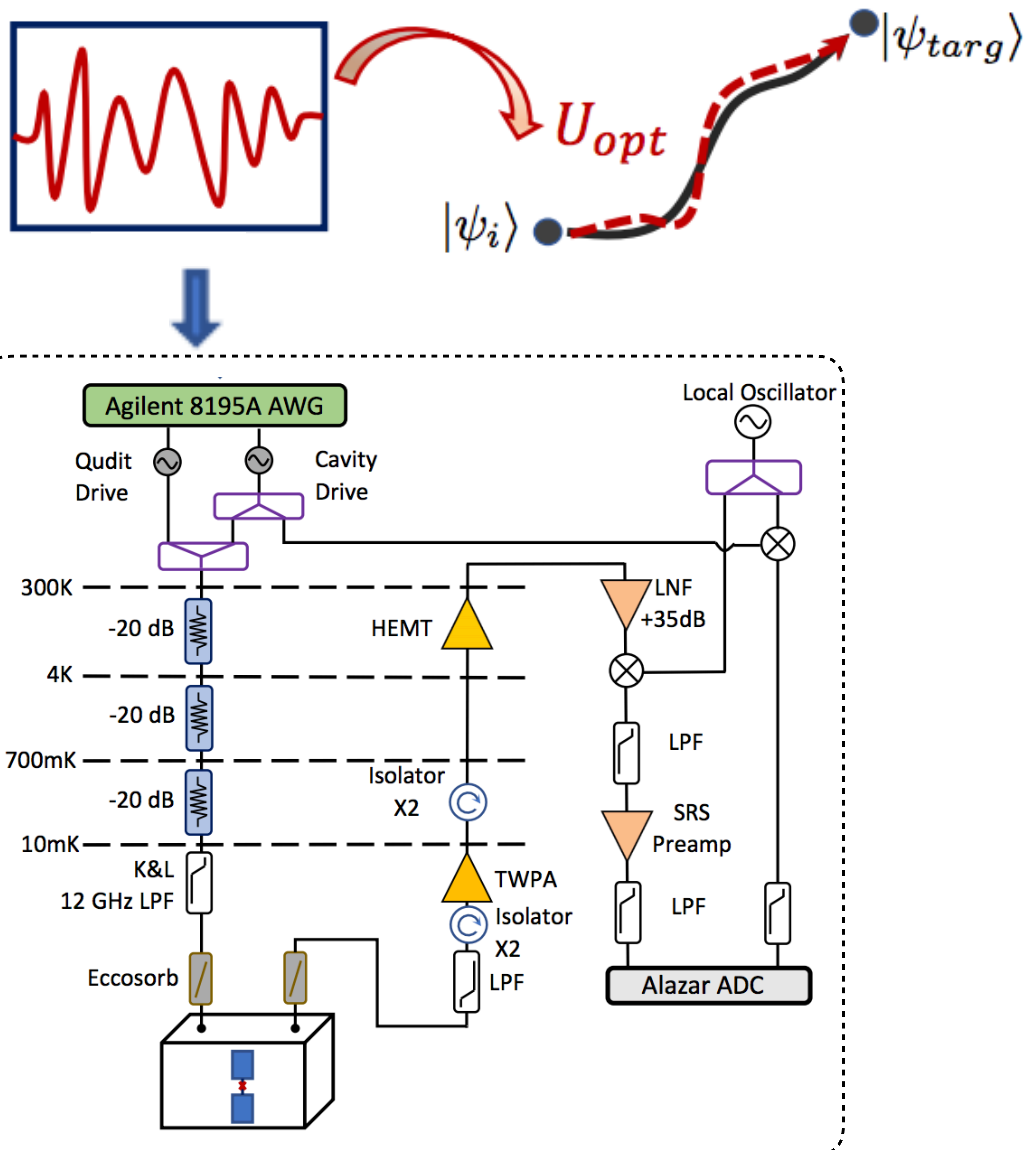
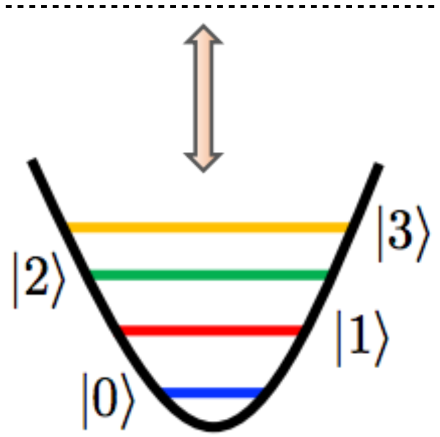
EXAMPLE: AN ANALOG-DIGITAL QPU FOR NP

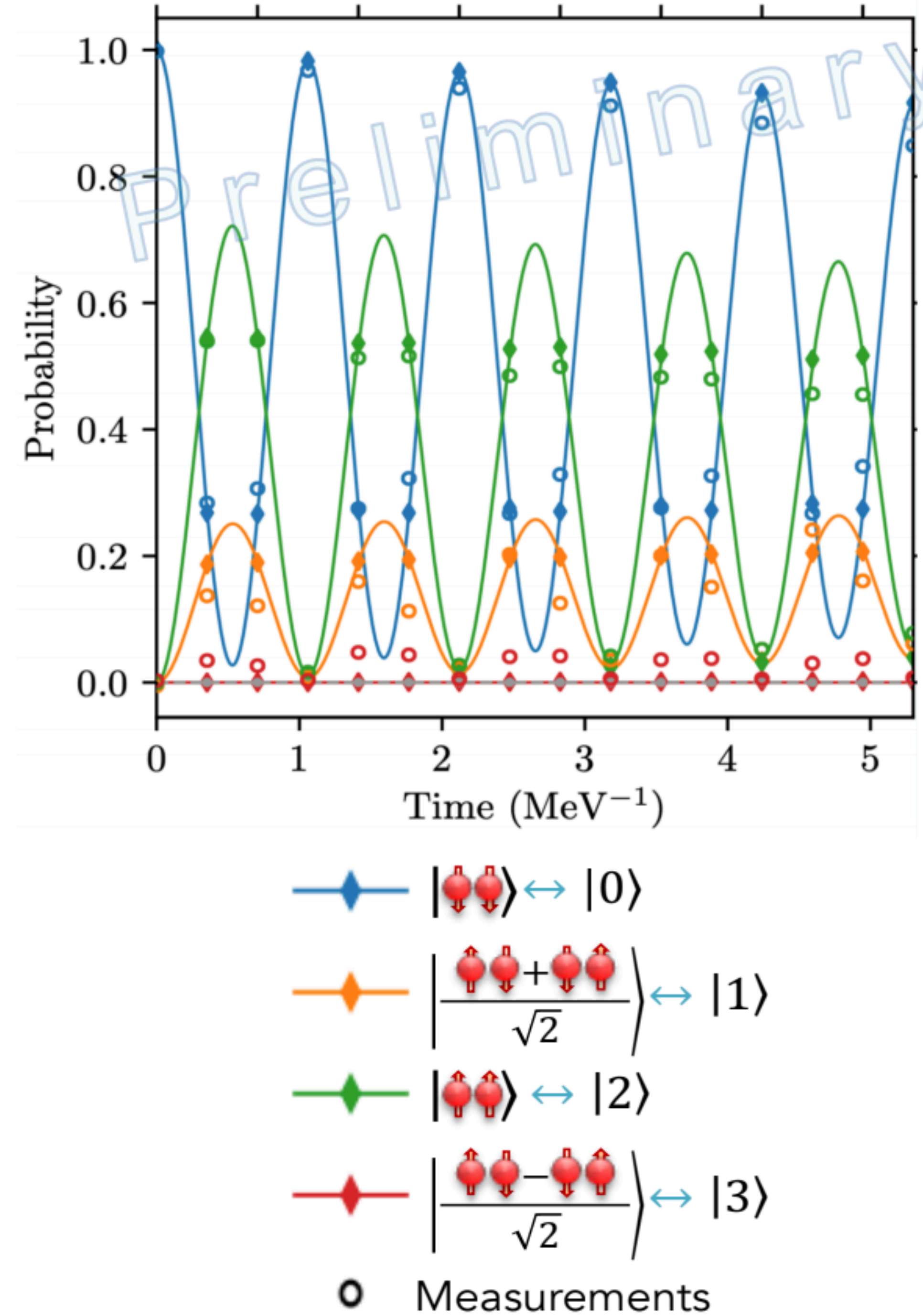
Programmable gates with superconducting qudits





Wu, Tomarken, Petersson, Martinez, Rosen, DuBois arXiv:2005.13165

Two-neutron spin dynamics with LLNL superconducting-cavity QPU



Holland et al., Phys. Rev. A 101, 062307 (2020) Wu, Wendt, Kravvaris, Ormand, DuBois, Rosen, Pederiva, and Quaglioni (2020).

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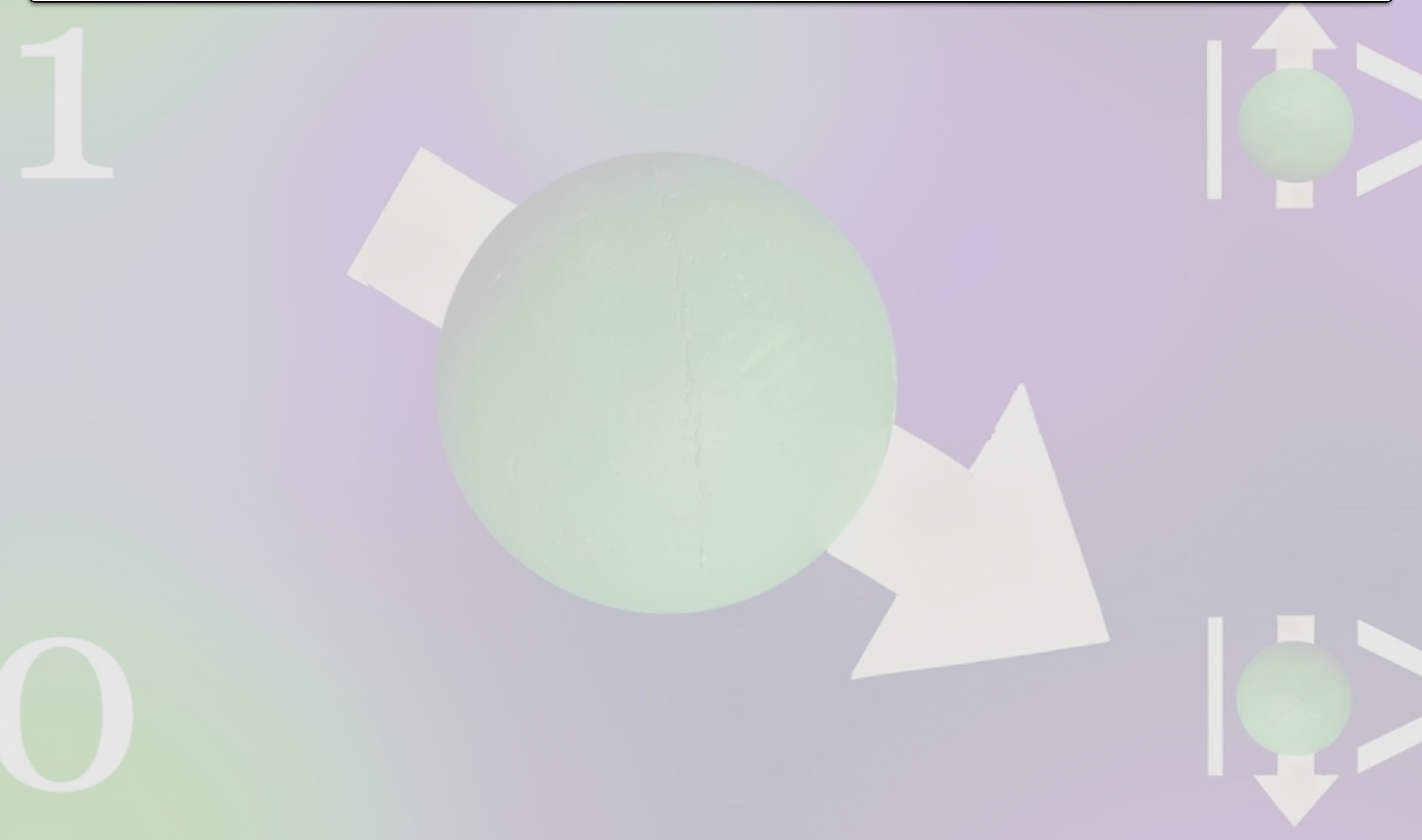
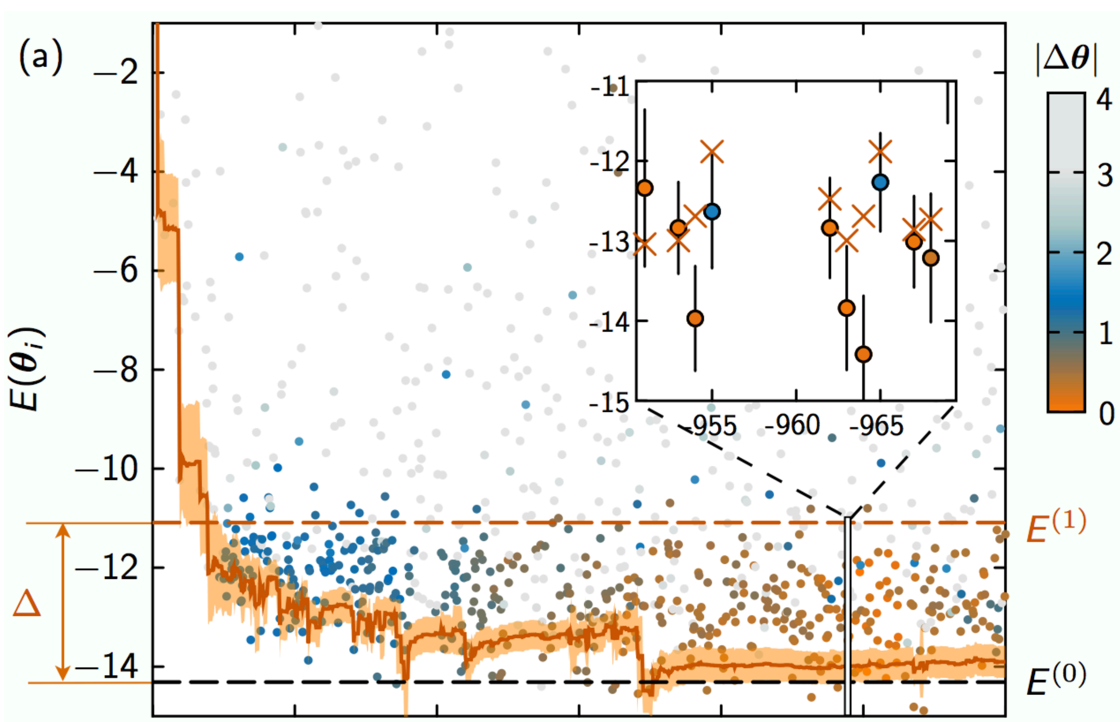
EXAMPLES OF ENHANCING SIMULATIONS IN THE NEAR TERM WITH CLASSICAL AND QUANTUM SIMULATING METHODS COMBINED…

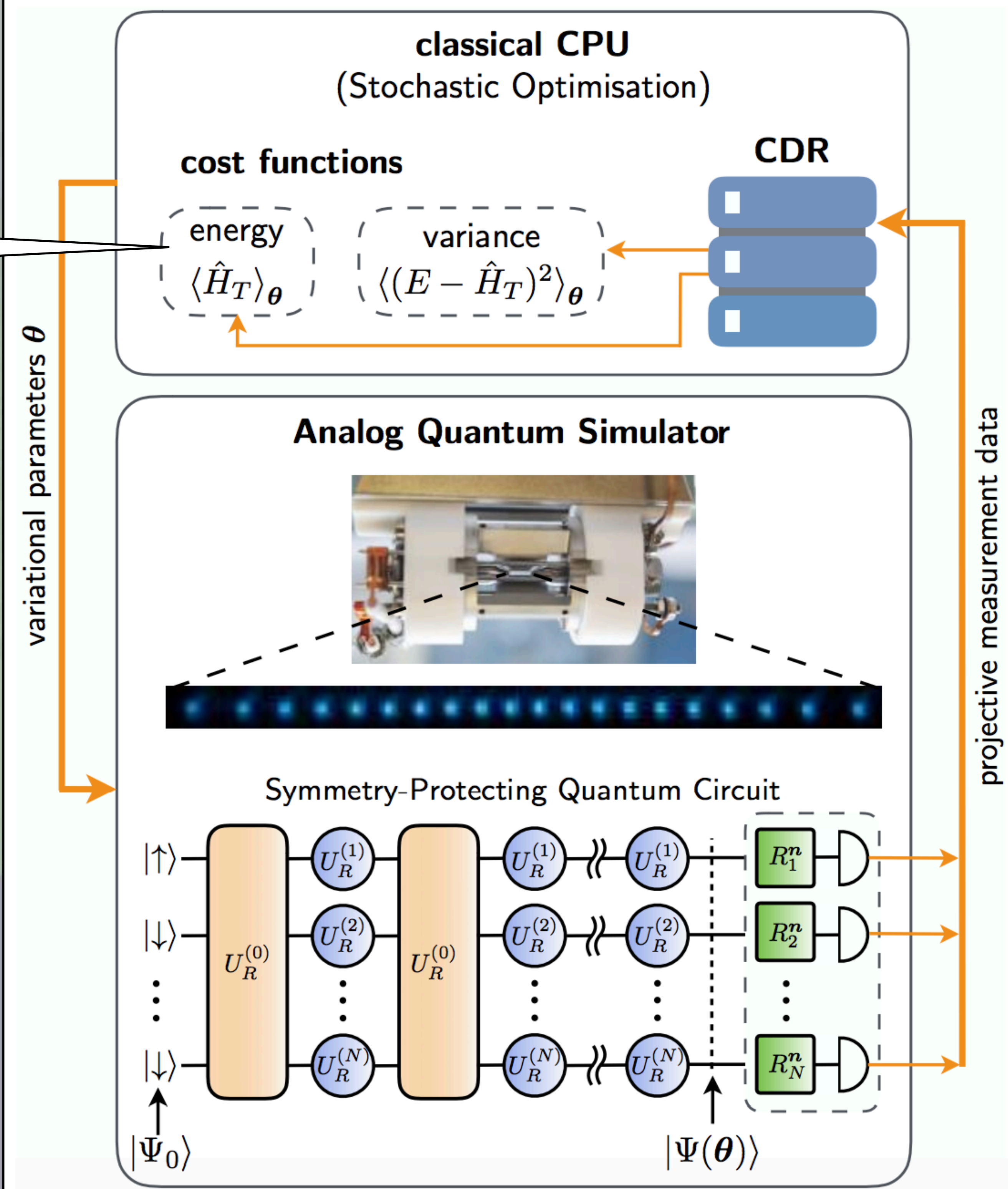


Veritasium@Yutube

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.



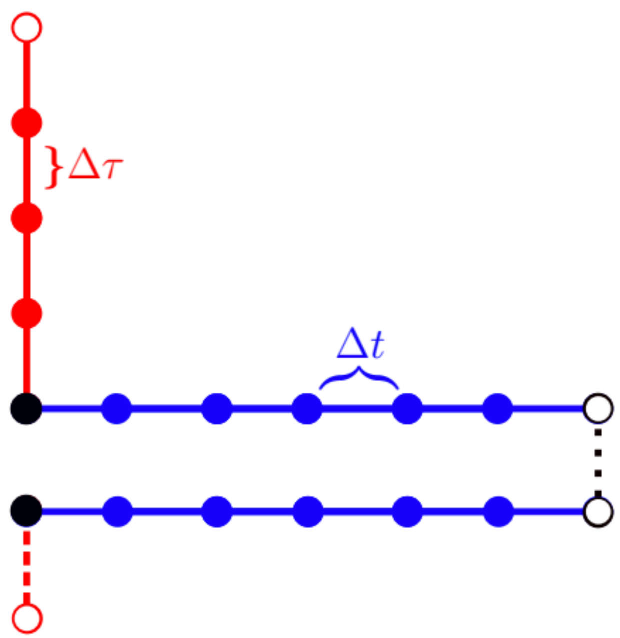


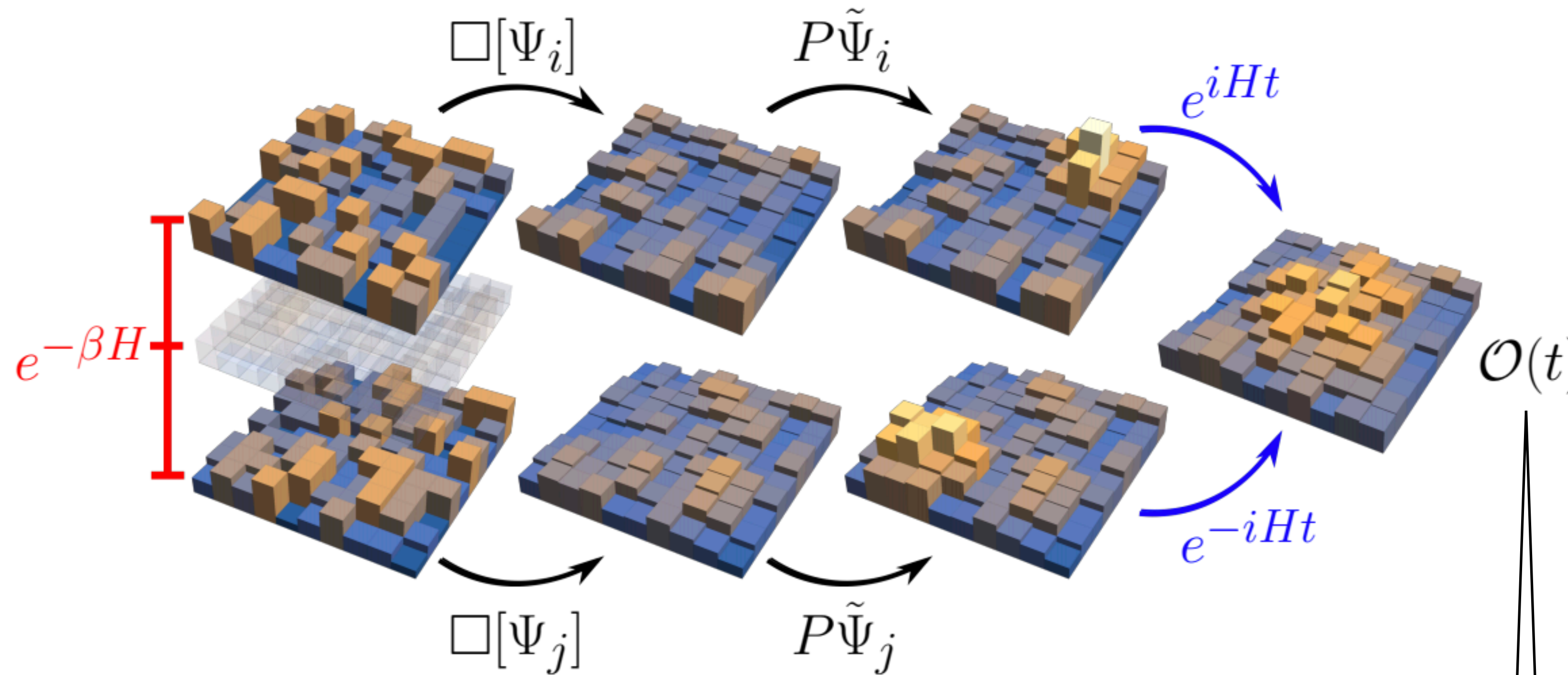
Kokail et al, Nature 569, 355 (2019).

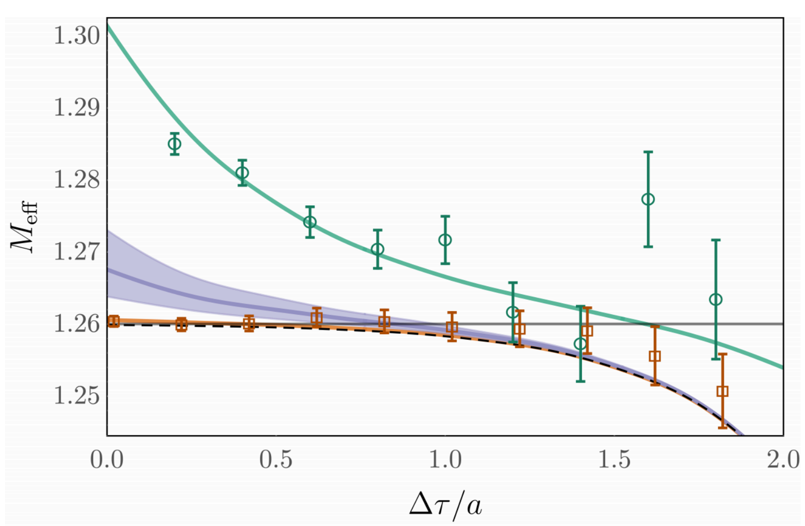
See alo the VQE applied to calculation of neutron binding in Dumitrescu, McCaskey, Hagen, Jansen, Morris, Papenbrock, Pooser, Dean, Lougovski Phys. Rev. Lett. 120, 210501 (2018)

EXAMPLE II: STATE PREPARATION ROUTINE FOR LATTICE GAUGE THEORIES

State preparation can be done using Monte Carlo methods if no sign or signal-to-noise problems occur, and time evolution can be ported to quantum hardware.

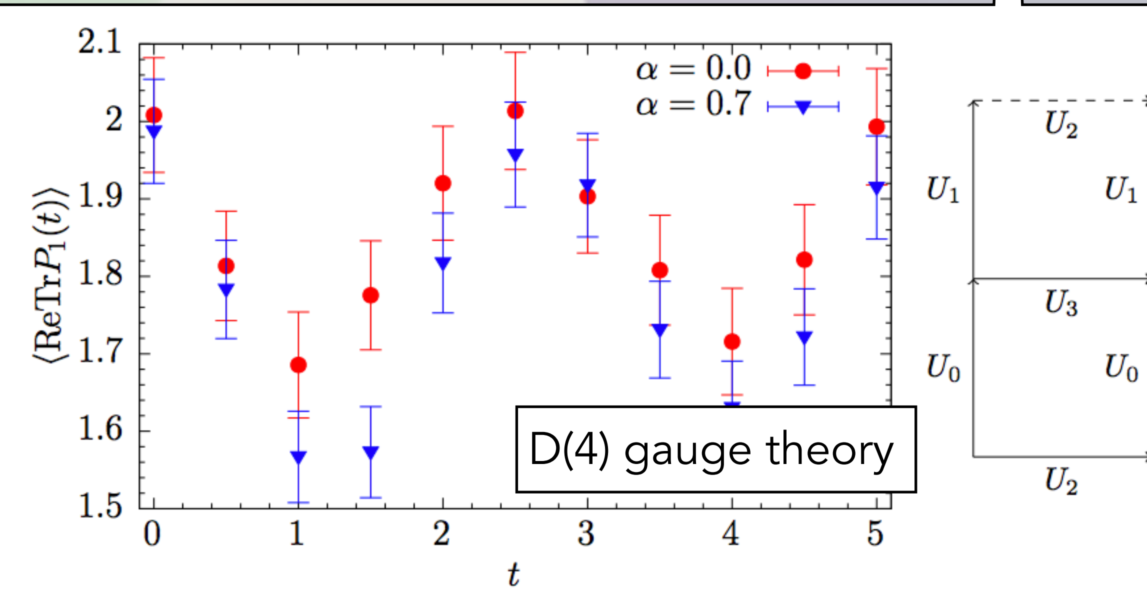






The use of VQE to generate optimized operators to in Monte Carlo simulation of lattice Schwinger model.

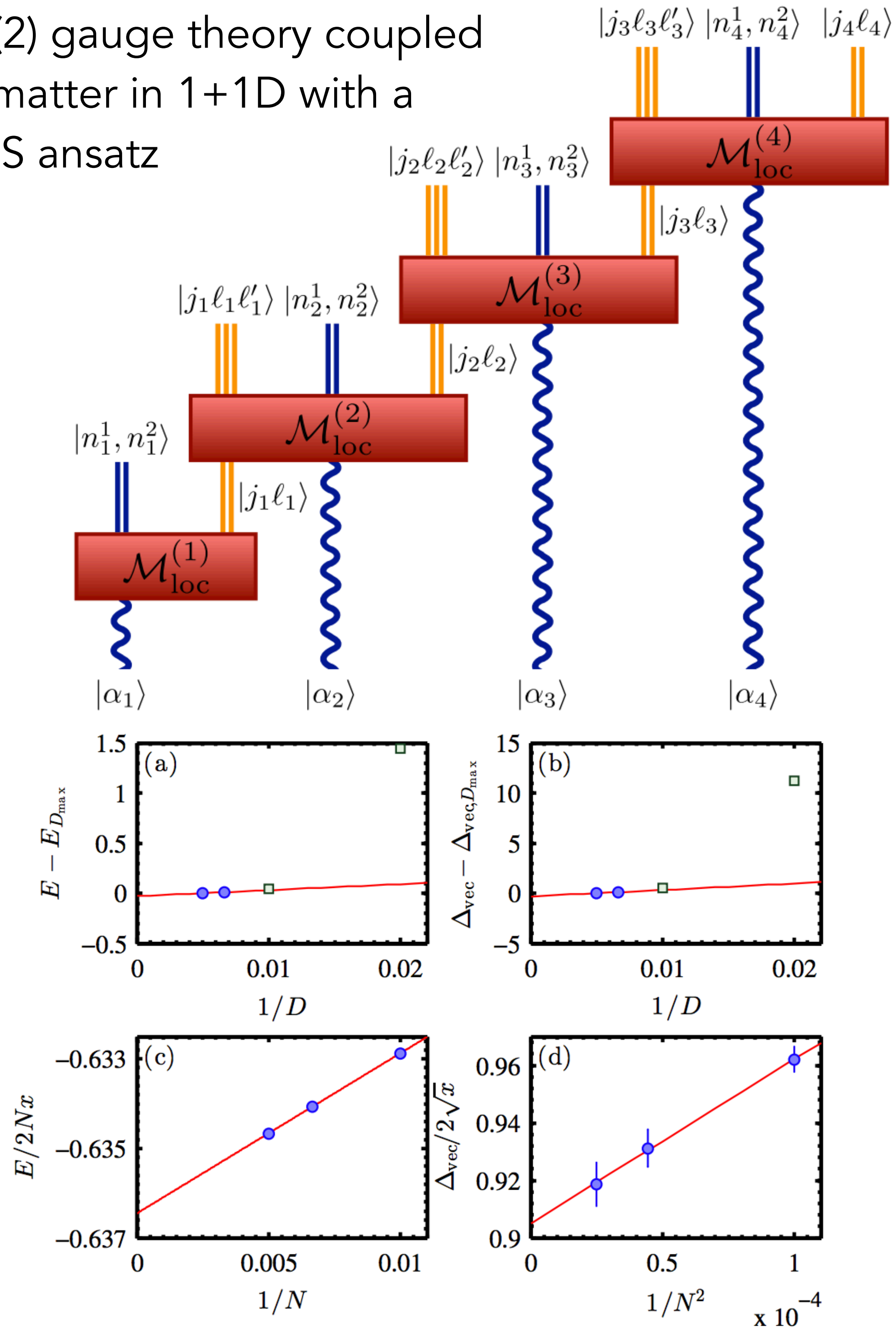
Avkhadiev, Shanahan, Young, Phys. Rev. Lett. 124, 080501 (2020)



Harmalkar, Lamm, Lawrence1, arXiv:2001.11490 [hep-lat]

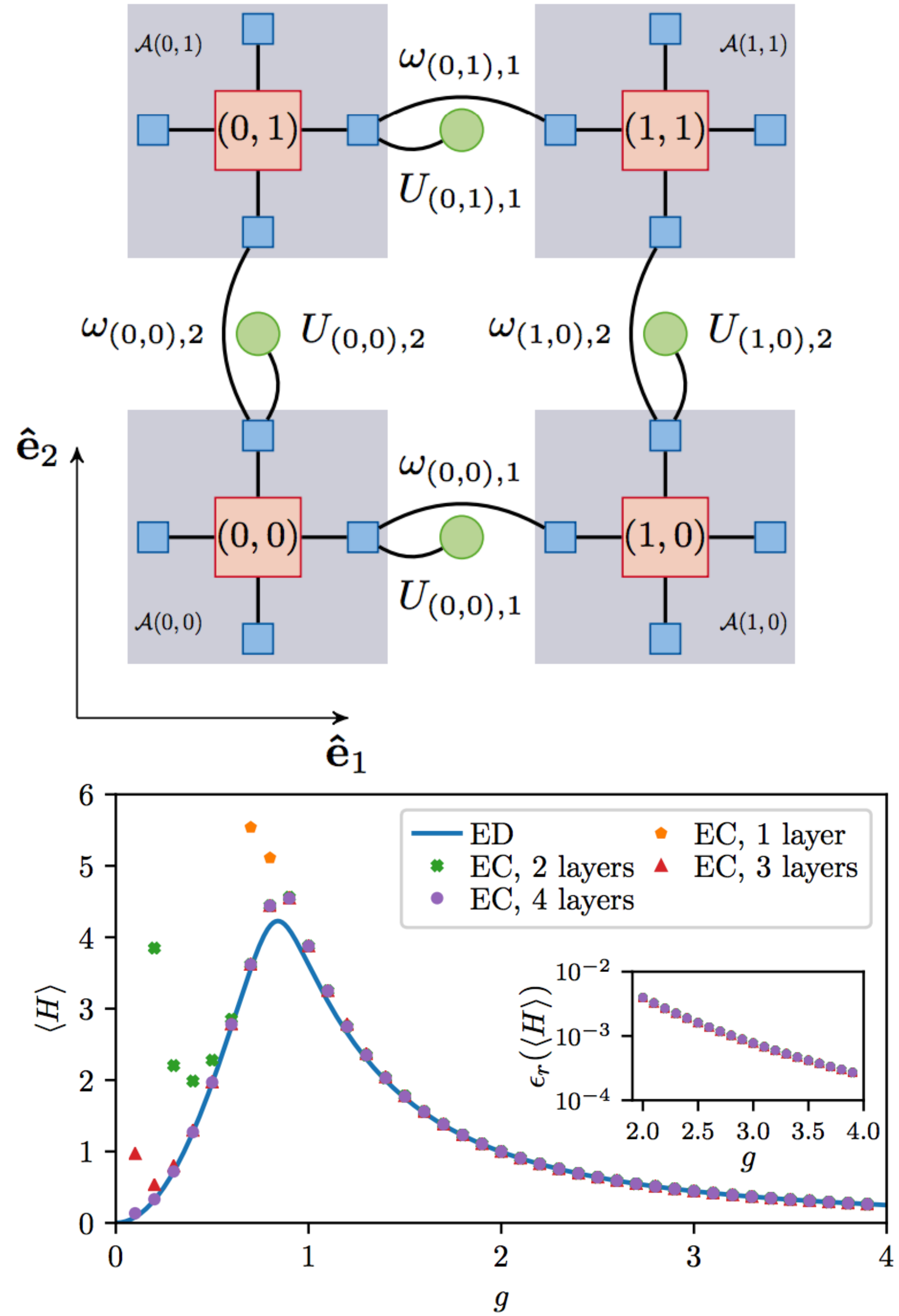
EXAMPLE III: TENSOR NETWORKS FORM CLASSICAL TO QUANTUM COMPUTING

SU(2) gauge theory coupled to matter in 1+1D with a MPS ansatz



Bañuls, Cichy, Cirac, Jansen, Kühn, Phys. Rev. X 7, 041046 (2017)

Z(3) gauge theory in 2+1D with a PEPS ansatz



Emonts, Bañuls, Cirac, Zohar, Phys. Rev. D 102, 074501 (2020)

For a recent nice review see: Meurice, Sakai, Unmuth-Yockey, arXiv:2010.06539 [hep-lat]

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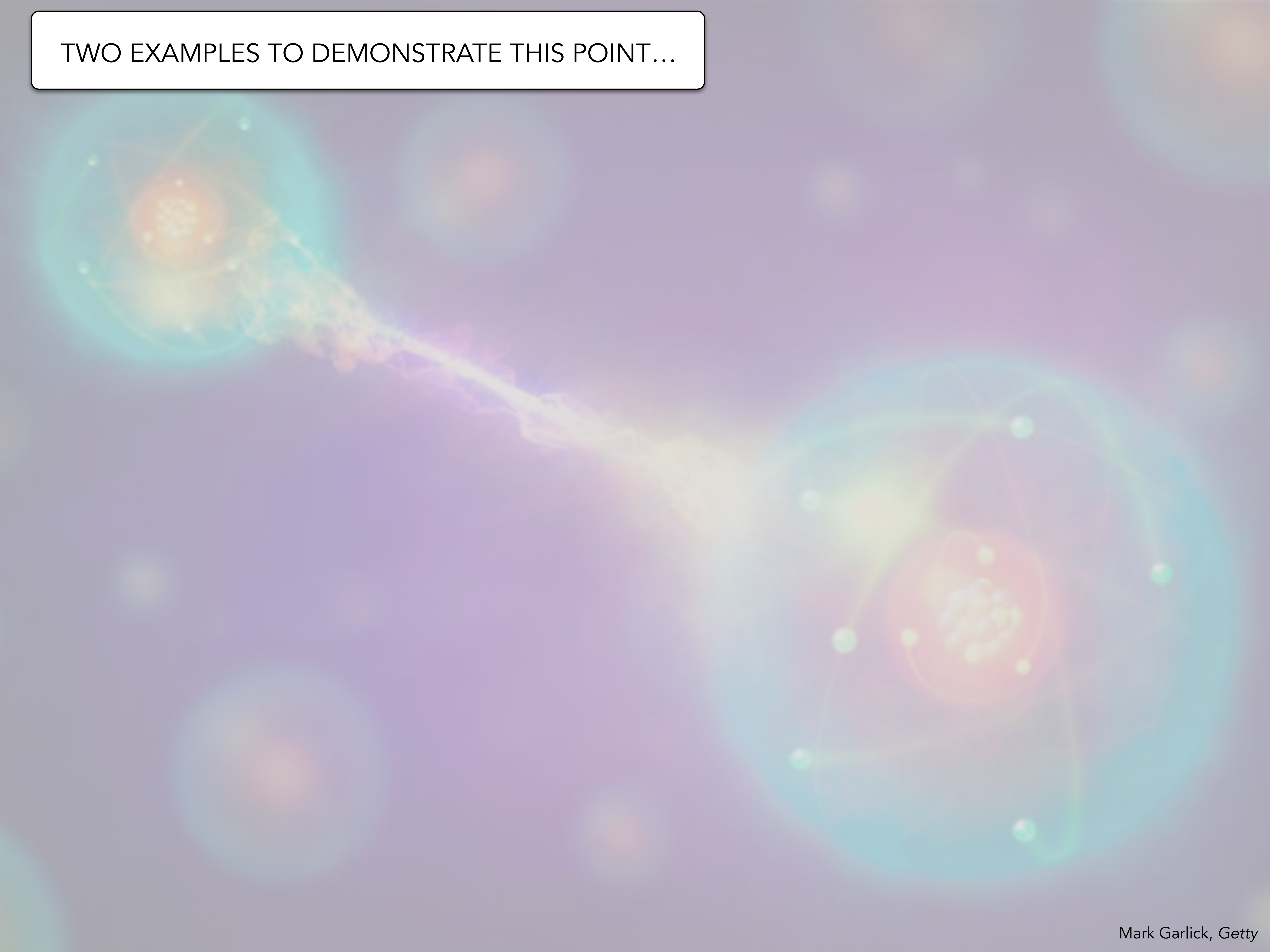
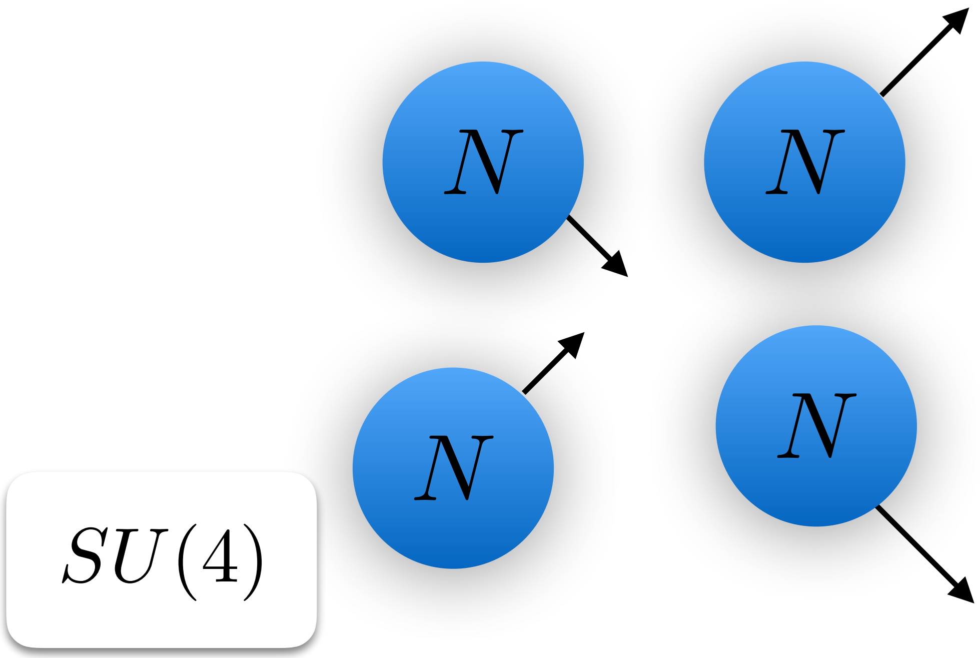
TWO EXAMPLES TO DEMONSTRATE THIS POINT…

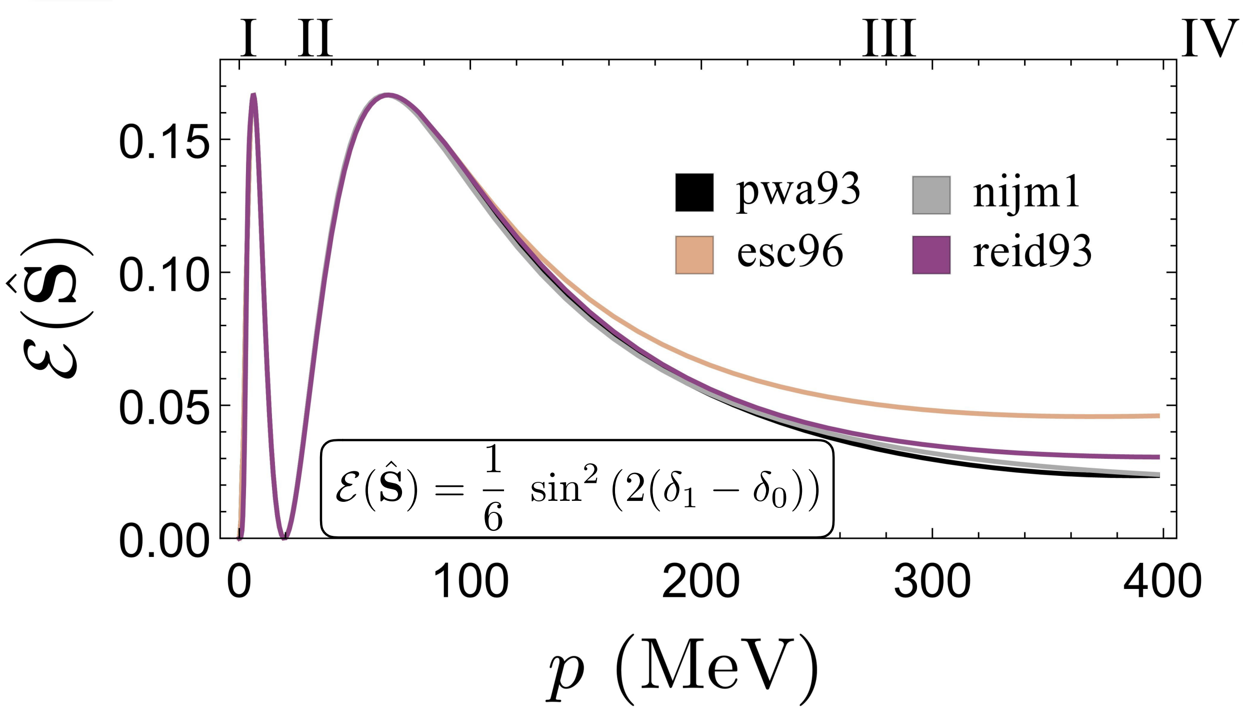


Mark Garlick, *Getty*

EXAMPLE I: QUANTUM ENTANGLEMENT IN LOW-ENERGY NUCLEAR PHYSICS

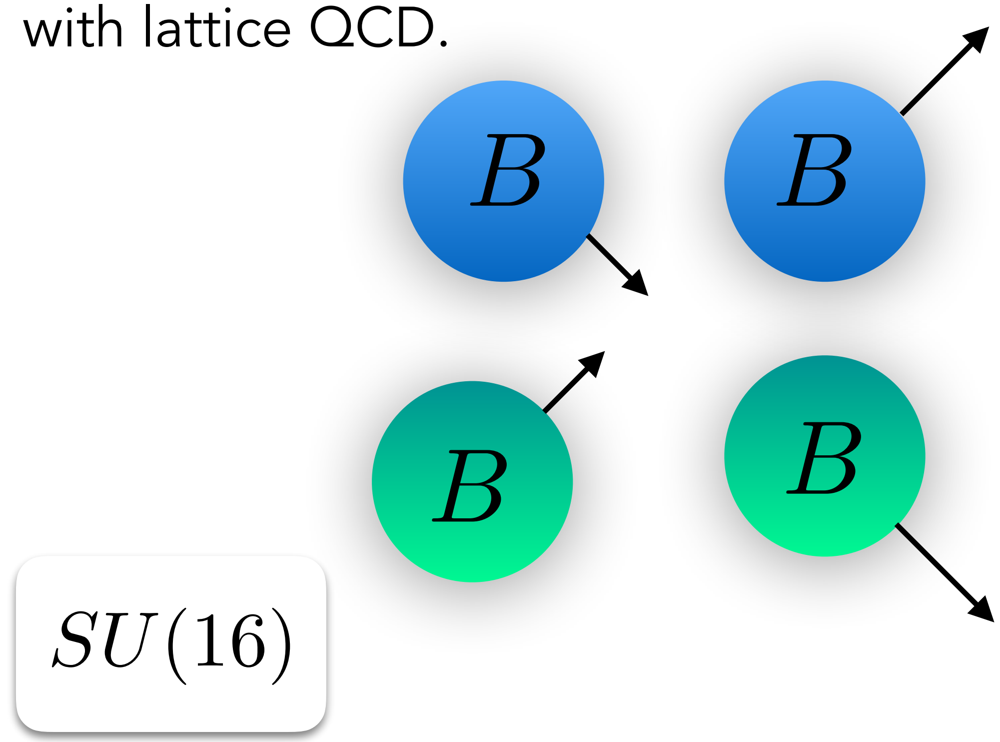
NN interactions at low energies are consistent with vanishing entanglement…

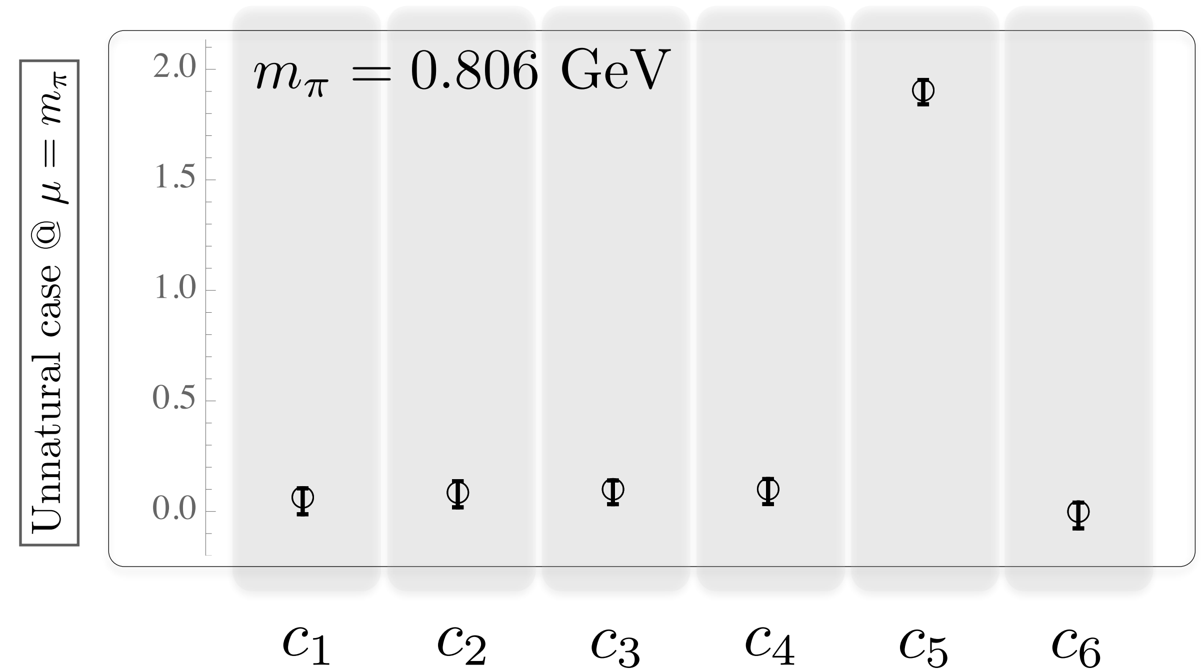




Beane, Kaplan, Klco and Savage, Phys. Rev. Lett. 122, 102001 (2019)

…as are low-energy BB interactions as obtained with lattice QCD.





Wagman, Winter, Chang, ZD, Detmold, Orginos, Savage, Shanahan (NPLQCD), Phys. Rev. D 96, 114510 (2017)

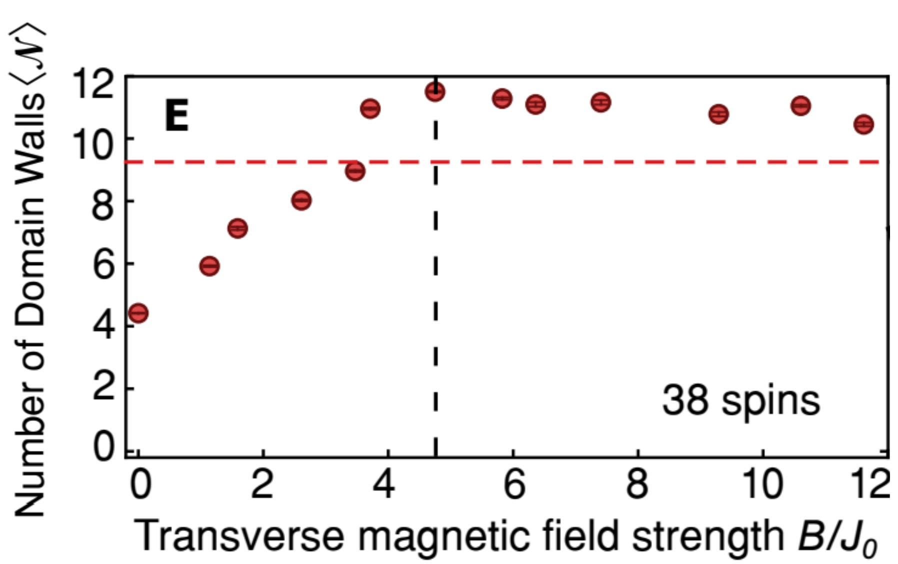
EXAMPLE II: SPIN MODELS AS PROTOTYPES OF QCD? CAN THEY REVEAL ENTANGLEMENT ASPECTS OF CONFINEMENT AND COLLISIONS?

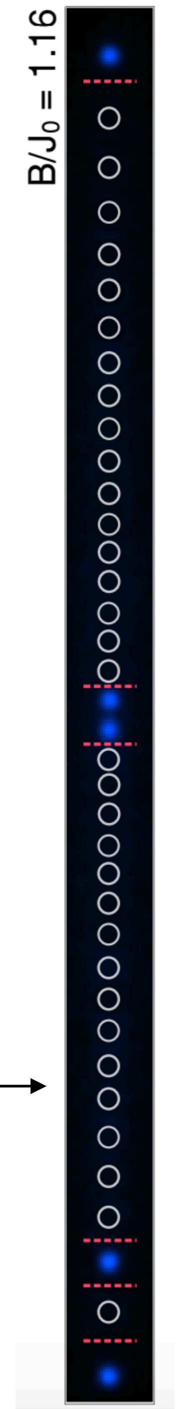
Transverse-field Ising model with long-range interactions in 1+1D exhibits an effective confining potential among domain walls: the "mesons"!

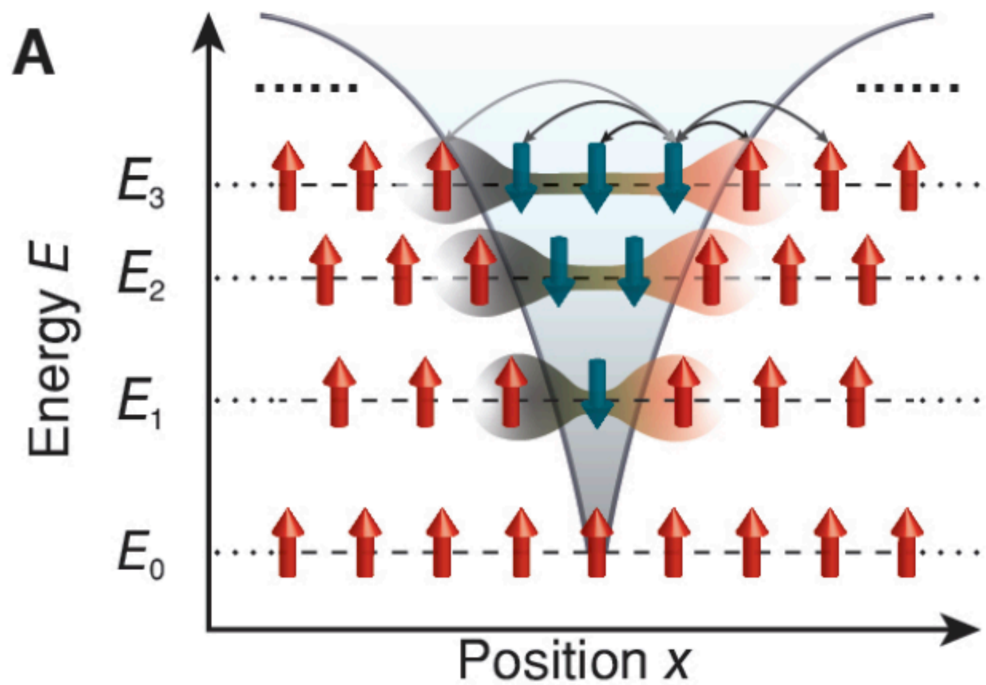
$$H = -\sum_{i<j}^{L} J_{i,j}\sigma_i^x\sigma_j^x - B\sum_{i}^{L}\sigma_i^z.$$

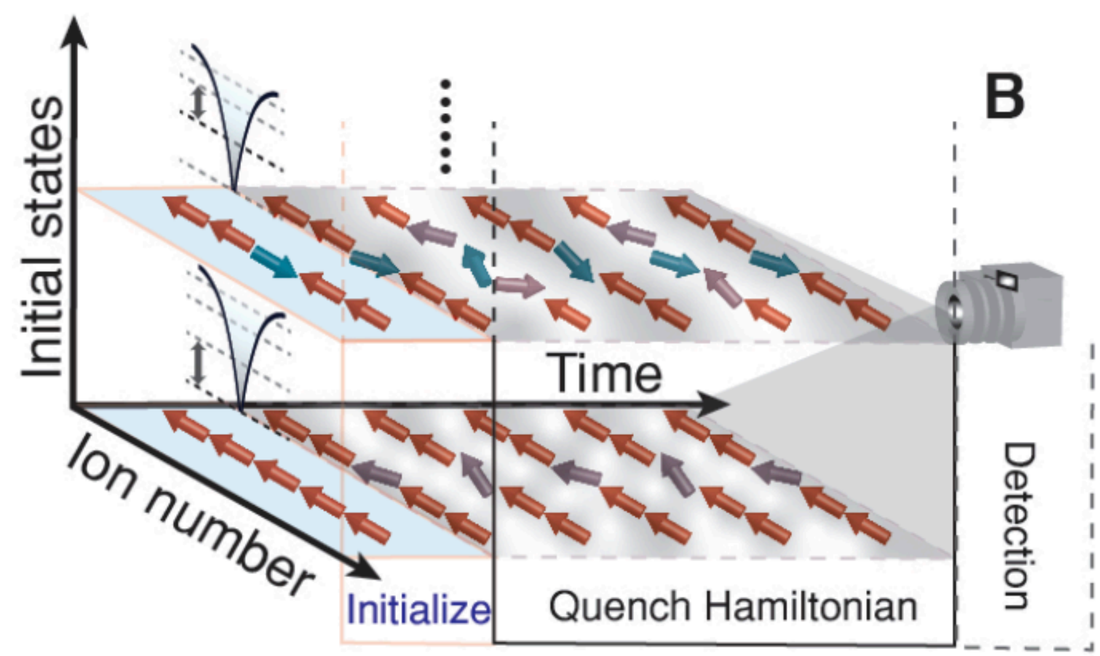
↓

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 F. Pederiva's talk regarding similar explorations at Trento.

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WITH THE INVOLVEMENT OF NP GROUPS AT UNIVERSITIES AND NATIONAL LABORATORIES, NUCLEAR PHYSICS IS ON THE PATH TO DEVELOPING A QIS-EXEPRT WORKFORCE.

IN PARTICULAR, THE ACTIVITIES IN THE U.S. HAVE RAMPED UP IN 2020…

Office of Science

Department of Energy Announces $17.7 Million for Quantum Information Science Research for Nuclear Physics

OCTOBER 29, 2020

University of Colorado	Argonne National Laboratory	Lawrence Livermore National Laborator
University of Maryland	Argonne National Laboratory	Purdue University
Michigan State University	University of Washington	Mississippi State University, Mississippi State, Mississippi
Massachusetts Institute of Technology	Lawrence Berkeley National Laboratory	Argonne National Laboratory (ANL), Lemont, IL
Pacific Northwest National Laboratory	Lawrence Livermore National Laboratory	University of Connecticut
University of Colorado	Massachusetts Institute of Technology	Thomas Jefferson National Accelerator Laboratory
Pacific Northwest National Laboratory	Pacific Northwest National Laboratory	

Department of Energy

Department of Energy Announces $625 Million for New Quantum Centers

JANUARY 10, 2020

Q-NEXT · Next Generation Quantum Science and Engineering

Director: David Awschalom
Lead Institution: Argonne National Laboratory

C^2QA · Co-design Center for Quantum Advantage

Director: Steve Girvin
Lead Institution: Brookhaven National Laboratory

QSA · Quantum Systems Accelerator

Director: Irfan Siddiqi
Lead Institution: Lawrence Berkeley National Laboratory

SQMS · Superconducting Quantum Materials and Systems Center

Director: Anna Grassellino
Lead Institution: Fermi National Accelerator Laboratory

QSC · The Quantum Science Center

Director: David Dean
Lead Institution: Oak Ridge National Laboratory

EXAMPLE: MARYLAND'S INTERDICIPLINARY TEAM

Nuclear Physics

I. RAYCHOWDHURY (P)

N. MUELLER (P)

J. STRYKER (P)

A. SHAW I (S)

Y. YAMUACHI (S)

UNIVERSITY OF MARYLAND 1856

MARYLAND CENTER for Fundamental Physics

JOINT QUANTUM INSTITUTE

JOINT CENTER FOR QUANTUM INFORMATION AND COMPUTER SCIENCE

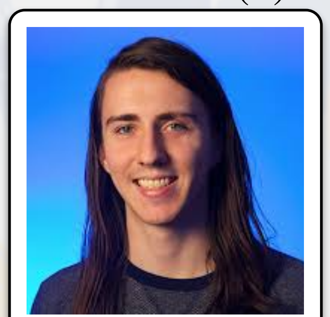
C. WHITE (P)

Condensed Matter Physics

A. BAPAT (S)

A. SHAW II (S)

T. SEWELL (S)

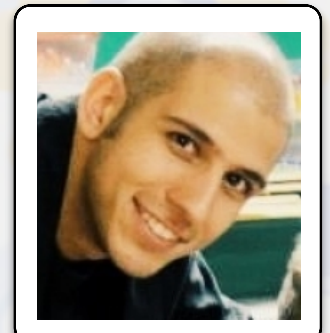


J. BRINGEWATT (S)

QIS/CS

N. NGUYEN (S)

A. SEIF (S)



Atomic, optical, and Molecular Physics

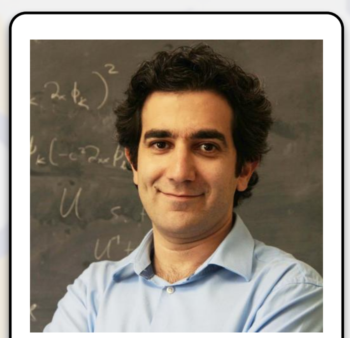
And many more starting to get involved!

P. BEDAQUE

A. CHILDS

A. GORSHKOV

M. HAFEZI



N. LINKE

C. MONROE

G. PAGANO

RICE

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THANK YOU